KU LEUVEN

ARENBERG DOCTORAL SCHOOL
FACULTY OF ENGINEERING SCIENCE

Assessing Circularity of Wood Cascading

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Dissertation presented in partial
fulfilment of the requirements for the
degree of Doctor of Engineering Science

ASSESSING CIRCULARITY OF WOOD CASCADING

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Dissertation presented in
partial fulfilment of the
requirements for the degree of
Doctor of Engineering Science
(PhD): Materials Engineering

September 2022

Uitgegeven in eigen beheer, Kranti Navare, Leuven, Belgium

Acknowledgments

Little did I know or think in 2015, when I first landed in this university city of Leuven that I would still be here, in Leuven at KUL for more than seven years. The thought of embarking on a PhD journey hardly ever crossed my mind while doing my master's. Two of my best friends, Amalia & Jorge - who also did a successful PhD stint in KU Leuven later, planted the thought. Coincidentally, around that time, while I was toying with that thought in my head, I happened to attend a very insightful lecture from Karel on circular economy at KUL's Metaforum - giving me ideas on the field I must pursue with fervour. When I finally started applying to PhDs and was invited for interviews, the interviewer – Steven Van Passel – redirected me to Karel. He suggested I was more suited for a PhD position with Karel's research group – SAM Sustainability Assessments of Materials and Circular Economy. Bit by bit, the Universe was unfurling its plot; I was being purposefully nudged and pushed to here – from the idea of a PhD to this research group, to being here today, to setting off a PhD track and finally closing it.

During this time, every person I met and every interaction I have had, one way or the other, made this journey possible, enjoyable and most importantly worthwhile. I am at a loss of words to express my humble gratitude, especially for the people who have motivated me, supported me, given me the strength to press on and even challenged and criticised me when a course correction was necessary. I thank, from the bottom of my heart, all those who have inspired me just by being who they are – with their creativity at work, attention to details and a sense of perfection. Thank you very much for sharing your experiences, expertise and thoughts that are quintessence of a critical mind. I secretly wish to be them. I take this moment also to thank the strangest and rarest of interactions, co-passengers on train journeys who showed a genuine interest in the topic I was researching. Even without the technical expertise, they mentioned how relevant and important this work was. I thank you – the reader – as you are one or more of these. Know that every interaction gave me the strength to wake up every morning and realise that my PhD is contributing to making a difference.

With this and with everything I pursue, I hope to make my family proud. My grandparents, my greatest champions, would definitely have been proud if they were here today.

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Abbreviations

EU	European Union
CDW	Construction and demolition waste
CE	Circular economy
CFF	Circular footprint formula
CO_2	Carbon dioxide
GHG	Greenhouse gas(es)
GWP	Global warming potential
HWP	Harvested wood products
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LCI	Life cycle inventory
MFA	Material flow analysis
PEF	Product environmental footprint
PET	Polyethylene terephthalate
PLA	Polylactic acid
RCF	Reductive catalytic fractionation
RSE	Relative statistical entropy
SEA	Statistical entropy analysis
TEA	Techno-economic assessment
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

Abiotic resources	Abiotic resources are inorganic (such as metals or minerals), non-living matter (such as fossil fuels) or synthetic material from non-living matter (such as fossil-based plastic). These resources are non-renewable or finite by nature.
Anthroposphere	That part of the environment made or modified by humans for use in human activities and human habitats. This includes agricultural systems, human-managed forests, animal husbandry, urbanised locations, and industrial networks.
Bio-based materials	Materials derived from biomass, excluding that embedded in geological formations or fossilised
Bio-economy	Economy pertaining to the production of biotic resources and their conversion into food, feed, biobased materials and energy.
Bio-composites	Composites that are made of a mixture of plastic (synthetic) polymers and natural fibres, such as wood (wood-plastic composites) or agricultural crops.
Biodegradability	Refers to the capability of being degraded under the action of micro-organisms.
Biogenic carbon	The carbon contained in the biomass accumulated during plant/tree growth through photosynthesis. In this PhD thesis, the term biogenic carbon is used synonymously with the term 'carbon embedded in bio-based materials'.
Biological cycles	Biological cycles, typically described by the left-hand side of the Ellen MacArthur Foundation's butterfly diagram, are the management of renewable biotic resources that can (potentially) safely cycle in and out of the biosphere (Ellen MacArthur Foundation, 2017). In this cycle, the resources are harvested from ecosystems, cascaded through several material applications, and at the end of their product life decompose to re-enter the biosphere and restore the natural capital. It would be more appropriate to refer to it as the 'biogeochemical cycle' because on decomposition the materials cycle through both biotic (biosphere) and abiotic (lithosphere, atmosphere, and hydrosphere) compartments of earth. In this PhD thesis, the biological cycle refers to the anthropogenic biological cycles – the part of the biological cycle affected by human functioning. It refers to the ecosystems and biogeochemical cycles affected by biomass extraction from nature and its transformation for human use and decomposition of that biomass to return to the biosphere. The understanding is that the natural biological cycles are circular by their nature. While the anthropogenic biological cycles might not necessarily be and this PhD thesis is suggesting frameworks to improve the circularity of these cycles.
Biological nutrients	Raw materials that are essential for living organisms to carry on life processes such as growth, synthesis of carbohydrates and other complex functions. Biological nutrients are carbon-based compounds, fixed nitrogen, phosphate, a variety of other minerals (such as K, Ca, Mg and Na compounds), and metals (such as Zn, Cu and Fe)

Biotic resources	Biotic resources are living organic matter produced by the biological system using atmospheric carbon and solar energy (e.g. wood, silk). These resources are intrinsically renewable in nature. This definition does not include resources embedded in geological formations or fossilised.
Biosphere	Part of the Earth and its atmosphere occupied by living organisms.
Bio-polymers	Polymers derived from biomass, excluding that embedded in geological formations or fossilised
Cascading	The working definition of cascading used in the study - *Cascading is the sequential use of wood, - wood industrial residues and recovered post-consumer wood, in multiple applications as long, as many times, and as efficiently as possible. Cascading foresees a value-oriented hierarchical biomass utilisation – using wood firstly in multiple high material-quality applications, followed by applications with decreasing material quality and ultimately for energy when no other material application is feasible. It is a means to extend service life, enhance resource efficiency and increase biomass availability.* By this definition, cascading is to increase material utilisation time (by increasing the service life of each application – increasing durability, reusability, etc. – and increasing the number of sequential applications) and slowing down quality loss by considering an end-of-life option that uses it for the highest material-quality applications possible. In a way, as suggested by Mair and Stern (2017), cascading contains all end-of-life options (reuse, repurpose, etc.) within one term.
Dissipative losses	The losses to the environment. The material that is unrecoverable, and thus for which recycling is inherently not feasible.
Material	Material is a substance or a mixture of substances, which exhibit properties (mechanical, chemical, optical, electrical, thermal, magnetic) that determine its usability and hence its application. Unlike substances, it has a defined shape and size which provide it with its physical properties. With this definition, 'wood' is a material (not a substance).
Material flow	Flow (defined as mass flow rate) of a material or mixture of materials. It could be resource flow, product flows, components flows, or waste flows.
Material value	It is the use value – the benefit provided by the material to humans. It is the utility or functionality provided by the resource based on the inherent and intrinsic material quality (physical, chemical, mechanical or structural properties). In this PhD thesis, the term 'material value' is used to indicate (and used synonymously with) the functional value, use value, or utility. It does not refer to economic value. Odegard et al. (2012) define value as an alternative leaving as many options open as possible for subsequent use. This definition is not explicitly used for the PhD thesis but is relevant for the research.

Material quality	This has been derived from the definition proposed by Sirkin and Houten (1994). It is the measure of potential resource utility – the capacity to perform tasks of varying degrees of difficulty. It is a function of embodied energy, chemical composition or structural organisation of a given resource, substance or material. It is also a function of the effort required to produce or reproduce the quality.
Resource	A 'resource' is considered as such when it has an intrinsic 'value' or 'utility' for humans (Beylot et al., 2020), encompassing abiotic (fossils and minerals) and biotic (biomass) resources.
Substance	A substance is any (chemical) element or compound composed of uniform units. All substances are characterised by a unique and identical constitution and are thus homogeneous (Brunner and Rechberger, 2004). Substances differ only in size and shape but not in other specific properties such as colour, density, electric conductivity, solubility, etc. Using this definition, 'wood' is not a substance
Substance composition	Substance composition in a material flow is the relative amounts of the substances that constitute the material.
Technical cycles	Technical cycles, typically described by the right-hand side of the Ellen MacArthur Foundation butterfly diagram, contain flows of materials that are limited in the environment (Ellen MacArthur Foundation, 2015a, 2015b). Hence, technical cycles are designed to circulate resources in the anthroposphere as long as possible.
Technical nutrients	A material of human artifice required to provide products and services for human use.
Virgin wood	Wood that is derived from the forest. In this PhD thesis, this term is used synonymously with the term 'fresh wood' and 'primary resources' when referring to wood.
Waste wood	Wood that is a either a by-product of an industry (referred to as 'industrial residue') or from the end-of-life of a wood product (referred to as 'post-consumer waste wood'). In this PhD thesis, the term 'waste wood' is used synonymously with the term 'recovered wood' and 'secondary resource'.

Summary

"Waste is only waste, if we waste it"
Will.I.Am, musician

Waste is just a design flaw. This well-known saying underlines that waste is preventable by better design of products, processes, industrial systems and the functioning of society. That is also the underlying objective of the transition from a take-make-use-waste linear economy to a circular economy (CE): designing systems to reduce waste by maintaining the functionality and value of products and materials in the economy for as long as possible. Firstly, by reusing and repairing the products and components and subsequently recycling the materials in those products. These practices reduce the need for primary resources and the environmental impact of raw material extraction and waste treatment. This principle is valid for finite abiotic resources (such as metals and minerals) but not necessarily for renewable biotic resources (such as wood). Biomass use, in essence, does not need to be reduced but harvested in a manner that does not affect the regenerative capacity of ecosystems. Secondly, biotic resources degrade during their use and processing, and recycling them back to their original form and functionality is often unattainable. Alternatively, they are cascaded through sequential applications to minimise the need for primary raw materials. Lastly, these materials are biodegradable in the natural biological cycle and safely return to nature as nutrients. But in the anthropogenic biological cycles, these materials might not be biodegradable or are toxic or decompose in a place or at a rate that affects ecosystem functioning. If the release of nutrients is not in sync with ecosystem absorption capacity, they accumulate in the environment and cause pollution disrupting the natural biological cycles (e.g. eutrophication). So, CE monitors – that evaluate and guide the transition from linear to circular economy – need to assess more than the core principles of CE to achieve circularity in biotic resources. They also need to assess cascading use and ensure that harvesting these resources and their decomposition do not harm the ecosystem's functioning. These are the gaps in monitoring CE of anthropogenic biological cycles (hereinafter, referred to as 'biological cycle'), which need attention to ensure sustainable use of natural resources and avoid further degradation of ecosystems.

This PhD research focuses on closing one of the gaps for monitoring the circularity of biological cycles, specifically assessing cascading use. The word cascading originates from an analogy to the cascade of a river, in which the water descends through different levels with decreasing potential energy. In wood-cascading, wood passes through multiple sequential applications with declining material quality. Cascading of wood is promoted to maximise the value extracted from the wood to reduce the need for primary resources and ease the pressure on the environment. Material value (the functionality or utility provided by resources) is provided by material quality, i.e. inherent physical and chemical properties. Thus, cascading strategies aim to preserve the wood quality for as long as possible to maximise its value. So, the two dimensions of cascading are material quality and cascade lifespan. Cascading assessments commonly measure resource use efficiency and environmental impact but lack quantitatively assessing wood quality

and lifetime. This PhD research aims to fill the gaps by developing a methodological framework to evaluate wood cascading by accounting for the material quality and cascade lifespan.

Statistical entropy analysis (SEA) has been proposed as a generic methodology to assess the quality of material flows and could be a tool for evaluating the 'material quality' dimension of cascading. SEA is applied to material flows to measure the distribution of substances, considered an indicator of the quality of material flow. With a higher concentration of a substance in a material flow or a lower number of substances present in a material flow, the effort needed to recover and recycle the substance tends to decrease – quantified as lower statistical entropy. The substance concentration, indicating composition complexity, is a proxy for the quality of material flows containing substances – metals and minerals. These flows degrade in quality (commonly observed in the recycling process) when mixed with other (often undesirable) substances. It lowers inherent properties (such as decreased mechanical properties) and increases the energy required to separate and recycle individual metals from the mix. However, for material flows containing materials themselves, such as wood, textiles, and plastics, the quality loss is not only due to undesirable substances (impurities) but also due to the physical degradation of the material. In wood, the natural fibres degrade, leading to size reduction or breakdown of wooden components and the loss of their physical and structural properties. For example, a wooden construction beam degrades during processing and use over time. After a point, it cannot serve as a beam anymore but can be cascaded to a lower-grade application, such as a window frame. Hence, statistical entropy for wood products needs to be defined based on the dimensional properties of wood elements. In this PhD study, the existing SEA methodology has been adapted to quantify the physical complexity of the wood flows (and products), in addition to compositional complexity, to apply it to assess cascading. The adaptions are demonstrated with a cascading case study, wherein statistical entropy values are calculated over time for the different cascading pathways, and the one that maintains entropy low for the longest time is considered the most circular resource use.

SEA methodology, which identifies the highest material-value cascading pathway, is complemented with life cycle assessment (LCA) to optimise and improve resource use along that pathway. LCA is a well-established methodology used to determine the resource inputs to the system and the associated environmental impacts. However, LCA studies rarely account for the cascade lifespan, while the wood is cascaded precisely to maximally extend the service life and, consequently, delay the emissions of carbon embedded in wood products. The duration over which carbon stays stored in the wood products affects the net global warming potential (GWP) of cascading systems. Hence, it is essential to consider the cascade lifespan in LCA while assessing its carbon balance. The LCA study, part of the PhD research, describes the approach to including the temporal information in the LCA.

This PhD research concludes that a combined assessment using SEA and LCA is adequate to evaluate cascading systems. SEA measures the material circularity of wood cascading, i.e. quantifies material value over time, over multiple applications and material flows (i.e. multiple material streams -

products, by-products and residues). It identifies the optimal resource-use pathway that maximally preserves the material value and functionality over time. Complementing it with LCA makes it possible to improve resource efficiency (by reducing the overall resources required) and reduce the environmental impact of the resource-use trajectory identified by SEA. Thereby, this PhD research contributes to closing the gaps in cascading assessment by providing a quantitative assessment of change in material quality over the cascade lifespan and is a step forward in filling the gap in CE monitoring by quantifying material circularity and the environmental impact of cascading systems.

Samenvatting

Afval is eenvoudigweg een ontwerpfout. Dit bekende gezegde onderstreept dat afval te voorkomen is door producten, processen, industriële systemen en het functioneren van de samenleving beter te ontwerpen. Dat is ook de achterliggende doelstelling van de overgang van een lineaire take-make-use-waste-economie naar een circulaire economie (CE): het ontwerpen van systemen om afval te verminderen door de functionaliteit en waarde van producten en materialen in de economie zo lang mogelijk te behouden, in de eerste plaats door de producten en onderdelen te hergebruiken en te herstellen en vervolgens de materialen in die producten te recycleren. Op deze manier vermindert de behoefte aan primaire grondstoffen en het milieueffect van de winning van grondstoffen en de afvalverwerking. Dit principe geldt voor eindige abiotische grondstoffen (zoals metalen en mineralen), maar niet noodzakelijkerwijs voor hernieuwbare biotische grondstoffen (zoals hout). Het gebruik van biomassa hoeft in wezen niet te worden verminderd, maar moet worden geoogst op een manier die het regeneratievermogen van ecosystemen niet aantast. Ten tweede degraderen biotische grondstoffen tijdens hun gebruik en verwerking, en is recycleren tot hun oorspronkelijke vorm en functionaliteit vaak niet haalbaar. Anderzijds worden zij in opeenvolgende toepassingen gecascadeerd om de behoefte aan primaire grondstoffen tot een minimum te beperken. Ten slotte zijn deze materialen biologisch afbreekbaar in de natuurlijke biologische cycli en keren zij veilig als voedingsstoffen terug naar de natuur. Maar in de antropogene biologische cycli zijn deze materialen misschien niet biologisch afbreekbaar, kunnen ze giftig zijn of worden ze afgebroken op een plaats of in een tempo dat de goede werking van het ecosysteem aantast. Als het vrijkomen van nutriënten niet synchroon loopt met de absorptiecapaciteit van het ecosysteem, hopen ze zich op in het milieu en veroorzaken ze verontreiniging die de natuurlijke biologische cycli verstoort (bv. eutrofiëring). CE-monitors - die de overgang van een lineaire naar een circulaire economie evalueren en begeleiden - moeten dus meer dan de kernbeginselen van CE beoordelen om circulariteit in biotische grondstoffen te bereiken. Ze moeten ook het cascadegebruik beoordelen en ervoor zorgen dat het oogsten van deze grondstoffen en de afbraak ervan geen schade toebrengen aan het functioneren van het ecosysteem. Dit zijn de hiaten in de monitoring van CE van antropogene biologische cycli (hierna "biologische cyclus" tout court genoemd), waarvoor aandacht nodig is om duurzaam gebruik van natuurlijke grondstoffen te verzekeren en verdere degradatie van ecosystemen te voorkomen.

Dit doctoraatsonderzoek richt zich op het dichten van een van de hiaten in het monitoren van de circulariteit van biologische cycli, specifiek het beoordelen van cascaderend gebruik. Het woord cascade vindt zijn oorsprong in een analogie met de cascade van een rivier, waarin het water door verschillende niveaus afdaalt met afnemende potentiële energie. In een houtcascade doorloopt hout opeenvolgende, meervoudige toepassingen met afnemende materiaalkwaliteit. Cascadering van hout wordt gepromoot om de waarde die aan het hout wordt onttrokken te maximaliseren en zo de behoefte aan primaire grondstoffen te verminderen en de druk op het milieu te verlichten. De materiaalwaarde (de functionaliteit of het nut van grondstoffen) wordt bepaald door de materiaalkwaliteit, d.w.z. de inherente fysische en chemische eigenschappen. Cascadestrategieën zijn er dus op gericht de kwaliteit van het hout zo lang mogelijk te behouden om de waarde ervan te maximaliseren. De twee dimensies van cascadering zijn dus de materiaalkwaliteit en de cascade-levensduur. Evaluaties van cascades meten gewoonlijk de efficiëntie van het grondstoffengebruik en de milieu-impact, maar kwantitatieve evaluaties van de houtkwaliteit en -levensduur ontbreken. Dit doctoraatsonderzoek wil deze leemtes opvullen door een methodologisch kader te ontwikkelen om houtcascadering te evalueren door rekening te houden met de materiaalkwaliteit en de cascade-levensduur.

Statistische entropieanalyse (SEA) wordt voorgesteld als een generieke methode om de kwaliteit van materiaalstromen te beoordelen en zou een instrument kunnen zijn om de dimensie "materiaalkwaliteit" van cascadering te evalueren. SEA wordt toegepast op materiaalstromen om de verdeling van stoffen te meten, die als een indicator voor de kwaliteit van de materiaalstroom wordt beschouwd. Bij een hogere concentratie van een stof in een materiaalstroom of een lager aantal stoffen in een materiaalstroom, neemt de inspanning die nodig is om de stof terug te winnen en te recycleren af - gekwantificeerd als een lagere statistische entropie. De stofconcentratie, die de complexiteit van de samenstelling aangeeft, is een proxy voor de kwaliteit van materiaalstromen die stoffen - metalen en mineralen - bevatten. Deze stromen verslechteren in kwaliteit (vaak waargenomen in het recyclageproces) wanneer ze worden gemengd met andere (vaak ongewenste) stoffen. Het verlaagt de inherente eigenschappen (zoals verminderde mechanische eigenschappen) en verhoogt de energie die nodig is om de afzonderlijke metalen uit de mix te scheiden en te recycleren. Voor materiaalstromen die materialen zelf bevatten, zoals hout, textiel en kunststoffen, is het kwaliteitsverlies echter niet alleen te wijten aan ongewenste stoffen (onzuiverheden), maar ook aan de fysieke degradatie van het materiaal. In hout degraderen de natuurlijke vezels, wat leidt tot verkleining of afbraak van houten onderdelen en tot verlies van hun fysische en structurele eigenschappen. Zo degradeert bijvoorbeeld een houten constructiebalk tijdens de verwerking en het gebruik in de loop van de tijd. Na een bepaald punt kan hij niet meer als balk dienen, maar kan hij worden omgevormd tot een toepassing van lagere kwaliteit, zoals een raamkozijn. Daarom moet de statistische entropie voor houtproducten gedefinieerd worden op basis van de dimensionele eigenschappen van houtelementen. Deze doctoraatsstudie heeft de bestaande SEA-methodologie aangepast om de fysische complexiteit van de houtstromen (en -producten) te kwantificeren, naast de compositorische complexiteit, om ze toe te passen bij de beoordeling van cascadering. De aanpassingen worden gedemonstreerd met een casestudy naar cascadering, waarin statistische entropiewaarden in de tijd worden berekend voor de verschillende cascaderingsroutes, en de route die de entropie het langst laag houdt, wordt beschouwd als het meest circulaire grondstofgebruik.

De SEA-methode, waarbij de cascaderingsroute met de hoogste materiaalwaarde wordt geïdentificeerd, wordt aangevuld met een levenscyclusbeoordeling (LCA) om het grondstoffengebruik langs die route te optimaliseren en te verbeteren. LCA is een gekende methodologie die wordt gebruikt om de input van grondstoffen in het systeem en de bijbehorende milieueffecten te bepalen. LCA-studies houden echter zelden rekening met de cascade-levensduur, terwijl het hout juist wordt gecascadeerd om de levensduur maximaal te verlengen en bijgevolg de uitstoot van de koolstof die in houtproducten is ingebed, uit te stellen. De duur dat koolstof in de houtproducten opgeslagen blijft, beïnvloedt het netto aardopwarmingsvermogen (GWP) van cascadesystemen. Daarom is het essentieel om in de LCA rekening te houden met de levensduur van cascadesystemen bij de beoordeling van hun koolstofbalans. De LCA-studie, die deel uitmaakt van het doctoraatsonderzoek, beschrijft de aanpak om de temporele informatie in de LCA op te nemen.

In dit doctoraatsonderzoek wordt geconcludeerd dat een gecombineerde beoordeling met behulp van SEA en LCA de evaluatie van cascadesystemen op adequate wijze kan doen. SEA meet de materiële circulariteit van houtcascadering, d.w.z. kwantificeert de materiële waarde in de tijd, over meerdere toepassingen en materiaalstromen (d.w.z. meerdere materiaalstromen - producten, bijproducten en residuen). Het identificeert de optimale route voor het gebruik van grondstoffen waarbij de materiaalwaarde en functionaliteit in de tijd maximaal behouden blijven. Door dit aan te vullen met een LCA kan de grondstoffenefficiëntie worden verbeterd (door de totale hoeveelheid benodigde grondstoffen te verminderen) en kunnen de milieueffecten van het door SEA vastgestelde traject voor grondstoffengebruik worden verminderd. Daarnaast draagt het doctoraatsonderzoek bij aan het dichten van de hiaten in de cascadebeoordeling door een kwantitatieve beoordeling te geven van de verandering in materiaalkwaliteit gedurende de levensduur van de cascade. Ten tweede draagt het bij tot het opvullen van de leemte in CE-monitoring door de circulariteit van materialen en de milieueffecten van cascadesystemen te kwantificeren.

Chapter 1: Introduction

"If I have seen further it is by standing on the shoulders of Giants"
Isaac Newton

Circular economy (CE) strategies are adopted to promote sustainable resource use and address environmental challenges. The European Commission defines CE as a system that maintains the value of products, components and materials in the economy for as long as possible and minimises the generation of waste (European Commission, 2015a). Products are designed and built to stay in use for longer, ease reuse, repair and remanufacture, and are ultimately recycled to keep the material in use for as long as possible. The European Union (EU) views the transition to CE as essential to attain a sustainable, resource-efficient, and competitive economy. While the focus was originally on reducing dependency on raw materials, the CE transition is now considered crucial to achieving climate goals and preserving biodiversity (European Commission, 2020).

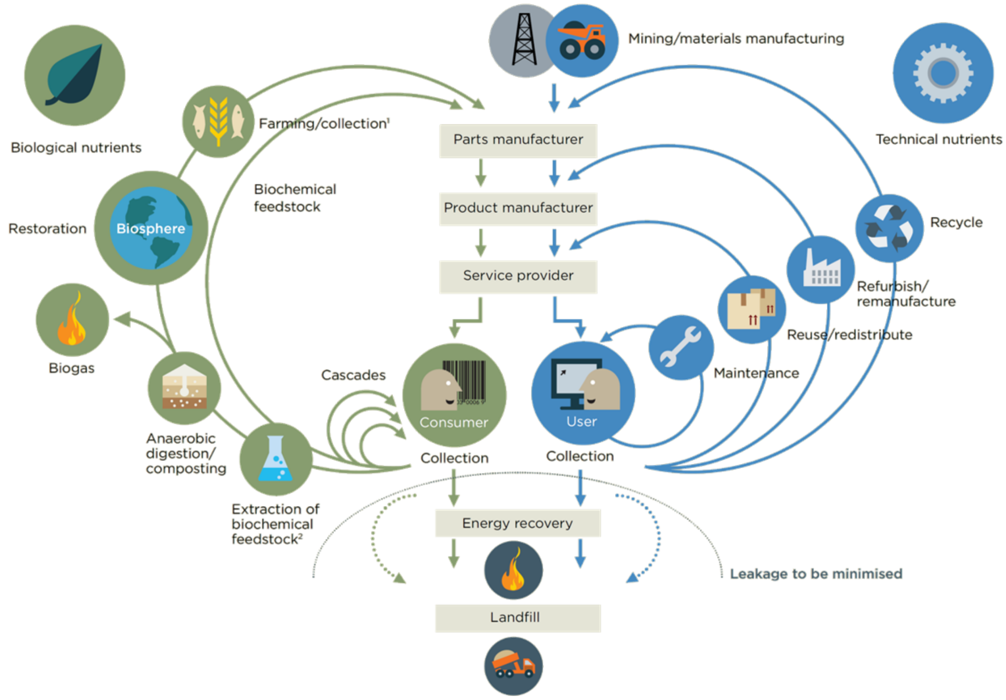


Figure 1.1: The circular economy butterfly diagram

The right-hand side refers to the technical nutrients cycles, and the left-hand side refers to the biological nutrients cycles (Ellen MacArthur Foundation, 2015a)

The CE principles distinguish technical and biological cycles (Braungart et al., 2007; Ellen MacArthur Foundation, 2015a). The distinction between these cycles is well illustrated in the CE 'butterfly diagram' by the Ellen MacArthur Foundation (Fig. 1.1; Ellen MacArthur Foundation, 2015a, 2015b).

Technical cycles involve managing non-renewable abiotic resources. Biological cycles apply to renewable biotic resources that can safely cycle in and out of the biosphere. Abiotic resources, being finite, must ideally be kept in the anthroposphere for as long as possible. These resources have to be mined (in the case of inorganic materials like metals and minerals) or produced (in the case of synthetic materials like plastics) and then transformed into a final product through a production process. In CE, firstly, the product value or functionality is preserved as much as possible for as long as possible (by maintenance, reuse, repair, etc.). When the product functionality can no more be in use, then the value of the material contained in that product is conserved by recycling (Ellen MacArthur Foundation, 2015a). Biotic resources, on the contrary, are used for consumption (such as food) or cascaded in use (textiles, wooded furniture), and subsequently, they decompose to re-enter the biosphere (Bocken et al., 2016; Braungart et al., 2007).

The shift from a linear to a circular economy needs monitoring to guide the transition and measure the extent to which the desired outcome is achieved. Numerous CE indicators or metrics already exist. Several review papers have collated a list of these indicators (Corona et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Rossi et al., 2020; Saidani et al., 2019). Saidani et al. (2019) published the most extensive list of CE indicators containing 55 CE monitors. Parchomenko et al. (2019) listed 63 indicators - although these also included indicators not specific to CE assessment but potentially applicable. The first step was to question the need for additional CE metrics when several exist already. Thus, **the first objective of this PhD research is to study existing CE monitors to evaluate their relevance and applicability for biological cycles.**

This study observed that most CE monitors mainly assess the extent of looping (reuse, recycling, etc.) resources back to the economy to reduce the need for primary resources and waste disposal. Biotic resources are, however, renewable and biodegradable. So, the core criteria for CE monitoring, i.e. reducing the input of primary resources and waste generation, are inadequate to assess the circularity of biological cycles. Their circularity depends, firstly, on sourcing these resources sustainably, i.e. harvesting them without affecting the functioning of the ecosystem. Secondly, it depends on whether the decomposition of biomass is in place and at a rate that is in sync with ecosystem absorption capacity, without which biological nutrients accumulate in the environment, causing pollution and disrupting the natural biological cycles. Additionally, the nutrients scarce and essential for ecosystem regeneration are deposited in the place where needed. Thirdly, the physical properties of biotic resources degrade with time, during use and processing, which limits their recycling potential. Therefore, in CE, they are cascaded – via sequential use of the resources in multiple applications – to minimise the need for primary raw material extracted from nature and slow down the material (nutrient/CO_2) release to the environment. Chapter 2 details these gaps in CE monitoring criteria and suggests adaptation to close those gaps and accurately monitor the circularity also of biological cycles.

The gaps in monitoring the circularity of biological cycles pertain to the sourcing of biotic resources, their cascaded use and end-of-life nutrient cycling. This PhD research aims to close one of these gaps, specifically, the assessment of cascading use. Most predominant examples of the implementation of cascading principles are found in the wood-based industry, so the focus was drawn to woody biomass from among the biotic resources, and the research focused on evaluating wood cascading. **The research objective was to assess the material circularity of cascading use of wood**.

There is no official or agreed-upon definition of 'cascading use', so the first step to achieving the objective was reviewing the commonly accepted definitions and determining a working definition for the study. That was followed by studying the concepts and elements of cascading and existing assessment methodologies of cascading use. Since several assessment methodologies exist already, the study evaluated the effectiveness of the existing ones to validate the need for a new methodology or adaptation to an existing methodology.

Despite the lack of agreement on the definition of cascading, a common thread is the aim to maximise the material value by preserving the material quality over time through several sequential applications. Yet, material quality and cascading lifespan did not appear in the existing assessment methodologies of cascading systems. Chapter 3 describes the concept and existing assessment methodologies of cascading and highlights the gaps in assessing cascading systems. This PhD research then focused on filling this gap. The goal was to identify methods that could evaluate the change in material quality over the cascade lifespan and thus potentially be a tool for assessing cascading use. Statistical entropy analysis (SEA) appears to be one such method. SEA is a generic method to quantify the quality of material flows based on the distribution of constituent substances (Laner et al., 2017; Rechberger and Brunner, 2002) and could evaluate that aspect of a cascading system. SEA can be complemented with life cycle assessment (LCA) methodology to assess the environmental impact of resource use in cascading. While one can use SEA to evaluate material quality over time to determine which cascading pathway maintains material quality for the longest time, LCA supports improving resource efficiency and reducing the environmental burden of that cascading pathway. **The research hypothesis was that a combined assessment using SEA and LCA would be a complete toolbox for assessing the circularity and the environmental impact of wood cascading.**

The next step in this research was to validate the applicability of these methodologies – SEA and LCA – to cascading systems. However, while doing so, this study found shortcomings in both these methodologies. SEA defines statistical entropy based on the compositional complexity of material flows, i.e. constituent substances and relative concentration of those substances. The higher the number of substances present in a product or material flow and the more uniform their distribution, the higher its statistical entropy. Substance composition is indeed relevant for the quality of abiotic materials. For example, the quality of metals degrades when mixed with other (often undesirable or lower grade materials) substances. This commonly occurs during recycling processes (e.g. aluminium recycling). Mixing often lowers inherent properties (such as inferior mechanical properties) and increases the energy required to separate and recycle the individual metal from a mix. However, in bio-based materials, especially wood, the quality loss is not only because of the mixture with other materials (or substances) but also because of the degradation of natural fibres. That leads to the size reduction or breakdown of the components built from wood and loss of their physical (dimensional and structural) properties, which diminishes their material value or utility. For example, a timber beam deteriorates over time. When discarded, the waste wood is shredded. Wood chips have lower structural properties but can be used in particleboards. Wood is cascaded further to chemicals or is incinerated for energy recovery, with further degradation of the natural fibre structures in wood at every stage. So, the subsequent step of this PhD research focuses on fixing this shortcoming in the SEA methodology. Statistical entropy is now defined based on dimensional characteristics (size, with mass as a proxy). The adapted methodology is demonstrated using a simplified case study to exemplify its applicability. Chapter 4 describes the adaptions made to SEA for wood cascading and demonstrates its use by comparing entropy evolution over time for different types of wooden pallets (multiple-use pallets, single-use pallets and cardboard pallets) and their cascaded use.

When wood loses structural properties and is no longer fit for solid-wood products, it can be used for fuel or chemical production. At this stage, the structural properties of wood components are irrelevant, but the molecular properties play a crucial role. Woody biomass constitutes (hemi-) cellulose and lignin. These heterogeneous polymeric compounds have a functional value of their own. Analogously to solid wood cascading, bio-refineries strive to maintain and utilise the molecular properties of these polymers. To extend the applicability of SEA to bio-refineries, this PhD research develops the statistical entropy definition based on molecular properties (molecular weight), and the methodological development is demonstrated with a bio-refinery case study. The purpose is to showcase the possibility of applying SEA to evaluate cascading strategies, even at a molecular level. It was a preliminary study meant to open a pathway for further research in that direction. Chapter 5 describes adaptions made to SEA for describing material quality based on molecular distribution and demonstrates its use by comparing different bio-refinery configurations.

Similarly, the applicability of LCA to cascading systems is validated. Several studies have already evaluated the environmental impact of cascading systems using LCA. However, many of them did not consider accounting for the cascade lifespan. Wood cascading keeps the carbon stored in harvest wood products (HWP) longer and delays emissions. Additionally, the rate of carbon uptake in forests from which wood is harvested influences the carbon balance of cascading systems. The study performs an LCA of a cascading system including these temporal aspects to validate whether it significantly contributes to the carbon balance. Chapter 6 describes, using a cascading case study, a way to include the temporal information in the LCA.

The final step of this research was to apply the complete toolbox – the combined assessment of SEA and LCA – to a cascading system. The preceding analysis observed the statistical entropy evolution when using a fixed amount of wood in different cascading systems. However, different cascading systems need different amounts of wood to provide the same service. Often cascading strategies (such as increased efficiency, increased durability or using recovered instead of virgin wood for a product) reduce the need for virgin material and make the surplus wood available for other applications. The potential use of that surplus wood in the market (or left behind in the forest) is often not included within the system boundaries of the studies, which underestimates the benefits of cascading. Chapter 7 tests this hypothesis. The analysis builds on the earlier case study on wood-based pallets (from Chapter 4). SEA and LCA are performed to compare different cascading systems providing the same functional value. The results identify the cascading system that provides the same functionality and maximally maintains the material value for the longest time.

Thereby, this study firstly fills in the gaps in the cascading assessment by providing a quantitative assessment of change in material quality over the cascade lifespan. Secondly, it fills the gap in CE monitoring for assessing the material circularity of wood cascading. Though demonstrated for wood cascading, it would have potential applicability to the other biotic resources part of biological cycles.

Investigating the **need for additional CE metrics** for biological cycles *(Chapter 2)*

1. Identifying the **gaps in monitoring circularity** of biological cycles
2. Suggesting adaptation to **CE monitoring** frameworks for them to be **inclusive of the biological cycle**

Developing a methodological framework to **assess the material circularity of cascading use** of wood

1. Identifying the **gaps in current assessment** of cascading use *(Chapter 3)*
2. **Developing methodological toolbox** to evaluate wood cascading
   Research hypothesis: Statistical entropy analysis (SEA) assess material circularity and Life cycle assessment (LCA) accounts for resource use and assesses the environmental impact. SEA and LCA adequately complete the evaluation of cascading
3. Validating the **applicability and** relevance of current **SEA** *(Chapters 4 & 5)* and **LCA** *(Chapter 6)* method to wood cascading
4. **Adapting** SEA and LCA to apply them to wood cascading
5. Demonstrating the modifications made to the methods with appropriate case studies

Demonstrating the **combined assessment of SEA and LCA** on a wood cascading case study *(Chapter 7)*

1. Describing guidelines to define a cascading system
2. Performing SEA and LCA on the cascading case study

Figure 1.2: Description of the thesis layout

Chapter 2: Gaps in circular economy monitoring

Based on: Navare, K., Muys, B., Vrancken, K. C. & Van Acker, K. **Circular economy monitoring – How to make it apt for biological cycles**? *Resources, Conservation and Recycling* **170**, 105563 (2021).

Abstract

Circular economy (CE) principles distinguish between technical and biological cycles. Technical cycles involve the management of stocks of non-renewable abiotic resources that cannot be appropriately returned to the biosphere. Whereas, biological cycles involve the flows of renewable biotic resources that can safely cycle in and out of the biosphere. Despite this distinction, existing CE monitors are typically developed for technical cycles and focus mainly on the extent to which resources are looped back in the anthroposphere. These monitors seem less apt to assess the circularity of biological cycles. This study aims to identify this gap by critically reviewing the CE monitoring criteria and CE assessment tools and evaluating if they include the four key characteristics of (anthropogenic) biological cycles.

Firstly, biotic resources, although renewable, require to be harvested sustainably. Secondly, while abiotic resources can potentially be restored and recycled to their original quality, biotic resources degrade in quality with every subsequent use and are, hence, cascaded in use. Thirdly, biotic resources should safely return to the environment and not affect ecosystem functioning. They are often essential nutrients to support the regeneration of ecosystems. Fourthly, biological cycles have environmental impacts due to resource extraction, resulting from land use and resource depletion, and biogenic carbon flows. The CE monitoring criteria lack in thoroughly assessing these characteristics. With the growing demand for biotic resources, the gap in the assessment could exacerbate the overexploitation of natural resources and cause the degradation of ecosystems. The study discusses measures to bridge this gap and suggests ways to design a CE assessment framework that is also apt for biological cycles.

2.1. Introduction

"A nation that destroys its soils destroys itself. Forests are the lungs of our land, purifying the air and giving fresh strength to our people"

Franklin D. Roosevelt

The CE principles distinguish between technical and biological cycles (Ellen MacArthur Foundation, 2015a). It could be a theoretical influence of the earlier work of the cradle-to-cradle concept by Braungart et al. (2007), which defined it as a design framework for products and industrial processes that enable a perpetual flow of nutrients within two metabolisms - biological and technical metabolism. Materials that flow through the biological cycle are called biological nutrients. These can be natural but also synthetic materials, like bio-polymers, that are by nature biodegradable and can be safely returned to the biosphere. So, these nutrients are used in products to be consumed and re-enter the biosphere to become nutrients for living systems. Technical nutrients do not degrade easily. Moreover, they are limited and often cause contamination within the biological cycles. So, materials and products are designed to retain embedded quality and energy (Braungart et al., 2007; Ellen MacArthur Foundation, 2015b).

Although the CE concepts prescribe the circular use of biotic resources, the CE assessment and monitoring seem insufficiently adapted to biological cycles (Haas et al., 2020; Leipold and Petit-Boix, 2018). A Google Scholar search for the term 'circular economy' combined with 'biological' or 'biobased' (in the title, keywords or abstract) gives only 25 results (Annex A – A.1). Most articles centre around (1) the design of products, supply-chain, bio-refineries and business models and (2) the conceptual distinction between technical and biological cycles. Concrete papers on CE assessment criteria and monitoring specifically for biological cycles or inclusive of biological cycles seem to be lacking (Haas et al., 2020). In biological cycles, resources should be cascaded in the application to maximise the resource value and eventually returned to the biosphere to become valuable feedstock for a new cycle (Ellen MacArthur Foundation, 2015a). However, most CE monitors mainly assess the extent of cycling resources back into the economy; the focus is on reducing raw material input and waste generation. Little attention has been on evaluating cascading use and the extent to which biotic resource extraction and decomposition are in sync with the ecosystem's regeneration and assimilation capacity. Robust CE criteria or comprehensive indicators to quantify the fraction of biotic resources that sustainably close the biological nutrient cycle are still unavailable (Haas et al., 2020).

The narrow focus on technical cycles could be because of the conceptual roots of CE in industrial ecology, which envisions a material symbiosis between various industries and production processes (Andersen, 2007). These industrial linkages will enable residual waste and by-products of one industry to be feedstock for another. The focus is on improving resource efficiency, reducing the need for virgin resources and minimising waste or emissions to the environment.

Overlooking the biological cycles could also be stemming from the popular but invalid notion that biotic resource use is circular and sustainable by nature (Haas et al., 2020; Hetemäki et al., 2017). There are several examples, in particular of bio-fuels (Fargione et al., 2008; Koh and Ghazoul, 2008; Searchinger et al., 2008), wherein the shift to biomass has led to overexploitation of forest resources, land-use change, biodiversity loss and increased competition for land for food and feed. Hence, assessing the circularity of biological cycles and their impact on the ecosystem is essential.

Against this backdrop, this study aims to highlight the gaps in current CE monitoring in assessing the circularity of biological cycles and suggest modifications to fill those gaps. Identifying and acknowledging this gap is crucial and would serve as a guideline for designing a comprehensive framework inclusive of biological cycles for assessing the progress toward the CE. It could, potentially, make way for sustainable and circular use of natural resources and avoid further degradation of ecosystems.

2.2. Material and method

2.2.1. Research design

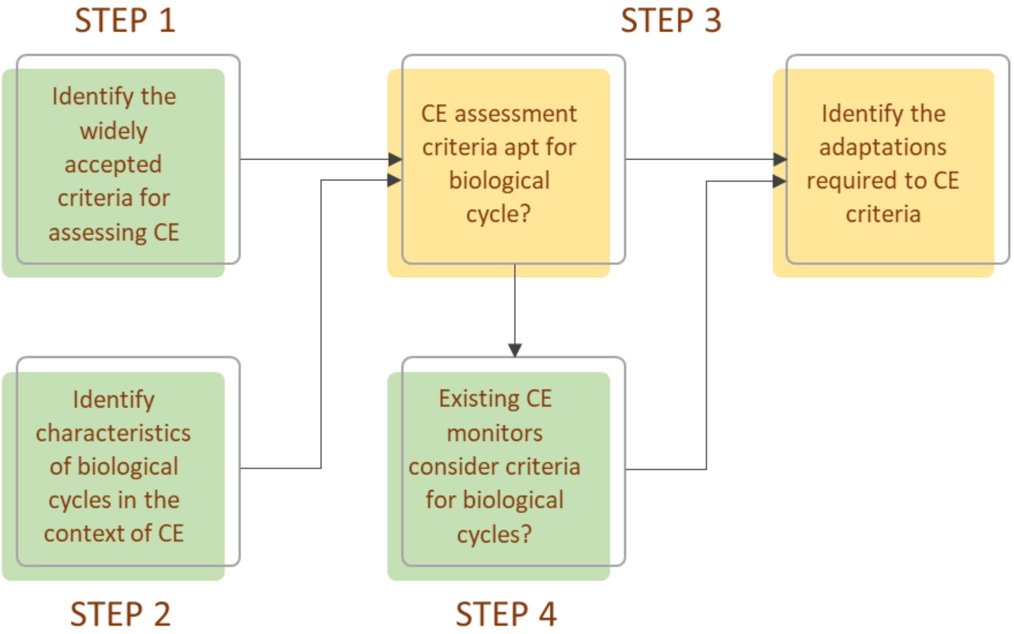


Figure 2.1: Research design – Illustrates the steps followed in carrying out the research

The methodology followed a series of steps, graphically represented in Figure 2.1. The first step was to identify the criteria for assessing and monitoring CE (step 1 in Fig. 2.1), i.e. the criteria validating the progress towards CE based on the definition of CE principles. However, there is no one agreed definition of CE. Thus, the CE definitions by themselves were insufficient to derive the CE monitoring criteria. A study of CE practices, adopted by various stakeholders, was needed to deduce the guiding principles for CE implementation strategies (i.e. what should the CE strategies aim to achieve) and determine the widely accepted CE assessment criteria (i.e. what measures indicate the transition towards a CE). That was done by studying the CE implementation strategies (Kalmykova et al., 2018) and the CE assessment criteria (Corona et al., 2019; Elia et al., 2017) identified by the CE review papers.

The second step was to identify the characteristics of biological cycles. This literature-based study started with the key sources Bocken et al. (2016), Ellen MacArthur Foundation(2017, 2010), European Environmental Agency (2018) and Hetemäki et al. (2017). These sources provide guidelines for enabling closing the biological nutrient loop. The search was followed by a semi-structured snowballing literature study, starting with shortlisting the fundamental characteristics that distinguish biological cycles from technical cycles. These characteristics were then studied in depth by a systematic review of literature from that specific field.

The third step was to evaluate if the CE monitoring criteria were sufficient to assess the characteristics of biological cycles. The study was further extended to analyse the current CE monitors – to study if they inherently assess the characteristics specific to the biological cycle (step 4). Step 3 and step 4 highlight the gaps in current CE monitoring criteria and serve as a guideline for the adaptation required to make them inclusive of the biological cycle.

2.2.2. Reviewing existing CE monitors

Numerous monitoring tools of circularity assessment – in the form of indicators, metrics, and frameworks – have been developed in the last few years. The question relevant for this study is – how many of these CE monitors evaluate the criteria for circularity of biological cycles. Additionally, the CE monitors that evaluate those criteria do so to what extent.

Firstly, the current CE monitors were listed, which was done by a systematic literature review (Annex B provides the complete list of indicators studied). Here, a monitor is defined as a quantitative measure of progress towards achieving an objective. Consequently, the search included broad fields of quantitative assessments of CE, i.e. CE indices, indicators, and metrics. The identification of CE metrics started with the search of the literature on the circular economy via Scopus and Google Scholar, using combinations of search words: ‘circular economy’, ‘circularity’, ‘evaluation’, ‘assessment’, ‘measure’, ‘indicators’, ‘indices’, ‘index’, and ‘metrics’ for the database search in title, abstract and keywords fields.

TITLE-ABS-KEY (("Circular economy" OR "Circularity") AND ("measure" OR "metric" OR "evaluation" OR "assessment" OR "indicators" OR "indices" OR "index"))

Note that the search limited to publications in English, and the materials reviewed (time coverage) were from the emergence of CE indicators, i.e. 2010, to the submitted date of this research, viz. Aug 2020. In addition to the literature search, review papers on CE indicators were studied to ensure the completeness of the list (Corona et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Rossi et al., 2020; Saidani et al., 2019). The most extensive list of CE indicators was published by Saidani et al. (2019), who reviewed 55

CE monitors. Some sources, mainly, Parchomenko et al. (2019) and Corona et al. (2019) consider even those indicators that are not specific to CE assessment but could potentially be useful for CE monitoring. These indicators were not included in this study, to maintain the focus only on CE monitors.

The analysis resulted in 59 sets of CE metrics, coming from 40 journal papers, 12 technical reports, and seven websites. The search for CE monitors was kept broad to include the CE monitors at different levels of implementation (micro, meso and macro), in different sectors (construction, manufacturing etc.) and across countries. The CE monitors specific to technical cycles were also included. Of the 59 indicators, 23 indicators were developed for a specific industry or were demonstrated using a case study from a particular industry. Of these, 21 were specific to material or industry from the technical sector. For example, Graedel et al. (2011) focus on the recycling rate for metals. Only two referred to a bio-based industry, which was the food sector. Despite being specific for technical cycles, these monitors were included to evaluate if the underlying criteria are relevant for biological cycles. Additionally, it also highlights the inequality in the number of CE monitors existing specifically for each cycle, with a clear weightage towards technical cycles.

CE monitors were then examined to validate whether each criterion relevant for biological cycles, as derived from the literature study, was considered. The framework for this evaluation is illustrated in Fig. 2.2. The first step was to examine whether there is a mention of the criterion. In case there is a mention, the second step was to determine whether the criterion is assessed and if assessed is it being assessed completely (marked in the results 'explicitly & completely assessed') or only partially (marked as 'explicitly & partially assessed'). Even in the case where there is no mention of the criterion, the next step was to determine whether it is assessed (marked as 'implicitly assessed'). There are cases where there is no mention of the criteria, but it is implicitly measured nonetheless. This framework accounts not only if the criteria are assessed but also to what extent are they being completely assessed.

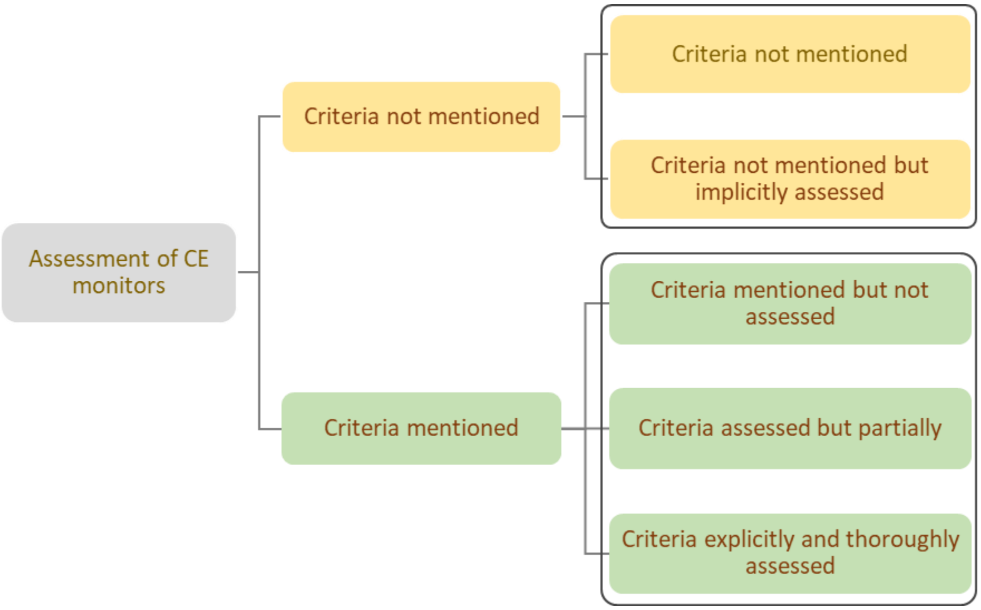


Figure 2.2: The framework for the evaluation of CE monitors
Designed to validate if the CE monitors measure the parameters critical for assessing the circularity of biological cycles

2.3. Results and discussion

2.3.1 CE monitoring criteria specific for biological cycles

The contours of CE are highly contested (Korhonen et al., 2018). The concept has been promoted by governments, academics and businesses (Kalmykova et al., 2018). However, there is no one agreed definition across these bodies. Several CE definitions exist. The most renowned definition has been framed by the Ellen MacArthur Foundation:

CE is an economy that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015b).

A recent literature review by Kirchherr et al. (2017) found 114 CE definitions. Kirchherr et al. (2017) synthesised these definitions and proposed a uniting definition:

CE is defined as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations".

This study uses these two definitions of the CE concept to deduce the guiding principles for CE practices and implementation strategies (i.e. the aspects CE strategies should strive to achieve). Since the study focused on material circularity in technical and biological cycles, only the first sentence of the definition by Kirchherr et al. (2017) is considered. The analysis suggests that CE implementation strategies mainly aim at closing the material loop and fall into five main categories:

1. Reducing the **input of resources**
2. Minimising the **waste** and **losses** produced
3. Increasing the input of **recycled (or secondary) materials**
4. Maximising the **value**, utility and durability of products

It has been assumed in this study that these requirements for CE strategies form the basis of the CE monitoring criteria, i.e. the measures that indicate the transition towards a CE.

Because of non-consensus over agreed definitions of CE, the CE definitions themselves were insufficient to deduce the CE monitoring criteria. Hence, the list of CE monitoring criteria was complemented with the monitoring criteria identified by Corona et al. (2019) and Elia et al. (2017), who based their analysis on the CE strategies and practices. Elia et al. (2017) built on the results of the European Environmental Agency (2018) and added the criteria 'increasing share of renewable resources' and ‘reducing emission levels’ in addition to the above-mentioned four criteria. Additionally, Corona et al. (2019) proposed adding three more criteria reflecting economic prosperity and social equity. These are creating local jobs at all skill levels, creating and distributing economic value and increasing social wellbeing. To complete the list of CE assessment criteria, but yet maintain the focus on material circularity, the criteria - increasing the share of renewable resources and reducing emission levels – have been included in this study. While the other three criteria, evaluating economic and social impact, have been considered out of scope for this study.

The question then arises whether these CE assessment criteria are adequate to evaluate the circularity of biological cycles. In answering that question, firstly, the characteristics of biological cycles in the context of CE were identified, in particular, those that are not assessed by existing CE monitoring criteria. These are:

1. **Renewability**, however, is limited by availability of land and natural regeneration rate.
2. Potential for **cascading** use of material to maximise the material value.
3. At the end of life, biodegrade and return to the biosphere to **close the biological cycle.**
4. Environmental impact of biological cycles associated with **resource extraction** and biogenic **carbon flows** during biomass growth and decomposition.

These features have been discussed in-depth in the next sections. The aspects of biological cycles, assessed already by the existing CE monitoring criteria, are not included in the discussion. For example, the production or use phase of biological cycles also have an environmental impact but are not included, as it is assessed by an existing CE monitoring criterion (namely, reducing emission levels).

The next step was to evaluate if these characteristics are assessed by the CE monitoring criteria mentioned above. Each trait of the biological cycle is analysed corresponding to the CE monitoring criteria to validate the extent to which they are aligned.

Renewability

Biotic resources are intrinsically renewable. Hence, the primary principle of CE ‘to reduce the input of virgin resources’ is less critical for these resources. That is widely accepted, as seen with the growing emphasis on the bio-economy (European Commission, 2012; European Environmental Agency, 2018). The substitution of fossil-based resources with biotic resources is being encouraged. However, the renewability of these resources can only be ensured by sustainably producing and harvesting them (Hetemäki et al., 2017; Sikkema et al., 2017); by extracting resources at a rate lower than their regeneration capacity (Hilborn et al., 1995). In the forestry sector, this principle is termed sustained yield (Muys et al., 2014). However, albeit essential, this is not sufficient to sustain the long-term productivity of the ecosystems. The harvesting or extraction processes could affect the ecosystem quality and capacity of biomass provisioning. Increasing agriculture and forestry productivity could lead to loss of species and landscape diversity, nutrient depletion or habitat loss (Muys et al., 2013). In marine ecosystems, some fishing techniques, such as dynamite fishing, trawling and dredging, could destroy habitat, which – in addition to the overfishing practices – deplete fish stock (Airoldi and Beck, 2007; Woods et al., 2016). These factors impact the intrinsic capability of renewal and affect the long-term yield. The forestry sector has thus widened the concept of 'sustained yield' into a broader concept called 'sustainable yield', which aims at maintaining the ecosystem services and long-term productivity of forest ecosystems by safeguarding biodiversity and monitoring soil productivity (Muys et al., 2014). The fisheries sector defines the 'Maximum Sustainable Yield' (MSY) as the limit that can safely be removed from the fish stock while maintaining its capacity to produce sustainable yields in the long term (Maunder, 2008). The forestry and fisheries sectors have long histories of concern about sustainability. However, the CE discussions seem to lag in considering sustainable exploitation of biotic resources (Hennig et al., 2016).

The growing need to reduce the dependency on fossil-based resources will see a shift towards biotic resources. A promising green alternative is lignin, one of the building blocks of woody biomass. It can substitute fossil-based resources in many sectors and products - fuels, resins, and pharmaceuticals (Liao et al., 2020; Smolarski, 2012). The commercialisation of lignin represents an opportunity to meet climate targets but could increase demand for biomass. Currently, lignin is abundantly available as residues in the paper and pulp industry and is used mainly for energy (Cline and Smith, 2017). But using this stream for material applications would mean finding alternative sources for energy supply, which could further increase the biomass demand. So, recovered (industrial residues or post-consumer waste) wood should be considered as an alternative feedstock to extract lignin to avoid increasing demand.

The increasing demand for biomass may exacerbate the overexploitation of natural resources and cause further degradation of ecosystems (Ceccherini et al., 2020; European Environmental Agency, 2018; Hetemäki et al., 2017; Worm et al., 2006). The CE assessments should validate the renewability of the resources. The aim should be to minimise the use of biotic resources along similar lines as abiotic resources. But, more importantly, ensure that it is within sustainable limits. In addition to validating that the extraction of biotic resources is below their natural regeneration rate, the CE monitors should also ensure that the ecosystem production capacity and other ecosystem services remain stable over time.

Potential of cascading use of material

It is harder to preserve the functionality or value of bio-based materials (European Environmental Agency, 2018). They degrade in quality during use and processing (Jarre et al., 2020), resulting in lower structural properties and utility and recycling these materials to their original form is difficult. That limits the applicability of the core CE principles – recycling and maximising the utility – to biological cycles. The use of biotic resources is, thus, optimised by using it in cascades.

Cascading is the sequential use of resources as long, as many times, and as efficiently as possible for material applications and only to recover energy from them when no other material application is feasible (Essel et al., 2014; Sirkin and Houten, 1994). The use of waste streams, i.e. post-consumer waste and industrial residues, is encouraged. For example, wood from construction and demolition waste (CDW) is used for particleboard production (Höglmeier et al., 2013; Merrild and Christensen, 2009). Inedible and unavoidable food waste and residues are potential feedstocks for bioplastics, organic acid, and essential oils (Teigiserova et al., 2019). Lignin, a by-product of pulp mills, is burned for low-grade energy. Better yet would be using it for material applications, such as chemicals or pharmaceuticals (Smolarski, 2012), instead of being incinerated. Even after incineration or biodegradation, the emission capture and utilisation technologies (Thomsen and Zhang, 2020) could extend the time these resources are in use. Cascaded use could enhance resource use efficiency, increase resource availability for other material uses, reduce dependency on virgin resources and reduce the environmental burden on ecosystems (Bais-Moleman et al., 2017; Fraanje, 1997; Höglmeier et al., 2015; Sikkema et al., 2013).

Cascading strategies aim to maximise the value retrieved from the material over multiple life cycles. The value here refers to the potential utility available due to the inherent and intrinsic material properties, such as structural organisation and chemical composition (Campbell-Johnston et al., 2020; Sirkin and Houten, 1994). Maximising the material value objective is achieved by preserving material quality over time. So, cascading strategies start with the use of resources for high-quality products, using the waste streams as much as possible, increasing the lifetime of each application and hence overall lifetime, and minimising quality loss with each application (Brunet-Navarro et al., 2018; Fraanje, 1997; Keegan et al., 2013). Cascading strategies also aim at minimising impurities in products because they limit the possibilities for further downstream cascading (Vis et al., 2016). These chemicals are added to improve their aesthetics (paints, varnish), mechanical material properties (by using substances such as binders, adhesives, and gluing agents) or durability (by adding preservatives such as chromated copper arsenate, pentachlorophenol and creosote that enhance resistance to decay; Faraca et al., 2019a). But some of these substances are toxic (e.g. creosote), which might be essential in applications like railway sleepers for wood to withstand severe weathering, but are forbidden from cascading as they may enter otherwise clean HWP stock (Faraca et al., 2019a). Some non-toxic substances might even limit the cascading by interfering with the utility of the downstream application. The residual glue in the waste wood inhibits the reaction of wood-fibres and particles with the new adhesive applied during downstream particleboard production and results in a significant drop in the material properties (Besserer et al., 2021). Cascading strategies, in a way, have to balance this dichotomy. These substances enhance product utility but reduce its cascading potential. So, improving material quality in one life might come at the expense of the degraded quality of downstream applications. Cascading assessment thus requires evaluating material quality across multiple life cycles of the products (Haberl and Geissler, 2000), ideally from cradle (harvest) to the grave (decomposition).

The CE research has majorly concentrated on material reuse and recycling, i.e. evaluating the share of products or material looped back in the anthroposphere, usually for the same application. However, cascading is often associated with use in a lower-grade application aiming to minimise quality loss. Additionally, cascading is maximising value over the material value chain. So, it is crucial to assess the multiple lives of wood, from cradle (harvest) to grave (decomposition), and all the material streams (i.e.

virgin feedstock, waste and residues) to identify the highest value pathway, i.e. identify a downstream application for each stream that minimises the overall quality loss (Campbell-Johnston et al., 2020; Fraanje, 1999; Sirkin and Houten, 1994). An integrated assessment of cascading - considering quality degradation over multiple-use phases and multiple streams - is generally lacking in CE monitoring and is essential to optimise the use of wood.

The cascading principles have primarily belonged to the biomass domain (Kalverkamp et al., 2017) because, unlike metals and minerals, bio-based materials cannot be recycled to their original form. Natural fibres in bio-based material degrade in structural properties during the recycling process. However, the materials from abiotic resources also face quality degradation during the recycling process, although the mechanisms might differ. Metals degrade in quality during recycling because they get mixed with undesirable elements or lower-grade materials, resulting in lower-quality recycled material, i.e. material with lower inherent properties such as lower mechanical properties (Koffler and Florin, 2013). That has been referred to as downcycling in CE discussions, which is recycling that results in products or materials of lower value. Yet, CE assessment has paid limited attention to considering material value (Campbell-Johnston et al., 2020), which merely necessitates its assessments for both technical and biological cycles.

Closing the biological nutrient cycle: biodegrade and return to the biosphere

Bio-based materials are biodegradable in natural biological cycles and decompose to nutrients that support ecosystem regeneration. However, bio-based materials in (anthropogenic) biological cycles might not always safely return to the environment. The core principle of CE, i.e. reducing waste and increasing recycling, seems essential but insufficient for biological cycles. Additionally, ensuring the safe closure of the biological cycle is fundamental. That is, whether the biotic resources on decomposition impact the ecosystem functioning and feed the regeneration of the ecological systems when needed.

Firstly, bio-based materials are not necessarily biodegradable. A clear example is bio-based polymers (such as bio-polypropylene and bio-polyethylene; Bocken et al., 2016). These are typical drop-in bio-based polymers. They have the same structure as their fossil counterparts and are thus non-biodegradable (Shogren et al., 2019), making them characteristic of technical cycles. Additionally, mixing biotic resources with abiotic resources, a frequently-used method for enhancing the material properties of products, can hamper the biodegradability of the biotic resources. For example, bio-composites may not necessarily be biodegradable (Jiang et al., 2020). The aim of CE should be to enhance the separability of the material from biotic and abiotic origin to enable the eventual decomposition of bio-based materials. When these materials are not separable or when bio-based materials are non-biodegradable, they should be treated as part of technical cycles, focusing on enhancing their reusability and recyclability. On the other hand, there are products of abiotic origin that are bio-degradable, such as fossil-based biodegradable polymer polybutylene adipate-co-terephthalate (PBAT), which must be treated as part of biological cycles.

Bio-based alternatives to fossil-based products face several challenges despite being biodegradable. For instance, bio-based plastic polylactic acid (PLA) is biodegradable but has an appearance similar to fossil-based alternatives (polyethylene terephthalate PET). Hence, these PLA and PET waste fractions get collected together, posing two problems. Firstly, the biodegradable PLA fraction should be composted (after cascading uses if possible), but mixing the two waste fractions means the waste stream cannot be sent for composting. Secondly, the presence of PLA seriously hinders the existing recycling process of PET (Alaerts et al., 2018). Hence, bio-based materials or products should be collected separately to enhance recycling (PET) and composting (PLA) potential. Separating the bio-based materials or products from their abiotic counterparts is crucial for closing both technical and biological cycles.

Yet another challenge is the dissipative losses, i.e. the losses to the environment that are not recoverable. The products that result in dissipative losses during use (such as lubricants, tires or paint) should be compatible with biological systems (Bocken et al., 2016; Braungart et al., 2007). They should degrade and not accumulate in nature, which is not always the case. The emissions to the environment contain non-biodegradable materials, also of abiotic origin. They gradually accumulate in the biosphere over time and interfere with the ecosystem's functioning (Thomsen et al., 2012). If toxic, they could severely impact plant, animal or human health. For instance, industrial emissions contain toxic pollutants that spread on agricultural land and are becoming part of food systems (Marini et al., 2021; Pizzol et al., 2010). So, dissipative emissions should not contain non-biodegradable substances that affect the ecosystem's functioning. Even biodegradable substances, if released at a rate exceeding ecosystem assimilation capacity, accumulate in nature, affect ecosystem functioning (e.g. agricultural fertilisers; Chojnacka et al., 2020), and should be avoided from dissipative emissions.

Bio-based materials, even when degradable, are not always safe to return to the environment. The emissions caused by their decomposition might also affect the ecosystem's functioning (Reijnders, 2008). For instance, using ash from biomass combustion to fertilise forests might seem like closing the nutrient loop but is often toxic because of the present heavy metals (Dodoo et al., 2014; Reijnders, 2008) or high pH (Pitman, 2006; Vance, 1996). Ash must be stabilised to slow its dissolution and avoid damage to the forest ecosystems (Dodoo et al., 2014). Similarly, wood impregnated with hazardous chemicals (such as creosote) to use in applications exposed to severe weathering (e.g. bridges) cannot just be incinerated at the end of life like clean waste wood. The flue gases from incineration have to be cleaned before releasing them (Faraca et al., 2019a; Höglmeier et al., 2013) and the ash has to be appropriately disposed of (Dodoo et al., 2014). The emissions, even when non-toxic, could be harmful if they are not in sync with the ecosystem absorption capacity. Biomass incineration releasing CO_2, currently at a rate higher than at which assimilated in the biosphere, is disrupting the carbon balance.

Additionally, bio-based materials contain biological nutrients that are scarce and critical for ecosystem regeneration. Nutrients are extracted from the environment as harvested food, energy and material, and are discharged back when these products decompose or incinerate. The nutrients, if not returned to the place or at a rate at which ecosystems absorb them, can disrupt the biological cycles (Skene, 2018). Adequate measures are required for nutrient cycling, without which shortages arise at the source of biomass and nutrient excess in the ecosystems where the biomass is consumed or discharged (De Oliveira Garcia et al., 2018; European Environmental Agency, 2018). That is especially true in the case of agricultural systems where the urban areas are becoming concentrators of nutrients (Chowdhury et al., 2014; Kalmykova et al., 2012; Papangelou et al., 2020) and the rural soils are degrading and relying increasingly on synthetic fertilisers (Lathuillière et al., 2014). This disruption of the nutrient system is damaging in both places (Battye et al., 2017). It causes environmental issues like eutrophication (Chowdhury et al., 2014; Lassaletta et al., 2014), where the nutrients are concentrated and discharged into waste streams. At the sites where nutrients are extracted, the soil fertility is reduced; increasing the dependency on synthetic fertilisers. Excessive use of fertiliser, causing fertiliser run-off from the agricultural system to water bodies, can also lead to increased toxicity levels and further reduce the capacity of soil to support growth (Chojnacka et al., 2020; Coppens et al., 2016; Dalin and Rodríguez-Iturbe, 2016; Lassaletta et al., 2014; Smil, 2011). Modern agricultural practices, such as excessive tillage and heavy machinery use, accelerate this process by increasing erosion and water runoff, carrying nutrients out of the soil and into water systems. Other than the farming practices, megatrends such as globalisation, international trade (Dalin and Rodríguez-Iturbe, 2016; Lassaletta et al., 2014; Schipanski and Bennett, 2012), and urbanisation further contribute to the relocation of nutrients and disruption of nutrient balance (Ellen MacArthur Foundation, 2017). These nutrient imbalances have a severe impact on human and ecosystem functioning. The Stockholm Resilience Centre has highlighted that the biogeochemical nutrient cycle (of nitrogen and phosphorus) is one of the planetary boundaries that has already been transgressed. There is sufficient evidence to say that this has been, radically, caused by human industrial and agricultural processes (Steffen et al., 2015). Hence, an assessment of a system's capability to close the biological nutrient cycle and maintain the ecosystem’s regenerative capacity is crucial and essential.

To summarise, CE concepts assume that the biomass that decomposes and returns to the biosphere contributes to closing the biological loop (Haas et al., 2020). However, it is evident that this is not always true. Hence, the CE monitors should assess that the bio-based materials, which cannot be cascaded further, decompose and safely return to the biosphere. That is, the emissions from decomposition do not accumulate (i.e. are bio-degradable and at a rate in sync with the ecosystem assimilation capacity), are not toxic and do not affect the ecosystem functioning. Lastly, the nutrients that are scarce and essential to sustain ecosystem regeneration are deposited where needed (Reijnders, 2008; Skene, 2018). This assessment should also include the biodegradable material of abiotic origin. While bio-based materials, which are non-biodegradable or are toxic to the ecosystem, should be avoided from entering the biosphere. They should be maintained within the anthroposphere and be part of monitoring technical cycles.

Environmental impact specific to biological cycles

Primary sectors producing biotic resources - agriculture, forestry and fisheries - have substantial environmental impacts. The biotic resource use impacts the quantity and quality of ecosystems, natural capital (soil, water and air), biodiversity and landscape amenity value. The planetary boundaries developed by Stockholm Resilience Centre point out that impact on five out of nine have a direct link to the bio-based economy: biogeochemical (nitrogen and phosphorus) cycle balance, land system change, freshwater consumption and the global hydrological cycle, loss of biosphere integrity (biodiversity loss and extinctions) and climate change (Steffen et al., 2015). Hence, biological cycles should not be assumed to be inherently environmentally friendly.

The biotic resource use has a local ecosystem impact due to resource extraction, resulting from resource depletion and land-use or ocean use interventions. The abiotic resource extraction impacts are mainly due to resource extraction and not due to depletion or scarcity. Abiotic resource depletion affects resource availability for the future generation but does not often affect the ecosystem's health or functioning (Heijungs et al., 1997). Though, there are exceptions, such as the extraction of sand or gravel that can affect riverine or marine habitats (Koehnken et al., 2020). Abiotic resource extraction might also impact local ecosystems, but biotic resources form an integral part of local ecosystems, and their extraction has a closer relation to the ecosystem functioning. Although the difference is that biotic resource depletion could be avoided by slowing down extraction and maintaining it at levels in sync with the natural regeneration rate. However, abiotic resources (gravel and sand) are not renewable, and their depletion could be avoided only by reducing extraction.

Overexploitation of biotic resources could lead to a reduction or extinction of species, directly challenging their future availability. But more importantly, it causes indirect biodiversity loss (Crenna et al., 2018), for example, through trophic interactions (Chapin et al., 2000). Both direct and indirect biodiversity loss diminishes the total biomass available for ecosystem functioning, which could impact the ecosystem health and affect the production capacity (i.e. provisioning of resources) as well as other life-supporting functions (e.g. climate regulation, flood control, carbon capture and storage capacity) of the ecosystem. An example is a potential threat posed by the overexploitation of marine resources to coastal water quality and ecosystem stability – by altering food web structures and reducing the population of non-target species (Woods et al., 2016; Worm et al., 2006). The resource depletion is relevant for extraction of non-cultivated biotic resources from the natural environment, e.g. hunting in the wild, timber from natural forests, fishing from oceans; and not for cultivation, i.e. harvesting from farms and plantations, for which the impacts are mainly due to land-use or ocean-use (Heijungs et al., 1997).

The impacts of land-use interventions are from land occupation and transformation. Land occupation is the continuous use of land for a specified land-use type for a certain period. Land transformation is modifying land to suit it for the intended use. Such as converting forests to agricultural land, draining land to establish arable fields, and intensifying farmland production (Koellner et al., 2013).

These interventions degrade ecosystem services due to a decline in vegetation, biodiversity, and soil- and water quality (Foley et al., 2005; Saad et al., 2013; UNEP, 2019). The ocean-based activities damage the marine ecosystems through habitat destruction (from fishing techniques, disturbances - dynamite fishing, fishery bottom trawling and dredging) and biodiversity loss (from habitat loss, by-catches; Kaiser et al., 2002; Woods et al., 2016). So far, concern about the impact of biotic resource extraction on ecosystem services has been limited in CE assessment. However, to ensure sustainable use of natural resources and to avoid burden shifting by moving from fossil-based to biotic resources, the impact of biotic resource extraction on ecosystem health, resulting from direct and indirect land-use impacts and resource depletion, needs to be taken into account.

Apart from these local ecosystem impacts, biomass use has a global environmental impact due to carbon emissions. Carbon flows differ between biological and technical cycles. Carbon is both sequestered from and emitted into the atmosphere in biological cycles. Trees absorb carbon dioxide (CO_2) from the atmosphere during growth and store carbon (termed biogenic carbon) in biomass. Carbon remains stored in bio-based products until biomass incinerates or decomposes when carbon is emitted back into the atmosphere as CO_2. The CO_2 emissions are assumed to balance out the initial carbon sequestration. Carbon storage in bio-based products, even though temporary, delays these emissions. Hence, carbon emissions from biogenic sources are often considered to be ‘carbon neutral’. Wood products have officially been accounted for as carbon sinks under the Kyoto Protocol (UNFCCC, 2012), and bio-based products are seen as a climate mitigation strategy. However, the ‘climate neutrality’ assumption holds only if the carbon emission is at a rate equal to that of sequestration. Harvesting a tree that grows over several years and using it for bio-energy could create a ‘carbon debt’ (Levasseur et al., 2013). So, biomass should be harvested at a rate below the sequestration rate. Additionally, continued harvesting could affect the net forest’s carbon stock by increasing soil carbon emissions or decreasing forest carbon capture and storage capacity (Kendall et al., 2009; Levasseur et al., 2012). As discussed in previous sections, biomass harvest must ensure ecosystem services are not affected, including the carbon capture and storage service of the ecosystem. The harvested biomass must then be used in long-lasting products and, further on, in cascaded applications to enhance their climate mitigation potential. Validating ‘carbon neutrality’ by evaluating a time-explicit account of carbon flux is essential to conclude the climate benefits of biological cycles, i.e. considering not only net carbon emission but, more importantly, the rates of biogenic carbon flows - the carbon sequestration rate, carbon storage period and the biogenic carbon emission rate (Head et al., 2021).

The biological cycles impact the environment also during other phases of the product life-cycle, i.e. production, use and end-of-life. However, these impacts are not specific to biological cycles and also occur in technical cycles. They are not discussed in this study as the criteria to reduce the environmental impact associated with these phases are already included in the existing CE monitoring frameworks. The aim was to identify the additional criteria required to assess biological cycles.

Summary

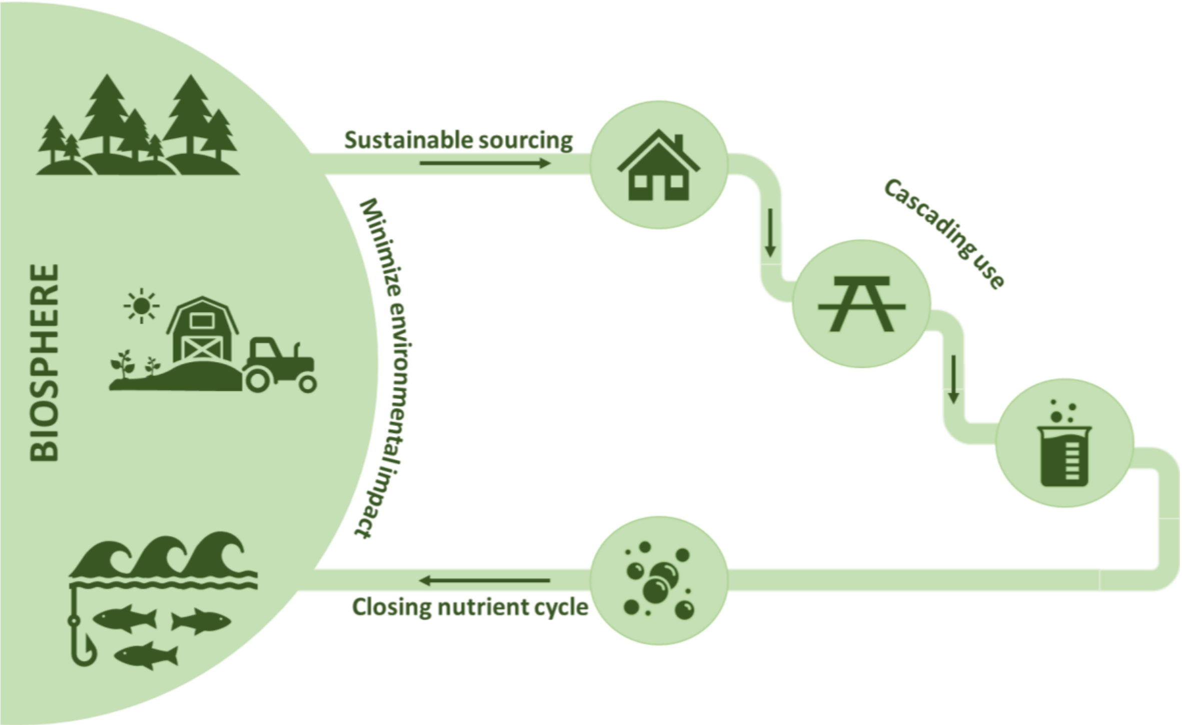


Figure 2.3: The aspects critical for circularity in (anthropogenic) biological cycles

Table 2.1 summarises the results of this evaluation. Each of the characteristics of the biological cycle (mentioned in the column header of Table 2.1) is reviewed and compared to the CE monitoring criteria (listed in the row headers) to showcase the extent to which they are aligned. The contradictions between the two or the aspects where CE monitoring criteria fall short of including the biological cycle (highlighted in bold) lay the ground for the adaptations required to these criteria to integrate biological cycles in the current CE assessments.

Table 2.1: Summary of the evaluation of the characteristics of the biological cycle
Comparing them with the CE monitoring criteria to validate the extent to which they are aligned (the gaps highlighted in bold)

Biological cycles' characteristics **CE monitoring criteria**	**Renewability**	**Cascading use of material**	**Closing of the biological nutrient cycle**	**Environmental impact**
Reducing input of resources	Important but not sufficient. Essential that resources are **sustainably sourced**			

Reducing waste			More importantly, validate **biodegradability, presence of hazardous substances & if decomposition sustains regeneration**	
Increasing input of recycled (or secondary) resources		Additionally, should **optimise the cascading use of material**		
Increasing the use of renewable resources	In contradiction with the criteria to reduce input. Validating if resources are **sustainably sourced** becomes more crucial			
Reducing emissions				In addition to the environmental impact associated emissions, it is crucial to **assess impacts of resource depletion and land use change, and assess the temporal aspect of emission**
Maximising value, utility & time in use		Additionally, should assess the **quality degradation** over multiple-uses		

It is evident that current CE monitoring *criteria* fall short of assessing the key characteristics of biological cycles. Based on the gaps highlighted in Table 2.1, it can be suggested that CE monitoring should include, along with criteria applicable to technical cycles, the following criteria for accurately gauging transition towards circular biological cycles:

1. To ensure 'renewability of biotic resources', the additional CE assessment criterion should be increasing the use of **sustainably-sourced** resources.
2. To optimise the 'cascading use of biotic resources', the criterion should be **maximising the value** by identifying the best utilisation pathway considering multiple-uses and multiple streams.
3. To 'close the nutrient cycle', the criteria should be to ensure that
    a. Enhancing **separability** and **biodegradability** of bio-based biological materials.
    b. Avoiding the **presence of hazardous substances** in the emissions to the environment.
    c. Emissions of biological nutrients at a rate at which they are assimilated in the biosphere.
    d. For the nutrients that are scarce and critical for ecosystem regeneration, increasing the **return of nutrients** at a place and rate that sustains the regeneration.
4. To minimise the 'environmental impact', the criterion for CE monitoring should be to assess the **impacts of biotic resource extraction on ecosystem services**, in particular, that resulting from land-use interventions and resource depletion and global climate impact of **carbon balance**, by accounting carbon sequestration, storage and release of biogenic carbon.

2.3.2 Gaps in existing CE monitors

The existing CE monitors were evaluated to determine whether they assess the circularity criteria relevant to biological cycles. The study reviewed 59 CE monitors - the summary of the results is provided in Figure 2.4 and the supplementary text (Annex A – A.2).

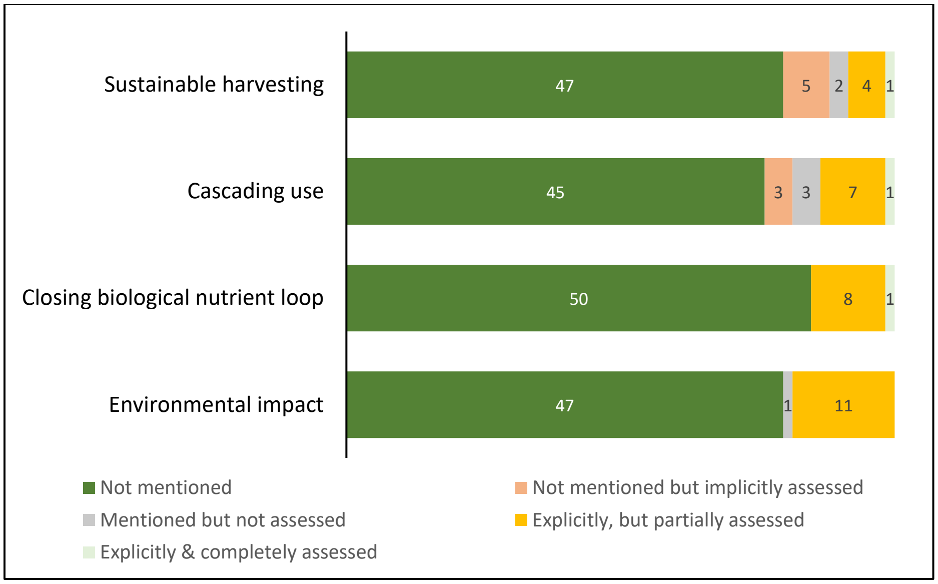


Figure 2.4: Results of the CE monitoring evaluation

Sustainable sourcing

The study evaluated whether CE monitors assess the sustainable sourcing of biomass – i.e. whether the monitors measure the biomass harvest rate and compare it to the biomass regeneration rate, and assess the ecosystem health to ensure that the harvest does not affect the ecosystem functioning and long-term provision capacity.

Out of 59 CE monitoring frameworks, only one considers this aspect. Two indicators mention the need to consider sustainable harvesting but do not assess it. Whereas five indicators implicitly assess it, albeit partially. Of these five, three indicators assess the criticality of resources based on economic value (Di Maio et al., 2017; Laso et al., 2018; Linder et al., 2017), which is considered in this study as an implicit assessment of renewability because, in principle, increased resource scarcity or compromised renewability of resources would reflect on their economic value. However, the use of monetary values has its disadvantages. Market values and prices fluctuate heavily over time. Problems also arise when prices are missing or distorted due to monopolies or government interventions, such as subsidies. Another implicit assessment is *Hybrid LCA*, offered by Genovese et al. (2017). *Hybrid LCA* is a framework to integrate the top-down environmental input-output model and bottom-up LCA model. It has been considered an implicit assessment because the criteria 'sustainable sourcing' will be included if the underlying LCA incorporates the relevant impact categories. Yet another indicator that implicitly assesses renewability is the 'per capita green area' (Yang et al., 2011) – considered an implicit (and partial) assessment because this could ensure that a certain amount of green areas are maintained.

The four monitors that explicitly but partially assess sustainable sourcing are the circularity assessment tool suggested by Circle Economy (Camacho-Otero and Ordoñez, 2017), the EU raw material scoreboard (European Commission, 2018a), the global resource indicator (Adibi et al., 2017) and the CE metric proposed by the U.S. Chamber of Commerce Foundation. The circularity assessment tool of Circle Economy evaluates the renewability and criticality of resources. The EU resource raw material scoreboard considers the growing stock and forest-felling rate. The global resource indicator uses scarcity, recyclability and criticality, wherein scarcity is measured based on the renewability rate (Adibi et al., 2017). As discussed in the earlier section, consideration of renewability rate is no guarantee for long-term yield, so these indicators have been considered a partial assessment. The CE metric used by the U.S. Chamber of Commerce Foundation includes a measure of the share of resources from a certified source of that resource, for example, the amount of FSC-certified wood supplied to the furniture and paper industry. Many of the certifications target sustainable management of resources, in particular FSC, which aims for forest management that ensures timber harvesting without affecting biodiversity, forest productivity and other ecosystem services (FSC, 2015). However, this monitor mentions only FSC certification, which covers forest ecosystems, and it is not clear if the certifications relevant to other ecosystems aim for sustainability in sourcing. The CE monitor has, thus, been marked as a partial assessment.

The only tool that explicitly and completely validates sustainable sourcing of biotic resources is the circularity measurement tool 'Circulytics' developed by the Ellen MacArthur Foundation (2020) for companies. It considers the share of virgin resources from renewable and sustainable sources and ensures that the resources are grown in a way that preserves the ecosystems, though the details on how they validate that are unclear.

To fill the current gap in CE monitors, they should essentially include a renewability score and assess if harvesting levels affect the long-term quantity and quality of ecosystem functioning. That could be by adopting methodologies or indicators from other sectors, such as fisheries and forestry. As mentioned earlier, the fisheries sector uses 'maximum Sustainable Yield' (MSY) as the limit to the fish stock that can be harvested. The sustainable forest management (SFM) indicators, used across Europe, include increments and fellings to assess the provisioning functions of the forests. They additionally use indicators, such as soil conditions, forest damage, and land degradation, to monitor the overall forest health and vitality (Forest Europe, 2015). Another methodology that can be integrated within CE monitoring is LCA. LCA already has resource depletion as an impact category, based on resource stock, harvest rate and regeneration rate (Guinée and Heijungs, 1995; Heijungs et al., 1997; Klinglmair et al., 2014). The recent developments in the LCA include the assessment of the renewability potential of biotic resources based on the recovery time, restoration time and renewal time (Crenna et al., 2018). These factors are affected by the magnitude of the pressure the ecosystems are subject to and indicate ecosystem health and capacity. To emphasise this issue, Dewulf et al. (2015) suggest that instead of having 'natural resources' as an area of protection, LCA could have 'provisioning capacity of natural resources' as a safeguard subject. These assessments and underlying goals are some of the proposals that could be considered in the CE monitoring frameworks to ensure the sustainable use of biotic resources.

Optimised cascading use

The second evaluation of CE tools was validating if they assess 'cascading use', i.e. validating if CE monitors assess resource-quality degradation over multiple uses (or lives) of the material. The assessment should ideally include the downstream uses of all the material streams (products, by-products and residues) produced in the system.

Relative to other requirements, a higher number of CE metrics displayed consideration for this category – 14 indicators, out of 59, consider the assessment of cascading. Out of the three indicators that implicitly assess it, two assume economic value as a proxy for material quality (Linder et al., 2017; Wen and Meng, 2015), while the third one, the *resource duration indicator* or the *longevity* indicator, measures the contribution to material retention based on the time a resource is in use (Figge et al., 2018; Franklin-Johnson et al., 2016). Increasing the duration of use supports increasing the value-extraction, one of the primary principles of cascading, and has been considered an implicit (and partial) assessment. Amongst the ten indicators that stress the need to assess material quality instead of mere recycling index, three indicators either do not specify the means to do so (Bracquené et al., 2019; Camacho-Otero and Ordoñez, 2017), or highlight that, currently, no data is available to create this indicator (European Environment Agency, 2016).

Among the indicators that explicitly assess cascading, *Recycling rates* proposed by Haupt et al., 2017 and the *Circular economy toolbox* by the U.S. Chamber of Commerce Foundation measure closed-loop and open-loop recycling rates. Closed-loop recycling implies using secondary resources to produce the same product, while open-loop recycling is producing something that differs from the preceding product. Similarly, Graedel et al. (2011) split the recycling rate into end-of-life functional and non-functional recycling rates. The functional recycling rate is the portion of resources that are separated and recycled to retain their functions. The non-functional recycling rate describes the share of collected resources recycled to be part of a larger material stream as impurity elements. That incentivises the prevention of dissipation of this material into the environment but represents the loss of the material's functional properties. Both these indicators acknowledge that often the material loses its quality during recycling, the information regarding which is not captured in the recycling rate. However, none of these indicators considers the extent of quality loss.

The *circularity index* explicitly considers quality during recycling based on the ratio of the energy required to recover the material from secondary sources (i.e. waste streams) relative to the energy required to produce the material from primary sources (i.e. nature; Cullen, 2017). It is regarded as a partial assessment because the energy required for recovery is technology-specific and might not always represent the material quality. Another CE tool that explicitly assesses cascading, *Circular Economy Index*, assumes market value as an indicator of material quality and measures the ratio of the material market value produced by the recycler to the intrinsic value entering the recycling facility *(Di Maio et al., 2017)*. The *Material recycling index* considers recyclate quality as a function of product design and recyclate composition (Van Schaik and Reuter, 2016). However, the product design could be a proxy and not an actual parameter for material quality. These indicators, which explicitly assess cascading, focus on single-step recycling and appear ineffective for multiple lifecycle assessments of the material. *Circularity material indicator* considers a weighted factor based on quality, purity and recoverability to assess the circularity of material (Pauliuk et al., 2017).

The *circular Economy Performance Indicator (CPI)* is the only metric that successfully evaluates the quality of material flows. CPI indicator is built on the existing recyclability benefit rate (RBR), which is a ratio of environmental benefit from recycling a product over the environmental burden related to production from virgin resources followed by disposal. To integrate the quality loss during recycling into the assessment, the study proposed CPI as the ratio of the actual obtained environmental benefit over the ideal environmental benefit according to quality (Huysman et al., 2017). The latter is the environmental benefit when the waste is re-directed to the state-of-the-art waste treatment option best suited to the waste stream according to its composition or quality. CPI is 1 when the waste is used to the best of its quality (assuming the impact and losses during recycling are minimal). The value of CPI lower than 1 would indicate that the waste stream is not utilised to the best of its technical capability (or the recycling process has a significant material loss or environmental burden). This tool can be aptly used to determine the most appropriate use of waste streams based on their quality, which is one of the key principles of cascading.

The selection of the highest-value application for a material stream, the aspect currently lacking in CE assessment, can be done based on a guiding principle, such as the one adopted by the EU Waste Framework Directive (European Commission, 2008). It provides a waste hierarchy, which sets priorities for waste handling techniques. Several other frameworks could aid in this selection process, for example, Lansink's Ladder, Van Gerven's Ladder, Bio-based pyramid (Odegard et al., 2012), and food waste hierarchy (Teigiserova et al., 2020). However, these frameworks only set preferences for applications or processes. They do not state the application best suited for the resource based on the inherent resource properties and the application that necessitates these properties the most. The Circular Footprint Formula (CFF) integrates quality ratios in the Product Environmental Footprint (PEF) and considers the quality difference between secondary materials – both the incoming and outgoing – and the primary materials used in the system (Zampori and Pant, 2019). Incoming secondary materials are the secondary content consumed by the system, and outgoing secondary materials are the system output available for (re)use. Considering the quality of incoming secondary materials would incentivise the use of lower-grade material (i.e. avoiding the use of higher material if not demanded by the system), and considering the quality of outgoing secondary materials would incentivise avoiding quality loss (i.e. producing as high-quality output streams as possible). This indicator follows the cascading principles and could be a measure of cascading. However, the quality ratio is the ratio of price (and not material quality) of the secondary compared to the primary material. The CFF guide specifies that when economic aspects are less relevant than physical aspects, the latter may be used. But does not detail how the physical parameters must be measured. Methodologies that evaluate the intrinsic material properties, such as statistical entropy analysis (SEA) or exergy analysis, could support filling this gap. SEA has been put forward as a method to assess resource quality (Laner et al., 2017) based on the concentration of a substance in a flow (Rechberger and Graedel, 2002). The higher the substance concentration in a flow, (theoretically) lesser efforts would be needed to recover it and, hence, the higher the potential utility. SEA could also quantify quality based on other physical properties that determine the material's utility. For example – for wood, the size of the wooden element is one of the parameters that define its utility. Sawn wood has a higher utility than wood chips. SEA applied to the entire lifecycle of material, as done in Laner et al. (2017) and Rechberger and Graedel (2002), reflects changes in the resource quality over time. The resource-use pathway that maximally preserves the quality and material value over time can be considered the most desirable material trajectory. SEA includes all three aspects – quality degradation, multiple life cycles & multiple streams – relevant for cascading and, thus, could be a powerful tool for assessing it. Exergy analysis uses the thermodynamic-based exergy concept, which is the maximum potential work that can be obtained from the resource when bringing it into equilibrium through reversible processes with the natural environment (Dewulf et al., 2008). Resource quality degradation is represented by the loss of potential energy, and hence the exergy approach too could be viable to study cascading. The use of exergy analysis to study cascading use has already been demonstrated by Risse et al. (2017). While SEA and exergy analysis can identify the highest material-value trajectory, complementary methods, such as LCA, support improve the resource efficiency and reduce the environmental burden of that material trajectory (Dewulf et al., 2008; Kaufman et al., 2008a; Rechberger and Brunner, 2002). Methods such as these should be integrated into the CE assessment frameworks to ensure the cascading use of biotic resources is optimised.

Closing the biological nutrient cycle

The third aspect evaluated refers to the closing of the biological nutrient cycle and validates if the CE monitors assess:

1. Biodegradability of the bio-based material – i.e. it safely returns to the biosphere and does not accumulate in the environment
2. Toxicity of substances present in the emissions to the environment resulting from biodegradation
3. Biotic resources return to the environment at a rate at which assimilated by the environment
4. For the nutrients that are scarce and critical for ecosystem regeneration, the nutrients return at a place and rate that sustain the regeneration of the ecological systems

It is observed that, of 59 CE indicators that were studied, only one indicator completely studied the end-of-life of biotic resources. Additional eight indicators assess only part of the criteria of biological nutrient loop closing.

The indicators that partially assess the end-of-life of bio-based material validate whether it is biodegradable or compostable. The circularity measurement tool 'Circulytics', developed by Ellen MacArthur Foundation (2020), evaluates the share of the total output flows, products and waste that are suitable for the biological cycle, i.e. that degrade and do not harm human health or the environment during or after their use. *EU Resource efficiency scoreboard* (European Commission, 2015b) evaluates whether the nutrients from end-of-life return as feedstock to the ecosystems. The indicators for that are area under organic farming, soil erosion and gross nutrient balance in agricultural land. The scoreboard focuses on the agricultural systems, and the evaluation of other biomass production systems, such as forestry and marine, is overlooked. The only indicator that evaluates biological nutrient loop closing is the *Cradle to Cradle Certification Program*. The assessment for this certification validates if the companies pursuing certification define components of their products as biological or technical nutrients, and design pathways for nutrient recovery and re-utilisation (The Cradle to Cradle Products Innovation Institute, 2014).

CE monitors should include, equivalent to the recyclability score for technical cycles, a biodegradability score for end-of-product-life bio-based materials. The monitors should also assess the potential impact of the non-biodegradable or toxic elements present in the waste streams on ecosystem functioning. Additionally and more importantly, for the streams that safely degrade, the CE assessment should assess the impact of biomass decomposition on the ecosystem services. The monitor could map nutrient flows at a regional scale (country or province), i.e. mapping nutrients in biomass, agriculture and forest soil, sewage sludge, livestock manure and water bodies (Mayer et al., 2019). The assessment could be at the ecosystem level aiming to protect ecosystem functioning, i.e. measuring soil fertility, water availability and quality, biodiversity and other measurements that indicate ecosystem health. Such indicators must be monitored for ecosystems affected by human interactions, i.e. ones where nutrients are harvested and where they are deposited, to ensure biological cycles do not harm ecosystem functioning.

Assess the environmental impact associated with biological cycle

The fourth element evaluated in this study is whether the environmental impacts associated with biotic resource extraction and the temporal aspect of carbon fluxes are being assessed in the CE monitoring frameworks. The study evaluated whether the environmental impact assessments considered the impacts of biotic resource extraction resulting from land use interventions and resource depletion on ecosystem services. And concerning the environmental impact due to biogenic carbon emissions, the study evaluated if the CE monitors validate the carbon neutrality of biological cycles by accounting for the rate of carbon sequestration, the amount of time over which carbon remains stored and the rate of release of biogenic carbon.

Only 11 out of 59 CE monitors assess environmental impact, but even they are incomplete. The framework defined by the European Environmental Agency mentions that bio-based material use can damage biodiversity and ecosystem services and contribute to climate change but does not assess it (European Environment Agency, 2016). Other CE assessment frameworks evaluate the environmental impact of biotic resource use but do so insufficiently. Many of them measure ecological efficiency in terms of land area, water consumption, energy consumption and emissions (especially SO_2) per unit output (Geng et al., 2012; Li and Su, 2012; Su et al., 2013; The Cradle to Cradle Products Innovation Institute, 2014). The *Regional Circular Economy Development Index* developed by Guogang and Jing (2011), in addition, also measures the amount of chemical fertilisers applied per unit planted area. These indicators are insufficient to gauge the total ecosystem impact of biotic resource depletion and land use. Additionally, carbon accounting is not present in these listings. The *EU Resource efficiency scoreboard* has a comparatively wider range of indicators, including an index of common farmland bird species, the extent of land fragmentation and soil erosion. This scoreboard does include greenhouse gas (GHG) emissions, but the emissions from the use of biomass and stock changes in forests are not included. The CE indicator system developed by Zhou et al. (2013) assesses the external environment damage cost caused due to the production process, i.e. the ecological damage originating from the overconsumption of natural resources. This metric assesses the impact of pollution on ecosystem services but not on resource depletion.

The remaining indicators base their assessment on the LCA methodology (Genovese et al., 2017; Scheepens et al., 2016; Smol et al., 2017). For instance, Scheepens et al. (2016) apply the *LCA-based Eco-costs Value Ratio* (EVR) model to analyse the potentially negative environmental effects of business initiatives. LCA is a widely used methodology to assess environmental impact. However, the environmental impacts associated with land use and biotic resource depletion are not always fully integrated or widely applied in many LCA studies (Heijungs et al., 1997; Koellner et al., 2013; Wagendorp et al., 2006). For the aspect of carbon balance, contribution to climate change (in LCA, impact category GWP) is often a central part of LCA, but consideration of the temporal aspect of emissions is often lacking (Levasseur et al., 2010). This suggests a clear need to explicitly include these aspects in CE monitoring for a complete assessment of the impact of bio-based materials or biological cycles.

Existing indicators that indicate the impact of biotic resource extraction and depletion measure the biologically productive land and sea required to provide a product or service. These are ecological footprint, agricultural land footprint and forest footprint. There are increasing attempts to evaluate impacts on biodiversity and ecosystem quality. Even for the LCA approach, concrete proposals have been put forward to incorporate the impact of biotic resource extraction, resulting from land use & land use change and resource depletion, on biodiversity and ecosystem health. Impact due to land-use interventions is based on the type of landscape that is disturbed and the duration of the disturbance (Heijungs et al., 1997), which considers the current occupation of land and change in land use, which affects the natural regeneration time and biodiversity (Koellner et al., 2013; Lindeijer, 2000). Wagendorp et al., 2006 provided an LCA-based assessment for land use impact based on ecosystem thermodynamics. Human impact, such as reduced biomass, is indicated in this study by a decrease in exergy, which is converse to what the ecosystem strives to achieve. Schmidt et al. (2015) provided a framework for evaluating indirect land use change. Koellner et al. (2013) proposed structured guidelines to assess the damages caused by land-use interventions on biodiversity and ecosystem services. This framework includes two impact pathways - biodiversity damage potential, based on the functional diversity of species in ecosystems, and ecosystem services damage potential, based on the impact on the potential of the ecosystem to produce biomass, the impact on climate and the impacts on water and soil quantity and quality.

Crenna et al. (2018) evaluated the consequence of biotic resource depletion on ecosystem quality. Crenna et al. (2019) showcase using the preliminary LCA-based impact assessment framework the role of EU food consumption in the current biodiversity decline. They studied the impact of the food system on different impact categories (climate change, eutrophication etc.) and then measured the rate of species lost in a particular area of land or volume of water during a particular time due to these impacts. A different perspective has been proposed by Dewulf et al. (2015) to acknowledge this issue. They recommend that instead of having ‘natural resources’ as an area of protection, LCA could have the ‘ecosystem functions or services’ as a safeguard subject. For instance, instead of considering wood from the forest as an asset to be protected, the functions trees provide to the ecosystem (e.g. climate regulation, water purification) should be protected. These are proposals for bridging the gaps in LCA but could also be relevant for CE monitoring.

Concerning carbon accounting in LCA, carbon sequestration during biomass growth is commonly accounted for as negative emissions. But the temporal profile of carbon sequestration, storage and emissions are not often considered (De Rosa et al., 2017). The attention toward this time-dependent accounting of biogenic carbon flows has recently increased (Levasseur et al., 2010). Several methodologies aim to integrate it into mainstream LCA (De Rosa et al., 2017), building on time-dependent life-cycle inventory data, which details emissions and sequestrations through time (i.e., the amount of carbon released or absorbed at every given time step). The dynamics of carbon flux significantly influence the LCA results, and therefore it is crucial to integrate the time-frames to accurately assess the global warming impact of the use of bio-based materials and biological cycles.

2.4. Conclusion

The use of biotic resources is not necessarily circular and sustainable. Thus, a critical evaluation of the biological cycles is essential in the context of CE, which is currently lacking. For circular biological systems, biotic resources should be sourced at a rate that ensures long-term yields and no harm to ecosystem services. Secondly, bio-based materials, which have no potential material applications, incinerate or decompose and return to the environment without affecting the ecosystem's functioning. In some cases, their return as biological nutrients is crucial to support ecosystem regeneration. Biotic resources should follow an optimised cascading use pathway to slow the need for primary resources and delay emissions (nutrients/CO_2) to the environment. In a way, cascaded use supports the former two objectives of sustainable harvesting and closing the biological nutrient loop. Thus, unlike abiotic resource use that needs to be reduced, biotic resource use needs to be slowed down. The bio-based materials that do not decompose or are toxic should be treated as part of a technical cycle and should be looped back into the anthroposphere to maintain their material value for as long as possible.

The biological cycles have an environmental impact, specifically from resource extraction and biogenic carbon emissions. Biotic resource extraction damage biodiversity, ecosystem health and functioning due to resource depletion and direct and indirect land-use change. These impacts should be closely monitored within circularity frameworks. The use of bio-based materials is encouraged because of their potential environmental benefit over their fossil counterpart, which will likely increase the demand for biotic resources. The circularity of biological cycles should be analysed to avoid overexploitation of natural resources and further degradation of ecosystems. Therefore, a thorough CE monitoring of the biological cycles should assess (1) sustainable sourcing, (2) cascading use of materials, (3) the extent to which nutrients effectively re-enter the biological cycles and (4) the environmental impact of sourcing biotic resources and carbon fluxes. These assessments do not necessarily have to be newly developed. Existing indicators and assessment frameworks from different sectors could assist in filling the gap. This study highlights that bridging the gaps in current CE assessment and making them apt also for biological cycles is crucial and would be a step forward in ensuring sustainable and circular use of natural resources.

Chapter 3: Cascading use of wood

"What we are doing to the forests of the world is but a mirror reflection of what we are doing to ourselves and to one another"

Mahatma Gandhi

3.1. Introduction

Wood is a natural, widely available and functionally renewable resource. It is biodegradable and has distinctive mechanical and thermal characteristics making it versatile and multifunctional. Wood-based products often have lower environmental impacts than equivalent inorganic- or fossil-based products (Buchanan and Levine, 1999; Geng et al., 2019; Petersen and Solberg, 2002). For example, wood building production uses less energy and emits less carbon than concrete building production (Sathre and Gustavsson, 2009). Wood can also substitute for fossil energy (or fuel) sources. Wood use generates little waste – most by-products and residues can be recycled or used for energy production. Wood products can also be (down-) recycled for other material or energy applications after use. Like trees in the forest, wood products store carbon and reduce the atmospheric CO_2 concentration, especially long-lasting ones. They have been officially accounted for as carbon sinks since the 17th Conference of the Parties in Durban (COP17; UNFCCC, 2012). With all these benefits, wood plays a potential role in climate change mitigation.

The renewed interest in wood has increased its use, both in traditional (long-established applications such as construction and furniture) and novel applications (such as bio-fuels and bio-chemicals). In addition to this growing relevance of the bioeconomy – to mitigate climate change and replace fossil resources – increasing population and expanding economy are driving the growth in the demand. Although wood is renewable, land availability and forest regeneration rates limit the wood supply. The sustainable wood supply available from European forests (EU28) for 2015 was 576 Mm^3, of which 75% was felled (Forest Europe, 2020). So, the yearly harvest can increase only by 144 Mm^3, beyond which the sustainability of wood supply is at risk. In Belgium, this wood utilisation rate is already 98.7% (Forest Europe, 2020). The wood demand is expected to exceed its supply by 2030 in Europe (Mantau et al., 2010).

The increase in wood consumption has been followed by a growth in waste wood production - during the manufacturing and end-of-life of wood-based products. These waste stocks are an abundant and inexpensive source of raw materials with a potential for material and energy applications. Europe (EU28) produced 55 million tonnes of waste wood in 2016 (European Commission, 2018b; Eurostat, 2016). Of these, 48 Mt were collected. However, only 24 Mt (50%) were recycled for material applications. Around 23 Mt (~49%) of the collected wood waste was burned for energy generation. 490 kt. were still landfilled or disposed of by incinerating (European Commission, 2018b).

In Belgium, Flanders produces approximately 1 million tonnes of wood waste yearly (OVAM, 2017). This PhD study developed the waste wood balance for 2014 (Fig. 3.1) to assess the quality and quantity of waste wood produced, its current downstream use and the potential for improvement. The results of this study, published in Marques et al. (2020) and Vandereydt et al. (2019), showed that the waste wood constitutes 820 kt of industrial- and 160 kt of household waste. Industrial residues (430 kt), the largest waste stream, are the waste generated during production processes in the sawmill and finished-products industries and constitute mainly wood chips, shavings and sawdust. The remaining industrial waste (390 kt) is post-consumer waste produced by the end consumer of wood products. Although originating from a wide range of applications, a large portion is packaging waste (pallets) and CDW. Industrial residues are mostly clean and untreated and can potentially be a feedstock for pulp, wood panels or energy applications. But, the post-consumer (industrial and household) waste is very heterogeneous in quality – depending on the presence of contaminants and other substances – challenging its downstream material application. Additionally, its production is geographically widespread and requires more complex logistics of collection, sorting and pre-processing the waste before redirecting it to the downstream industries consuming the waste wood.

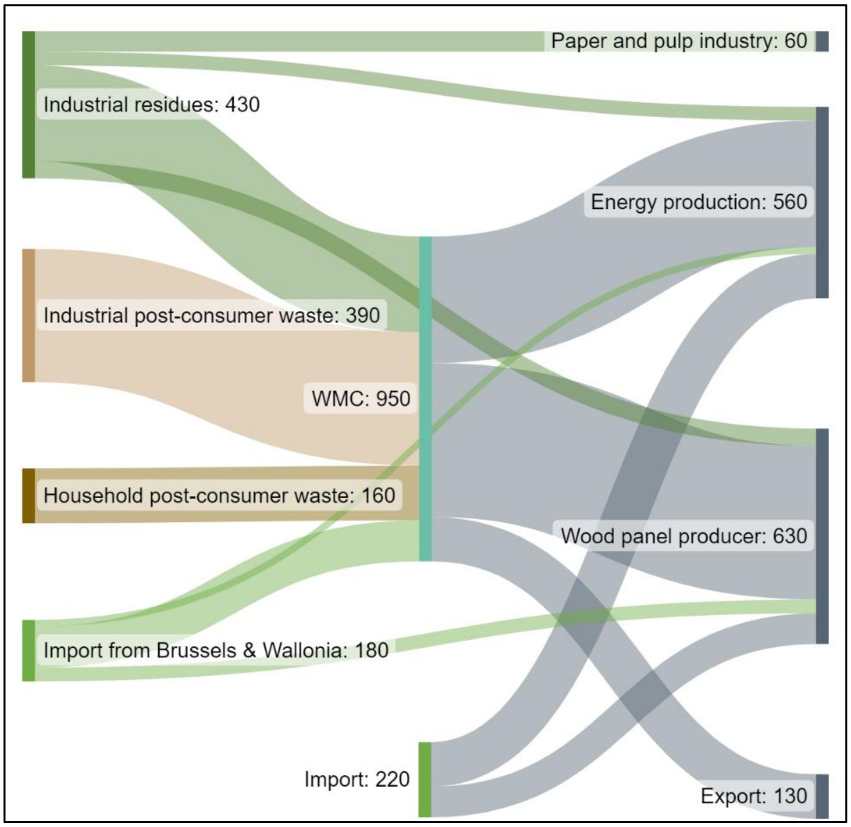


Figure 3.1: Sankey diagram of the waste wood flows in Flanders in 2014 (Marques et al., 2020)

The primary destination for downstream material application of waste wood is the wood-panel industry, consuming 630kt of generated waste wood. Yet, approximately 560 kt is burned for energy recovery. Although mostly the treated and highly contaminated waste wood is incinerated, burning is still a loss of material value and indicates the missed opportunity for optimised resource use. Using it for material applications could help handle the growing demand for wood. However, as mentioned above, the contaminants and non-wood substances in the waste wood often hamper their recycling potential. Other than minimising contamination, better sorting of waste wood is essential to improve their downstream application (Vis et al., 2016). High-quality waste wood (i.e. untreated and large dimension wood) often gets collected along with contaminated or lower-grade waste wood, especially CDW, and does not get recycled. An additional challenge is that wood deteriorates in size and structure with time, during use and processing. The utility of wood decreases with decreasing dimensions, and recycling it to its initial form and functionality is rarely possible. Often preservatives are used to slow down the decay during use, but these chemical substances (often toxic) might hinder the downstream application as they might not be permitted in other applications. For example, wood contaminated with certain preservatives cannot be used for toys.

With the challenges in recycling wood, cascading becomes a means to optimise resource use. Cascading is a holistic look at the 'wood use' from cradle (harvest) to grave (decomposition). It is designing sequential wood use to exploit its full potential (Fraanje, 1997) by prioritising the use of wood in high-quality (larger dimension and lower contaminants) products to increase options for downstream application at the end of life (Odegard et al., 2012) and minimising quality loss during use and processing. Cascading can improve resource use efficiency (Fraanje, 1997) and increase wood availability (Vis et al., 2016) for other applications to tackle the growing demand that threatens to exacerbate the overexploitation of forests and cause the degradation of ecosystems. Avoiding that and providing societal needs with available natural resources must be a primary concern of humankind because how we treat the forest reflects how we treat one another, as cautioned by Mahatma Gandhi.

3.2. Wood cascading

Currently, there is no consensus on a definition of cascading. Several wood cascading definitions are available in the literature (listed in Annexe B – B.1). This study consolidated these definitions to arrive at a single working definition for the analysis:

Cascading is the sequential use of wood – industrial residues and post-consumer wood – in multiple applications as long, as many times, and as efficiently as possible. Cascading foresees a value-oriented hierarchical biomass utilisation – using wood firstly in multiple high material-quality applications, followed by applications with decreasing material quality and ultimately for energy when no other material application is feasible. It is a means to extend service life, enhance resource efficiency and increase biomass availability.

An example of cascading is sawn wood used first for long-lasting construction elements. The CDW, still large in size and without contamination, is used for high-value applications such as furniture and post-consumer furniture is chipped and turned into wood panels instead of burning for energy. The production residues or by-products are, similarly, used for the highest material value application for which they are suitable (Höglmeier et al., 2013; Keegan et al., 2013); for instance, the sawdust from the sawmill industry is used for wood panels or pulp production instead of being burned for energy. These resources sometimes leave the wood-based product cycles and enter alternative sectors such as the textile, chemicals or pharmaceutical industry, forming a starting point for a new cascade chain. For example, cellulose fibres from sawmill residues can be the origin of cascading use of textiles. Sawmill residues could be a feedstock in bio-refineries to produce plastics and become a part of the synthetic material value chain (or technical cycle). Also, plastics might be recycled further multiple times before ultimately being incinerated. This cascading definition can be a guide to improving resource management. The aim is to increase material utilisation time (by increasing the service life of each application by increasing durability, reusability, etc. and increasing the number of sequential applications) and slow down quality loss (by considering an end-of-life option that uses it for the highest material quality application possible). In a way, as suggested also by Mair and Stern (2017), cascading contains all end-of-life options (repair, reuse, downcycle, etc.) within one term.

Sirkin and Houten (1994) were the first to describe the concept of cascading. They presented cascading as a design tool - for appropriate designing of products and production processes - for sustainable resource management. They suggested that cascading has four dimensions:

1. *Resource quality* measures the potential resource utility, which is the capacity to perform tasks based on the inherent and intrinsic material properties (displayed as the y-axis in Fig. 3.2).
2. *Utilisation time* is the time of resource use (displayed as the x-axis in Fig. 3.2).
3. *Salvageability* is the recirculation of the resources to higher levels of the cascade or alternative cascade chains.
4. *Consumption rate* is the rate at which resources are consumed, which should not affect the resource availability for future generations.

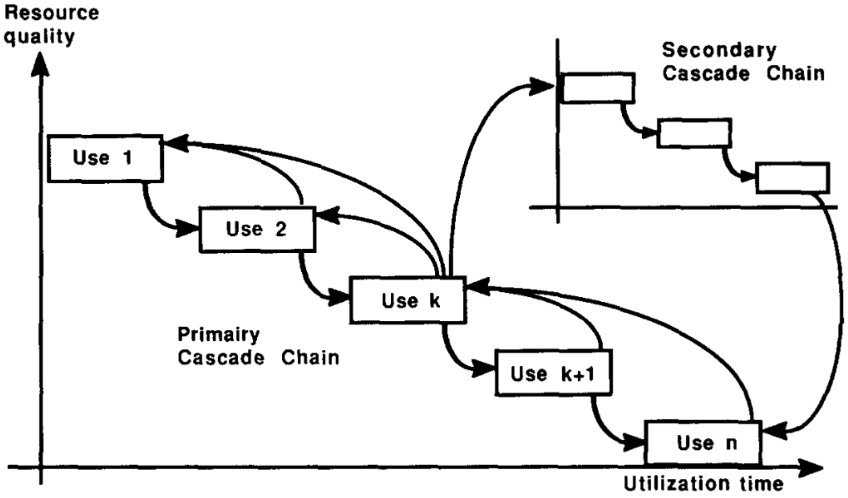


Figure 3.2: Theoretical description of cascading use of resources as described by Sirkin and Houten (1994)

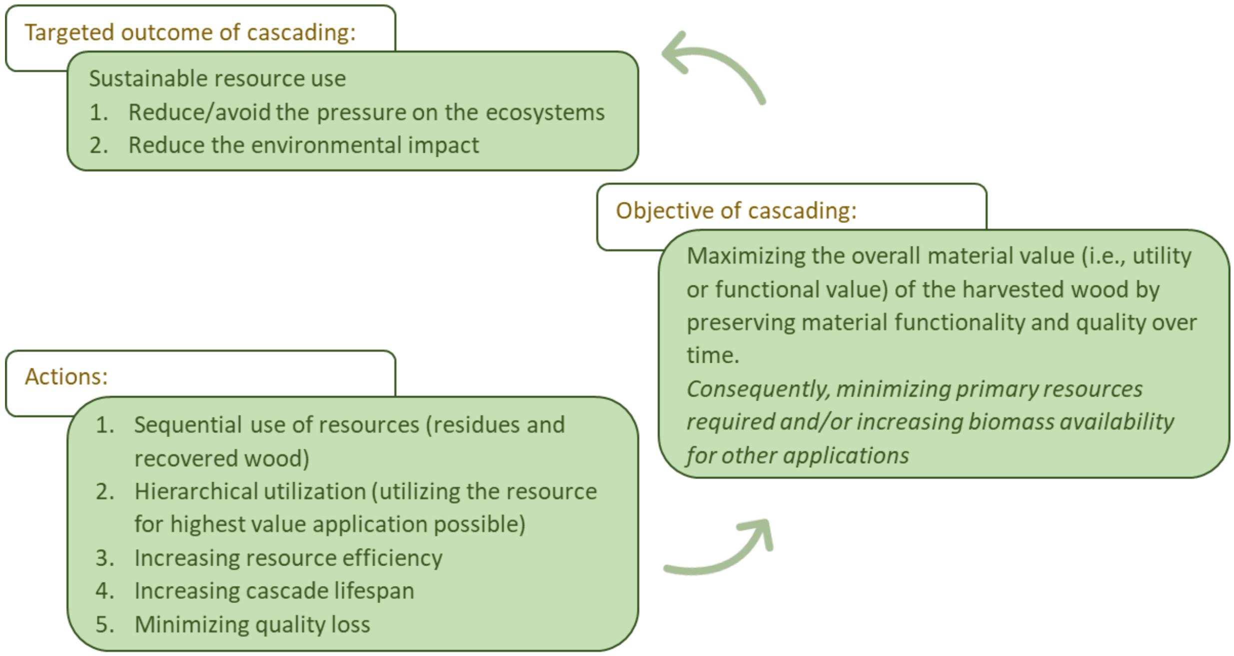
Sirkin and Houten (1994) incorporated these four dimensions in the four principles of cascading to guide sustainable exploitation and conservation of resources:

1. *Appropriate fit*: material quality of the resource is used for a task must match the quality demanded by that task. High-quality material is not used for an application that requires lower quality.
2. *Augmentation*: maximising the utility by increasing the utilisation time and minimising the decline in material quality.
3. *Consecutive relinking*: determining the optimal and highest value pathway for materials from all the possible alternative value chains.
4. *Balancing resource metabolism*: establishing a balance between resource consumption and extraction rate. This dimension seeks to incorporate the importance of inter-generational resource management.

Since then, several other frameworks have been presented. Fraanje (1997) proposed a framework – starting at a high resource quality, increasing the total time of resource use (increasing the lifetime of the individual applications and thus the overall service life of the resource) and minimising quality loss per application. Lafleur and Fraanje (1997) outlined a six-step methodology to achieve sustainable use of primary wood, arguing that cascading is essential for achieving sustainability: performing an input-output analysis of primary wood flows, reducing the (end) use of wood-based products, determining the appropriate fit (by applying resources to highest quality application possible), cascading, increasing process efficiency, and finally evaluating the overall sustainability of the process. Odegard et al. (2012) identified the optimal material use pathways based on:

1. *Cascading-in-time* is increasing the service time of the material use.
2. *Cascading-in-value* is optimising further 'cascading in time' , which is by achieving the highest possible value between alternatives and maximise the total material value over multiple life cycles.
3. *Cascading-in-function*: maximising the total functional use by utilising multiple streams – products, co-products and residue streams.

Cascading is a means, not a goal. The goal is to exploit maximum value (utility or functionality) from the available wood resource to reduce the need for primary resources and thus reduce the environmental impact and ease the pressure on the ecosystems. Cascading thereby contributes to the overall objective of the CE of the biological cycle. The inherent quality of the material (i.e. physical and chemical properties) provides the required functionality. Therefore, cascading strategies aim at preserving the material quality as long as possible to achieve the objective of a maximised material value. The study consolidates this understanding of cascading concepts and presents it as a framework to guide further analysis (Fig. 3.3).



Targeted outcome of cascading:

Sustainable resource use
1. Reduce/avoid the pressure on the ecosystems
2. Reduce the environmental impact

Objective of cascading:

Maximizing the overall material value (i.e., utility or functional value) of the harvested wood by preserving material functionality and quality over time.
Consequently, minimizing primary resources required and/or increasing biomass availability for other applications

Actions:

1. Sequential use of resources (residues and recovered wood)
2. Hierarchical utilization (utilizing the resource for highest value application possible)
3. Increasing resource efficiency
4. Increasing cascade lifespan
5. Minimizing quality loss

Figure 3.3: Conceptual framework for cascading

3.3. Assessment of wood cascading

3.3.1. Existing assessments of cascading

Several studies evaluated the impact of cascading use of wood. Most of these studies observed an environmental and resource use benefit of cascading. Fraanje (1997) examined the use of pine wood in the Netherlands and concluded that cascaded use could reduce the need for primary resources. Other authors also proved that cascaded use could improve resource use efficiency (Haberl and Geissler, 2000; Risse et al., 2019, 2017) and reduce GHG emissions (Bais-Moleman et al., 2017; Kim and Song, 2014; Sathre and Gustavsson, 2006; Sikkema et al., 2013; Taskhiri et al., 2019) by replacing fossil-based resources (Sathre and Gustavsson, 2006; Sikkema et al., 2013), increasing carbon stocks (Brunet-Navarro et al., 2018) and delaying emissions resulting from incineration or decomposition of wood at the end of products lifetime (Faraca et al., 2019b; Mehr et al., 2018).

The methodologies adopted for cascading analyses were primarily the LCA and Life Cycle Inventory (LCI). They respectively assessed the environmental impacts and the resource-use efficiency of wood cascading. Risse et al. (2017) additionally used exergy analysis to study the consumption and efficiency of resource use in cascading chains. Cornelissen and Hirs (2002) used an exergetic LCA to quantify the depletion of natural resources. Haberl and Geissler (2000) evaluated the result of a cascading strategy on biomass use by measuring the net primary production of biomass. Vis et al. (2014) suggested three groups of indicators for evaluating cascading: resource use (resource input, recycling rate and resource efficiency), carbon emissions (carbon footprint, savings and storage in HWP) and economic performance (gross value added, resource productivity and employment generation). Mantau (2012) was the first to propose an indicator specifically for cascading use, namely the cascade factor, based on the number of times a resource is utilised in a wood-based product value chain, which indicates wood-use efficiency. Indufor (2013) published a slightly different indicator called the ‘total cascade factor’. It is the total wood used divided by the roundwood component. Another indicator, the ‘biomass utilisation factor’, proposed by the Nova Institute quantifies the extent to which and the number of times the wood is (re-)used, considering cascading factors and production efficiency (vom Berg et al., 2022). Another difference between the ‘biomass utilisation factor’ and the 'cascade factor' is that the former includes different value chains - both wood-based products industry and other sectors of which wood becomes part, such as the chemical industry (Vis et al., 2016; WWF - World Wide Fund For Nature, 2016).

3.3.2. Gaps in the existing assessments

Cascading definitions and frameworks emphasise maintaining material quality as the primary objective of cascading. Yet, most studies do not include material quality in their evaluation. Kim et al. (1997) and Rehberger and Hiete (2019) considered material quality while performing LCA but did so to describe methods to allocate the environmental burden onto different products produced in cascading based on the quality of raw material. Most cascading studies assess resource use efficiency and the environmental impact. However, material circularity assessment of cascading would require quantifying the degree to which the material value (i.e. functionality and material quality) is preserved over time in a cascading pathway. That would need assessing the material quality over time of different cascading systems to identify the one that retains the material quality for the longest time.

That is the difference between effectiveness and efficiency. Effectiveness is the degree of achieving an objective, whereas ‘efficiency’ is the effort or cost (monetary or environmental) for achieving that objective. Most of the mentioned studies measure the reduction in cost or effort (as resource input or GHG emissions) because of cascading and do not assess the extent of achieving the objective of cascading, which (as shown in Fig. 3.2) is preserving the material quality of wood as high as possible for as long as possible. Another reason to focus on resource effectiveness instead of efficiency is that costs often depend on the background systems. The monetary value and environmental impacts depend on the factors - such as the composition of the energy mix of the country, available technology, local cost of human resources, and local access to resources. For example, water use has a higher impact in places where water is scarce, or the environmental impact of production is lower in countries where more energy comes from renewable sources. The resource effectiveness perspective looks beyond these societal influences and geographical contexts. It identifies an ideal system for resource use based on material properties, which is optimised further by enhancing efficiency as a second step.

Additionally, most methodologies used for assessing cascading assess the impact (on the environment or resource use) and do not facilitate decision-making for designing and developing cascading systems (Campbell-Johnston et al., 2020). Since cascading involves sequential material use, it needs a tool to decide which application best utilises the remaining material quality for the available resource (i.e. the principle of appropriate fit; Sirkin and Houten 1994). These could be virgin, recovered or residual resources. It needs to choose an appropriate downstream application for all the parallel streams to maximise the overall material value. Hence, cascading assessment needs to be a macro-level assessment to identify the highest material-value pathway from all the possible alternatives (i.e. the principle of consecutive relinking; Campbell-Johnston et al. 2020).

In summary, designing cascading systems requires a holistic perspective on material flows. Cascading includes multiple life cycles and multiple side streams and involves two dimensions - material quality and time. Hence, the cascading assessment needs - in addition to resource efficiency metrics - resource effectiveness metrics to evaluate the material value change over time for all the possible alternatives material use pathways and identify the one that maximises the material value (i.e. the one that has the slowest degradation of material value).

3.3.3. Closing the gaps

As mentioned earlier, the evaluation of cascading systems requires a metric for the measurement of resource effectiveness – i.e. the degree to which the cascading system maintains material quality. Material quality refers to the potential of resource utilisation based on inherent and intrinsic material properties and not market value (Sirkin and Houten, 1994). These are physical attributes not altered by human interests or interference. It is a function of the material's embodied energy, chemical composition or structural organisation (Campbell-Johnston et al., 2020; Sirkin and Houten, 1994). In addition, material quality is the number and type of options left open at the end of life by the material for its subsequent use (Odegard et al., 2012). Following this definition, two factors that influence the quality and utility of (virgin and waste) wood are dimensions (material and structural integrity – size and volume) and purity (presence of non-wood substances; Höglmeier et al., 2013).

Firstly, wood large in size has a higher utility and quality and loses quality due to the degradation of natural fibres, causing size reduction or breakdown of components built from wood and loss of their physical and structural properties. For example, fresh wood from forests has a high material value (i.e. robust carrying capacity) and is usable for applications such as timber beams for construction purposes. But its physical and structural properties deteriorate with time and use, resulting in a decrease in size as it breaks or degrades. The beam is cascaded to a downstream application, such as flooring. However, processing reduces further the beam size. After a certain period, these flooring planks are discarded but can be shredded into wood chips for particleboard production.

Secondly, the impurities or contaminants (physical and chemical) hinder the utility of wood. Physical impurities are non-wood materials present in waste wood, such as plastics and metals. Chemical impurities are the chemical substances added to improve aesthetics (such as paints and varnish), mechanical material properties (such as binders, adhesives and gluing agents) or resistance to decay (preservatives such as chromated copper arsenate, pentachlorophenol and creosote; Faraca et al., 2019a; Ramage et al., 2017). Some of these chemicals are hazardous (e.g. creosote), and waste wood containing those chemicals cannot be cascaded down (Faraca et al., 2019a). The non-toxic additives, such as paints and glues, also make utilising that wood difficult. Particleboard, the only application that can use contaminated wood (Vis et al., 2016), faces challenges with the glue present in wood, as it inhibits reaction with the new adhesive in the downstream application and results in a significant drop in the properties (Besserer et al., 2021).

The impurities, on the one hand, enhance the durability and utility of wood products and slow size degradation in wood. On the other hand, they could reduce the cascading potential of wood products. Cascading is finding a trade-off between the two. Cascading assessment thus needs to evaluate both the dimensions of wood quality – size and purity – across multiple life cycles of the products (Haberl and Geissler, 2000), ideally from cradle (harvest) to the grave (decomposition).

SEA is a method that evaluates material quality based on the substance composition (Laner et al., 2017; Rechberger and Brunner, 2002). It could be used to assess cascading systems (by evaluating wood quality over time) and compare different wood cascading pathways to identify the one that maximally preserves the material quality. SEA quantifies statistical entropy based on substance distribution in a material flow. The larger the number of substances present in a material flow and the more uniformly they are distributed, the higher the statistical entropy. This compositional complexity can be well explained for metals and minerals. Metals degrade in quality (often observed in the recycling process) when mixed with other metals, undesirable elements, or lower grade materials and display inferior material properties like decreased mechanical strength (Koffler and Florin, 2013). Additionally, the more the number of substances present in a material flow and the more uniformly they are distributed (i.e. high statistical entropy), the more effort is required to recover these metals from the mixture. The compositional complexity or substance composition can describe one of the dimensions of wood quality, namely purity or contamination with non-wood materials, by accounting for the contaminant (or non-wood materials) concentrations in the product. However, the other dimension of wood quality, namely size and structure, cannot be assessed with the current statistical entropy definition. So, modifications to the current statistical entropy definition are needed to assess the dimensional aspect of wood quality.

Statistical entropy is a generic method to quantify distribution function. So, *the research aimed to evaluate whether the dimensional aspect (size) of wood quality could be expressed as a distribution function and, by doing so, redefine statistical entropy based on the distribution function*. For that, the material quality was described as a size distribution function. For a conceptual explanation, consider virgin wood, which has the largest size and highest quality within the value chain. It can be seen as having a narrow size distribution (assume it to be a single piece of wood with the largest size). When it breaks, the size distribution widens as now there are several pieces of smaller size. As the size of wooden pieces decreases, the size distribution widens, and the statistical entropy increases, indicating decreasing wood quality.

When wood is no longer fit for solid-wood or particle/fibre-based applications, it can be used for fuel or chemical production. At this stage, the size distribution of wooden elements is no longer significant. However, molecular size distribution plays an important role. Analogues to solid wood cascading, the molecular properties degrade from this point onwards. Wood constitutes (hemi-) cellulose and lignin. These are polymeric compounds with a functional value. However, the processing in the bio-refineries might degrade or disintegrate part of these valuable compounds into a mix of monomers. The bio-refineries strive to conserve the molecular properties and functionalities of these polymers. So, statistical entropy could be based on molecular weight distribution at this stage.

SEA thus enables identifying the highest material-value cascading pathway. The next step is optimising and improving the efficiency and reducing the environmental impact of that pathway. LCA is a well-established methodology to determine the resource input into the system and the associated environmental impact. However, most LCA studies rarely account for the cascade lifespan, while the aim of cascading is to extend the service life of the wood and consequently delay the emissions of carbon embedded in wood products. The time of carbon emissions affects the net GWP potential. *Hence, the research aimed to assess the carbon balance of cascading systems by accounting for the duration of carbon storage in cascading systems and validate whether cascade lifespan affects its GWP*.

The study hypothesises that an assessment using SEA and LCA adequately completes the evaluation of cascading. SEA measures the material circularity of wood cascading, i.e. quantifies material value over time, over multiple phases (multiple applications) and material flows (i.e. multiple material streams - products, by-products and residues) and identifies the optimal resource-use pathway that maximally preserves the material value over time. LCA accounts for the resources consumed and the environmental impact of the resource use and enables improving resource efficiency (by reducing the overall resources required) and reducing the environmental impact of the resource-use trajectory identified by SEA.

3.4. Research objectives

The PhD research objective was to *develop a methodological framework to assess the wood cascading* and close the existing gaps in the assessment of cascading and monitoring of CE for the wood value chain. The sub-objectives to achieve the overarching research objective were:

1. Determine the adaptation needed to SEA and LCA to apply it to measure resource-use effectiveness and efficiency of cascading systems.
2. Demonstrate the adaption using a wood cascading case study.
3. Validate the research hypothesis that SEA and LCA jointly form a comprehensive toolbox for measuring the circularity of wood cascading systems.
4. Demonstrate the complete assessment using SEA and LCA on a wood cascading case study.

Chapter 4: Statistical entropy analysis to assess material circularity of wood cascading

Based on: Navare, K., Parchomenko, A., Vrancken, K. C. & Van Acker, K. **Statistical entropy analysis to evaluate cascading use of wood.** *(In preparation for submission)*

Abstract

Circularity assessment of cascading systems needs to quantify the degree to which the cascading systems maintain material quality over time. Statistical entropy analysis (SEA), a method put forth to evaluate the material quality, could fill the gap in the assessment of cascading. The statistical entropy function measures the variance of a distribution pattern. In the evaluation of material systems, it has been used to measure substance distribution in material flows (i.e. resource-, products- or waste flows). The substance distribution is the number of substances present in these flows and their relative concentration. This composition complexity is a relevant proxy for the quality of material flows constituting substances. As more the number of substances present or the more sparse their occurrence, the more effort is required to retrieve and utilise those substances. However, the systems containing materials (such as wood) have characteristic physical (structural and dimensional) properties, such as size and volume. The quality and utility of such products or material flow depend on these physical characteristics of materials. This study aims to adapt the current SEA method to describe statistical entropy based on size, assuming mass as the proxy and demonstrate the adaptation with a case study - comparing different wood-based pallets (multiple-use pallets, single-use and cardboard pallets) and their cascaded use.

The results suggest that the multiple-use pallet is the most effective use. For single-use, the wood pallets are better than the cardboard pallets assuming that the wood pallets are cascaded to particleboard. It highlights that the choice of feedstocks and the downstream products need to be reconsidered to improve the resource use effectiveness of an entire value chain. This study proves that comparative RSE values accurately represent the difference in material quality and values and the RSE trend determines the most circular system – the one which displays the slowest loss of material quality. The study thereby proposes SEA as a tool for assessing the circularity of cascading systems.

4.1. Introduction

> *"Just as the constant increase of entropy is the basic law of the universe, so it is the basic law of life to be ever more highly structured and to struggle against entropy"*
>
> ***Vaclav Havel***

SEA is based on the Shannon entropy function from the field of information theory (Shannon, 1948), wherein it measures the loss or gain of information in a system, calculating the variance of a probability distribution. The higher the variance, the lower the available information of interest (Rechberger and Brunner, 2002). In material management, statistical entropy quantifies the substances distribution pattern (Rechberger and Brunner, 2002) and describes the compositional complexity of a material flow. The probability function from the original Shannon entropy function is translated to the substances concentration function. They are analogues as the substance concentration can be interpreted as the probability of the occurrence of a substance in a material flow and is considered a proxy for the material quality (Laner et al., 2017). The higher the substance concentration, the higher its availability and, thus, recoverability and recyclability. Theoretically, lesser effort or energy is needed to recover the substance from a purer stream than from a heterogeneous mixture. The statistical entropy value for a flow with a single and pure substance is zero, representing a state of lowest statistical entropy. The increase in the number of materials or substances in a mixture and the more uniform their distribution, the higher the statistical entropy value. Often, mixing substances is essential to improve functionality or durability or to fit a specific application, like in plastics and metal alloys, so increasing statistical entropy is inevitable in any production process. However, a system must seek to provide a function with minimal statistical entropy increase, and once the intended functionality has been attained, maintain it for as long as possible. SEA has been used to compare different material flows, considering the one that maximally avoids entropy generation – i.e. the system that maintains the achieved functionality and utility of substances/materials for longer with minimal efforts – as a more resource-effective and hence desirable system (cf. Parchomenko et al., 2021).

SEA has been applied on the micro-level to assess the ability of waste treatment (Kaufman et al., 2008a, 2008b; Rechberger and Brunner, 2002), production (Bai et al., 2015) or recycling processes (Velázquez-Martinez et al., 2020) to concentrate valuable substances to provide or recover functionality. On the macro-level, it has been used to evaluate the life cycle of copper in Europe (Rechberger and Graedel, 2002) and, later on, also for copper flows in China (Yue et al., 2009) and phosphorus use in Austria (Laner et al., 2017). However, SEA has, so far, been used to assess material flows (resource-, product- or waste flows) for which quality depends on the substance distribution – i.e. constituent substances and relative concentration. It has not been used to assess material flows containing materials themselves, such as wood, plastics, paper, and textile, with the quality of material flow dependent on the characteristic intrinsic physical and dimensional properties (size and volume) of constituent materials. Such material flows might also have quality dependent on their compositional complexity. For example, the quality of clothing depends on the fibre length of the textile, but also fibre diversity (i.e. mixing of different fibre types - such as cotton and polyester blend) and contamination (glues or coatings). These factors affect textile utility and recyclability (Duhoux et al., 2021; Rex et al., 2019). So, SEA for such material flows must be based on materials' compositional and dimensional properties. The latter is currently lacking and is needed for SEA to be suitable for assessing the wood cascading.

For wood (or a wood product), the potential utility and quality depend on purity and mixture with other materials (hybrid or composite materials) and dimensional properties (volume and size; Fraanje, 1997; Höglmeier et al., 2013; Ihnat et al., 2020). Material purity pertains to the presence of contaminants – the substances (such as paints and glues) in a wood product that, although essential for increasing lifetime and durability, inhibit the reusability of the material and reduce its cascading potential. The volume and size (individual wooden component or piece within a solid-wood product or fibre size for paper and pulp products) provide structural and mechanical properties, such as strength and natural durability (Fraanje, 1997; Höglmeier et al., 2015, 2013; Ihnat et al., 2020; Jarre et al., 2020). Size reduction disintegrates the original structural integrity and affects the functionality of the wood-based product (Ihnat et al., 2020). For example, timber has structural strength, making it suitable for construction elements. However, it cannot be used for the same application when shredded into wood chips (Fraanje, 1997). Cascading strategies strive not only to avoid contamination but, importantly, to retain the structural integrity and dimensional quality of solid wood in the different functional applications as long as possible to maximise the material value.

Current SEA evaluation – based on the substance distribution within products or materials flow – can describe wood quality in terms of purity or mixture with other materials by accounting for the contaminant concentrations or non-wood material in the different products. Material quality grades based on physical properties are, however, not reflected. That limits the applicability of SEA to materials, such as wood, for which physical characteristics are a vital factor influencing utility. The present study aims to define the statistical entropy function based on size distribution (assuming mass as the proxy) of wood components in a product and validate if SEA could potentially be a tool for assessing cascading use. The study aims to demonstrate the adapted SEA method with a simplified case of wood cascading. The case study chosen is different management strategies for wood-based pallet types (multiple-use pallets, single-use and cardboard pallets) and their cascaded use.

4.2. Material and method

4.2.1. Statistical Entropy Analysis

The SEA approach, based on the Shannon entropy function (Eq. 4.1), has originally been developed to evaluate the outcome of a Material Flow Analysis (MFA). MFA is a method that assesses flows and stocks of materials within a system (Brunner and Rechberger, 2004). Statistical entropy (*H;* Eq. 4.2) is at its minimum, with a value of zero, when the substance under consideration is concentrated in a single flow (output flow in Fig. 4.1a). The other extreme is when the substances are distributed evenly in different material flows with the same concentration in each flow (output flow in Fig. 4.1b). This material set represents the substance in the highest possible diluted form and has maximum entropy. Any other distribution produces an *H* value between these extremes.

$$H(X) = -\sum_{i=1}^{n} p(x_i) * \log_2 p(x_i)$$

Equation 4.1

Where entropy *H (X)* of a discrete random variable *X* with possible values $\{x_1, x_2 ..... x_n\}$ and probability mass function *P(X)*

$$H(c_{ij}, m_i) = -\sum_{i=1}^{k} m_i * c_{ij} * \log_2(c_{ij})$$

Equation 4.2

Where c_{ij} is the concentration of substance *j* in mass flow of good *i*

m_i is the normalised mass fraction of k material flows

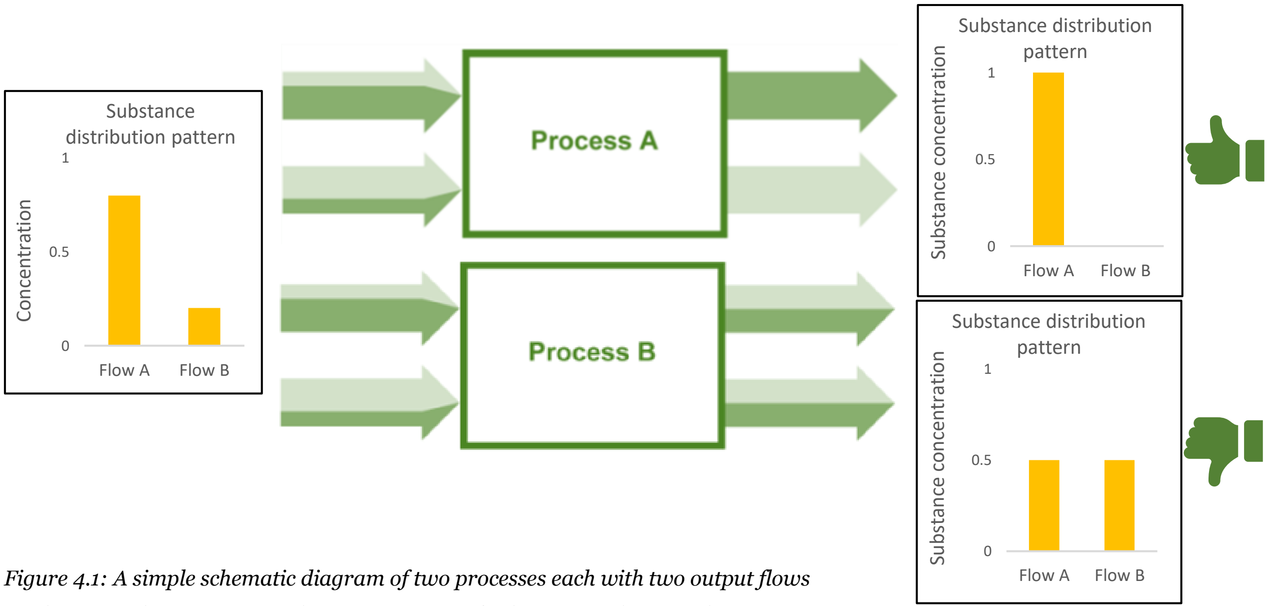


Figure 4.1: A simple schematic diagram of two processes each with two output flows
Dark green colour represents the concentration of substance under consideration.
(a) Process A produces an output flow with maximum (i.e. 100%) concentration of the substance under consideration, whereas (b) Process B produces an output flow with the substance under concentration distributed equally across the two flows (This diagram is based on the illustration used by Sobańtka et al., 2012)

The value of statistical entropy (*H*) is dependent on the number of flows (*k*) and the mass of the different substances present in those flows. Hence, to be able to compare material flows with a number of sub-flows, the statistical entropy value (*H*) of each individual sub-flow is normalised to relative statistical entropy (*RSE*) by dividing it by the maximum entropy value (H_{max}; Eq. 4.3).

$$RSE_i = \frac{H}{H_{max}}$$

Equation 4.3

$$H_{max} = log_2 \sum_{i=1}^{k} m_i$$

Equation 4.4

The resulting *RSE* is a dimensionless value between 0 and 1. Comparing the *RSE* of the process input and output flows denotes whether the process dilutes or concentrates a substance. The output flows' *RSE* greater than the input flows' indicates that the process dilutes the substance (e.g. Fig. 4.1b), and lower means that the process concentrates it (e.g. Fig. 4.1a). *RSE* is calculated at each stage (or after each process) along the value chain to analyse the evolution of statistical entropy value across the complete system.

4.2.2. Adaption of the SEA Method to wood cascading systems

As mentioned above, the dimensional properties (volume and size of the wood components in a product) and substance composition (purity or presence of contaminants) determine the utility of wood products (Fraanje, 1997; Jarre et al., 2020). So, the statistical entropy value needs to include both these aspects of material characteristics for SEA to be a tool to quantify wood quality and assess wood cascading.

Statistical entropy analysis evaluating material quality based on substance composition

The first aspect of the wood quality – purity or degree of contamination – can already be accounted for by the current statistical entropy definition. Originally, SEA was used to analyse the distribution of a single substance (for instance, considering only dark green in the schematic diagram – Fig. 4.1). Parchomenko et al. (2020) adapted the methodology to consider all substances present in a material flow system (i.e. taking into account both dark green and light green in the schematic diagram – Fig. 4.1). This way single substance assessment was extended to assess multiple substances and materials. Statistical entropy values can now be expressed for substance and material flows, components and products, which enables the evaluation of more complex product – component – material systems over time.

Statistical entropy (H_c) can be calculated over time for every material flow (or product stream) in a cascaded value chain based on its substance concentration (using Eq. 4.5). The substances under consideration are wood and contaminants. Contaminants in wood products are mainly of two types: physical (e.g. nails, staples) and chemical (e.g. glue, paints). In Equation 4.5, c_{ij} is the concentration of substance j in wood flow i. The statistical entropy value is normalised to *RSE* (Eq. 4.6) by dividing it by the maximum level of statistical entropy (H_{max}). The statistical entropy is highest when all the substances are present in an equal concentration in different flows and are, therefore, maximally diluted (Eq. 4.7). The *RSE* of individual flows (RSE_i) is aggregated into $RSE_{(c)total}$ for a stage using mass-weighted average (Eq. 4.8). The $RSE_{(c)total}$ is then calculated for each stage or overtime to determine the evolution of statistical entropy for the cascading system.

$$H_{c(i)} = -\sum_{j=1}^{n} c_{ij} * \log_2(c_{ij}) \qquad \text{Equation 4.5}$$

Where c_{ij} is the concentration of substance j in mass flow of each wood flow i

(n = 3, with j being wood, physical contaminant, chemical contaminant) for each wood flow i

$$RSE_{(c)i} = \frac{H_c}{H_{max}}$$ *Equation 4.6*

$$H_{max} = \log_2(N)$$ *Equation 4.7*

Where N is the number of substances in that material flow

$$RSE_{(c)total} = w_1 * RSE_{(c)1} + w_2 * RSE_{(c)2} + \cdots + w_i * RSE_{(c)i}$$ *Equation 4.8*

Where w_i is the relative weight of the wood stream i

Statistical entropy analysis evaluating material quality based on the dimensional properties

For SEA based on the variance in the dimensional properties of materials, statistical entropy is defined using the size distribution of wood elements. The element here refers to the individual wood components assembled into the final product – the wood planks in the case of a pallet, wood chips for particleboards, or cellulose fibre for paper. The wood components (planks, wood chips, fibres or particles) here are analogous to substances in the preceding analysis. The probability function in the Shannon entropy index (Eq. 4.1) is changed to the relative size (mass) of each wooded element, which can be interpreted as the probability of the occurrence of the wooden component in a material flow. A conceptual explanation: for a material flow containing only one plank of 10 kg, the probability of occurrence of the plank is 1 (Fig. 4.2a – relative mass is 1, narrow size distribution and minimum entropy). When the plank breaks down into 10 pieces of 1 kg, the probability of occurrence of each piece is 1/10 (Fig. 4.2b – relative mass is 1/10, the size distribution widens and entropy increases). Here, for simplicity, the mass of a wood element is assumed to be a proxy for its size. Other dimensional properties, such as volume or length, could also be considered.

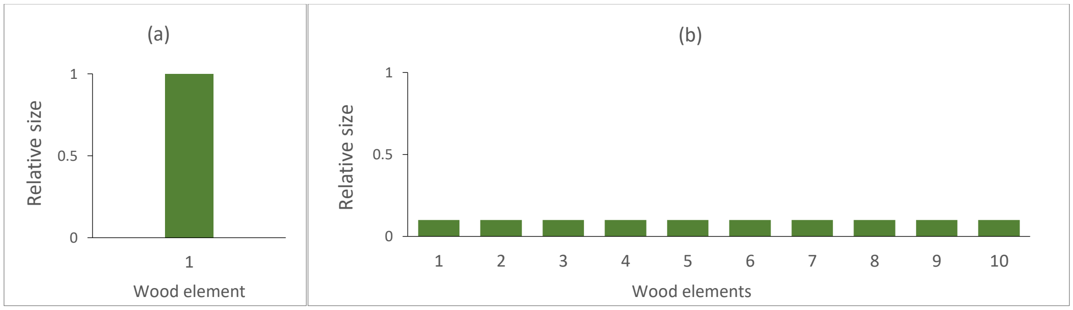


Figure 4.2: The size distribution pattern to support the conceptual explanation
Relative size distribution in the flow containing only a plank (a) and when plank is broken down (b)

Statistical entropy for the material flow is calculated based on the relative mass of its wood components (s_{ij}), which is the mass in proportion to the heaviest wooden piece in the system (Eq. 4.9). For example, in the case of wood pallets (i.e. the case under consideration in this analysis), the mass of individual wooden planks in pallets is 2 kg. The relative size of each wood component at this stage is 1. With the degradation of plank (for instance - when shredded to wood chips to make particleboard), the relative size of each wood component decreases. The smaller the size of an individual piece, the lower would be the value of s_{ij} (and higher statistical entropy, as conceptually explained earlier). Statistical entropy H_s is calculated (using Eq. 4.10) for each wood component (*j*) in each wood flow (*i*) based on the relative mass of that wood component (*j*), with k being the total number of wood components in that material flow. For example, assume waste wood entering the waste treatment facility includes pre-consumer waste (i.e. sawmill residues) and post-consumer waste (for instance, waste furniture). The wood flows (*i*) in Equation 4.10 are the two waste streams, i.e. sawmill residues and discarded furniture, and j is the each of the wood component in those flows. In the sawmill residue stream, wood components are wood chips, and in discarded furniture stream, wood components are each piece of furniture (each wood component that can be physically separated). The simplified assumption here is that all the pieces in a flow are the same size (i.e. all wood chips have the same mass). Hence, calculating the statistical entropy value for each individual wood component is not required as this assumption (Eq. 4.12) reduces Equation 4.10 to Equation 4.11, and the H value is calculated using the mass of one component.

Note that the statistical entropy value of a product (or flow) depends on the reference wood component. So the same product (or flow) can have different statistical entropy values in different systems, as the relative mass of the product (or flow) would be in proportion to the wood component mass in the respective reference product (or flow). The absolute value of H of a product (flow) is of lesser significance. The evolution of statistical entropy is relevant show case the change in the material value from the initial wood component to observe the time over which material value is preserved by the system (elaborated in the discussion section).

$$s_{ij} = \frac{mass\ of\ piece\ j}{\begin{array}{c} maximum\ mass \\ (for\ the\ specific\ case\ study) \end{array}} \qquad \text{Equation 4.9}$$

$$H_{s(i)} = -\sum_{j=1}^{k} s_{ij} * \log_2(s_{ij}) \qquad \text{Equation 4.10}$$

Where s_{ij} is relative mass of individual wood element j in flow i

k is the total number of pieces of a type of wooden element (i.e. the normalised fraction of wood flow i)

$$H_{s(i)} = -\log_2(s_{ij}) \qquad \text{Equation 4.11}$$

Where s_{ij} is relative mass of individual wood element j in flow i

$$\sum_{j=1}^{k} s_{ij} = 1 \qquad \text{Equation 4.12}$$

$$RSE_{(s)i} = \frac{H_{s(i)}}{H_{max}} \qquad \text{Equation 4.13}$$

$$RSE_{(s)total} = w_1 * RSE_{(s)1} + w_2 * RSE_{(s)2} + \cdots + w_i * RSE_{(s)i} \quad \text{Equation 4.14}$$

Where w_i is the relative weight of the wood stream i

The statistical entropy value (H_s) is normalised to RSE (Eq. 4.13) by dividing it by the maximum value of statistical entropy (H_{max}) possible for the specific system. RSE is 0 for the flow containing entirely of the heaviest wood elements in the system under study ($s_{ij} = 1$, $H_s = 0$) and 1 for the flow that consists entirely of wood components of the minimum size found in the case study ($H_s = H_{max}$). All the possible wood streams in that system will produce a RSE value between these extremes. The aggregated $RSE_{(s)total}$ for the stage is calculated based on the mass-weighted average (Eq. 4.14). Similar to $RSE_{(c)total}$, $RSE_{(s)total}$ is calculated over time to analyse the evolution of statistical entropy across the cascading system.

Aggregation to a single-score

The cascading principle emphasises prioritising the use of material for high-quality (or low entropy) functional application, maximising the lifetime per application, hence overall cascade lifespan, and minimising quality losses with every application (Fraanje, 1997). Thus, the statistical entropy evolution curve, used as a proxy for quality, should ideally be as low as possible for as long as possible. Hence, the area above this curve could be a means to reduce it to a single score and enable the comparison between entropy curves of different cascading systems. The higher the area above the curve, the more desirable the system could be. Hence, the RSE values across different stages of a wood cascade are aggregated into a single score by calculating the area above the RSE curve over the cascade lifespan, with the higher value indicating a more resource-effective cascading system.

4.2.3. Case study description

The case study compares the different wood-based pallet types operating in different management strategies. Pallets are used for carrying and delivering products and form a critical component of the complex global supply chain. There are around 10 billion pallets (KraftPal Technologies Ltd., 2020) and more than 600 million EPAL pallets in circulation globally (EPAL, 2018). Wood remains the most common pallet material accounting for at least 90% (Bhattacharjya and Kleine-Moellhoff, 2013; Carrano et al., 2015). The pallet industry represents a critical market for wood lumber and represents roughly 17% of the EU's sawn timber production (Buehlmann et al., 2009; Vis et al., 2016). Wood pallets are easily repairable, and their components are easily replaceable, which increases their service life. Wood from pallets can be recycled and used for many purposes at the end of their useful life (Tornese et al., 2019).

Pallets come in different forms and sizes and are designed for different management strategies: single-trip (single-use or lower-reuse intensity) or intended for several trips (Deviatkin et al., 2019). The multiple-use pallets (often managed in pooling or buy/sell systems) work in a closed-loop system and constitute around 55% of total solid-wood pallets. In the pooling strategy, pallets have a mark of the owner company (e.g., by using a specific colour) to track and distinguish these pallets from those of other companies. These pallets make multiple trips – collected after use by the pooling companies, inspected periodically, repaired if needed, and then reused until they are too faulty for the repair to be economically feasible (Deviatkin and Horttanainen, 2020). Solid-wood pallets, being more durable, are preferred as pooled or multiple-use pallets. However, one-way pallets (or lower-reuse intensity) are also popular and make up the remaining 45% of solid-wood pallets. They come in handy for customer-specific applications (Vis et al., 2014) or long-distance deliveries (Bengtsson and Logie, 2015). In overseas transactions, pallets typically cannot be used on their return trip, making it economically challenging to return the pallets. So, they are most likely disposed of or given a brief use before being discarded at the destination (Mazeika Bilbao, 2011). Corrugated cardboard pallets are a potential alternative to single-use solid-wood pallets. These pallets are less durable and suitable only for single-use but are easy for recycling and disposal (Bengtsson and Logie, 2015; KraftPal Technologies Ltd., 2020).

Multiple-use pallets reduce the total material requirement. However, designed to be more robust to withstand multiple journeys, these pallets require more material per trip, both wood and fasteners (such as nails and staples). Single-use pallets, on the contrary, have a simple and lighter structure. They require lower amounts of wood per trip and use fewer nails (Bengtsson and Logie, 2015; Carrano et al., 2014). With no need for identifying their owner, these pallets are unpainted and can thus be better recycled as they are not contaminated. Cardboard pallets – introduced as an 'eco' alternative for single-use solid-wood pallets – are often made from secondary resources (recovered wood or pulp), which saves primary resources. Cardboard pallets have higher recovery and recycling rates, but the cardboard fibre length decreases with every recycling step, and the cardboard pallets cannot be recycled anymore when the fibre length is too short (Schmidt et al., 2007). However, at that stage, cardboard can still be used to produce lower-grade applications such as newspapers or incinerated for energy production.

So, the question arises whether multiple-use pallets provide more optimal use of resources than the other alternatives. Also, for single-use (or lower intensity use), which of the two alternatives – wood or cardboard pallet – is optimal? SEA has been used here to compare the performance of the different pallets operating in different management strategies. The objective is to assess the effective use of wood in various pallet options and determine which cascading system maximises the material value.

The cascading systems for different types of pallets are built based on data available in the literature (Bengtsson and Logie, 2015; Deviatkin and Horttanainen, 2020; Gasol et al., 2008; KraftPal Technologies Ltd., 2020). Cascading systems considered are:

1. Multiple-use of solid wood pallet (system W_m)
2. Single-use (or lower-reuse intensity) solid wood pallets (system W_s)
3. Cardboard pallets made from virgin wood (system C_v)
4. Cardboard pallets made from recovered wood (system C_r)

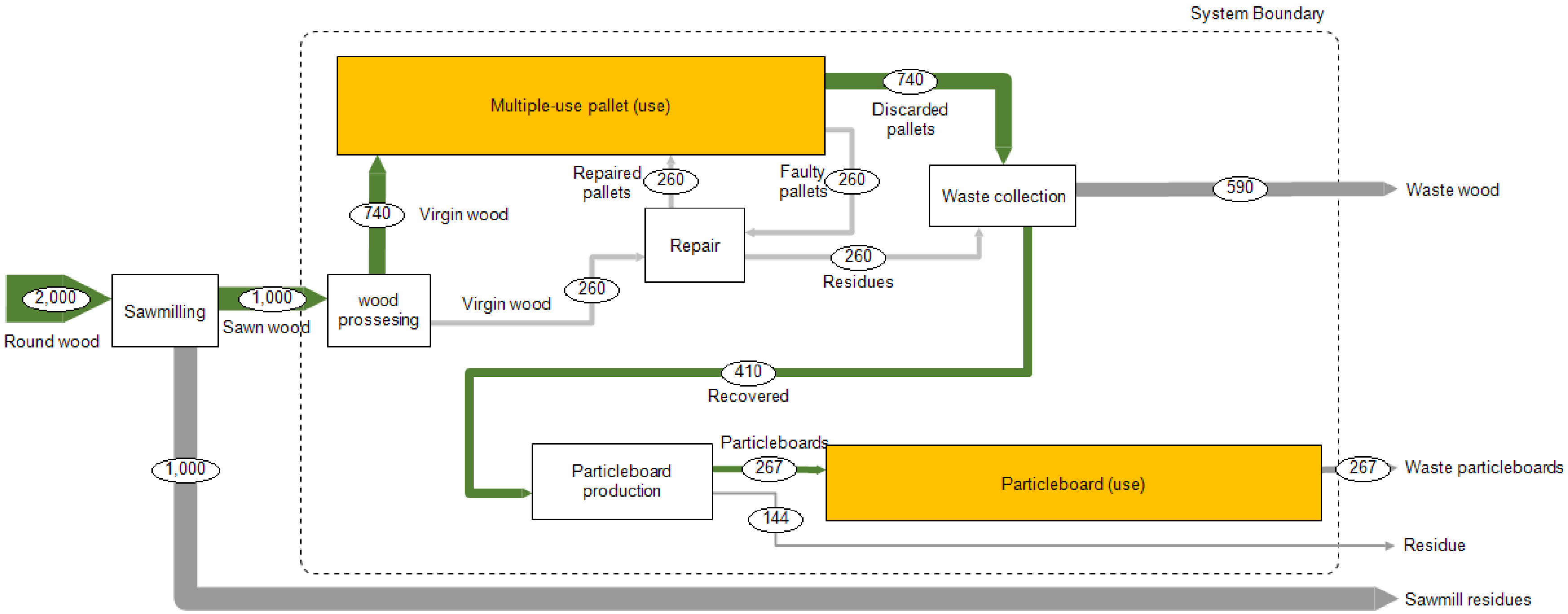
Material flows for the four systems (Fig. 4.4) are built with 1000 kg of wood as input – considered the functional unit for the comparison. The aim is to compare the total material value provided by different cascading systems using the available forest resource. The wood from the forest (roundwood) is processed into sawn wood for its use in solid-wood pallets. While, it is reduced to pulp to make cardboards. The efficiency of the sawmilling and the pulping process is approximately equal (50%), so the same amount of sawn wood and pulp is produced from the harvested wood. Thus, the reference flows are 1000kg sawn wood for solid-wood pallets and 1000 kg pulp for cardboard pallets. As the same amounts of residues are produced in both sawmilling and pulping processes, which are mainly burned for energy recuperation, this stream is excluded from the system boundary. Table 4.1 presents the key characteristics of the different pallet types (details and references are in Annexe C – Table C.1). The stock of products for each year (Table C.3) is determined based on the resource input to the system (i.e. 1000kg wood), the lifespan of pallets, and system parameters, such as recycling rate (Table C.2).

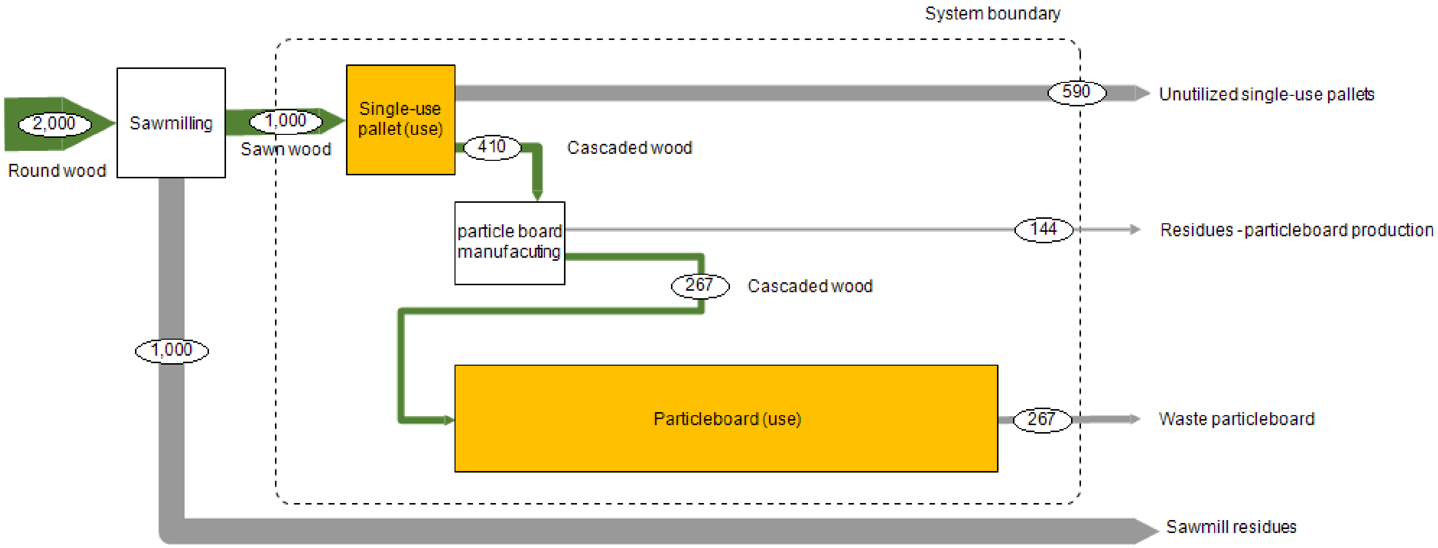
Figure 4.3: Images of the three types of pallets

From top (a) Multiple-use Euro Pallet (Pallet Centrale, 2022a) (b) Single-use light weight pallet (Rotomshop, 2022) (c) Cardboard pallet (Pallet Centrale, 2022c)

Table 4.1: Characteristics of different types of pallets

	W_m (Multiple-use pallets)	**W_s (Single-use pallets)**	**C_v (Cardboard pallets from virgin wood)**	**C_r (Cardboard pallet from recovered wood)**
Raw material used	Timber (99.75% by wt.) Nails (0.2% by wt.) Paint (0.05% by wt.)	Timber (98% by wt.) Nails (2% by wt.)	Pulp from virgin wood	Pulp from post-consumer solid-wood
End-of-life	41% - Recycled into particleboards 59% - Either not recovered or incinerated	41% - Recycled into particleboards 59% - Either not recovered or incinerated	85.5% Recycled 14.5% - Either not recovered or incinerated	85.5% Recycled 14.5% - Either not recovered or incinerated
Mass of individual pallet	25kg	15kg	4.5kg	4.5kg
Mass of individual wood element	1.44 kg (mass of each board)	0.864 kg (mass of each board)	$8 * 10^{-11}$ kg (fibre mass)	$4 * 10^{-11}$ kg (fibre mass)
Dimension	1200mm*800mm	1200mm*800mm	1200mm*800mm	1200mm*800mm
Payload capacity	1500 kg	400 kg	600 – 1500 kg	600 – 1500 kg
Avg. lifetime (years) of pallet	10	2	2	2
Avg. lifetime (years) of the second life of wood	Pallets are cascaded to particleboard, Avg. lifetime of particleboard = 10 yrs.	Pallets are cascaded to particleboard, Avg. lifetime of particleboard = 10 yrs.	Pallets are cascaded to lower-grade cardboard, Avg. lifetime of lower-grade cardboard = 2 yrs.	Pallets are cascaded to lower-grade cardboard, Avg. lifetime of lower-grade cardboard = 2 yrs.
Cascade lifespan	20 years	12 years	4 years	4 years


System Boundary
Multiple-use pallet (use)
740
Discarded pallets
Waste collection
590
Waste wood
Repaired pallets
260
Faulty pallets
260
Repair
260
Residues
740
Virgin wood
2,000
Round wood
Sawmilling
1,000
Sawn wood
wood prossesing
Virgin wood
260
410
Recovered
Particleboards
267
Particleboard production
Particleboard (use)
267
Waste particleboards
144
Residue
1,000
Sawmill residues


System boundary
2,000
Round wood
Sawmilling
1,000
Sawn wood
Single-use pallet (use)
590
Unutilized single-use pallets
410
Cascaded wood
particle board manufacuting
144
Residues - particleboard production
267
Cascaded wood
Particleboard (use)
267
Waste particleboard
1,000
Sawmill residues

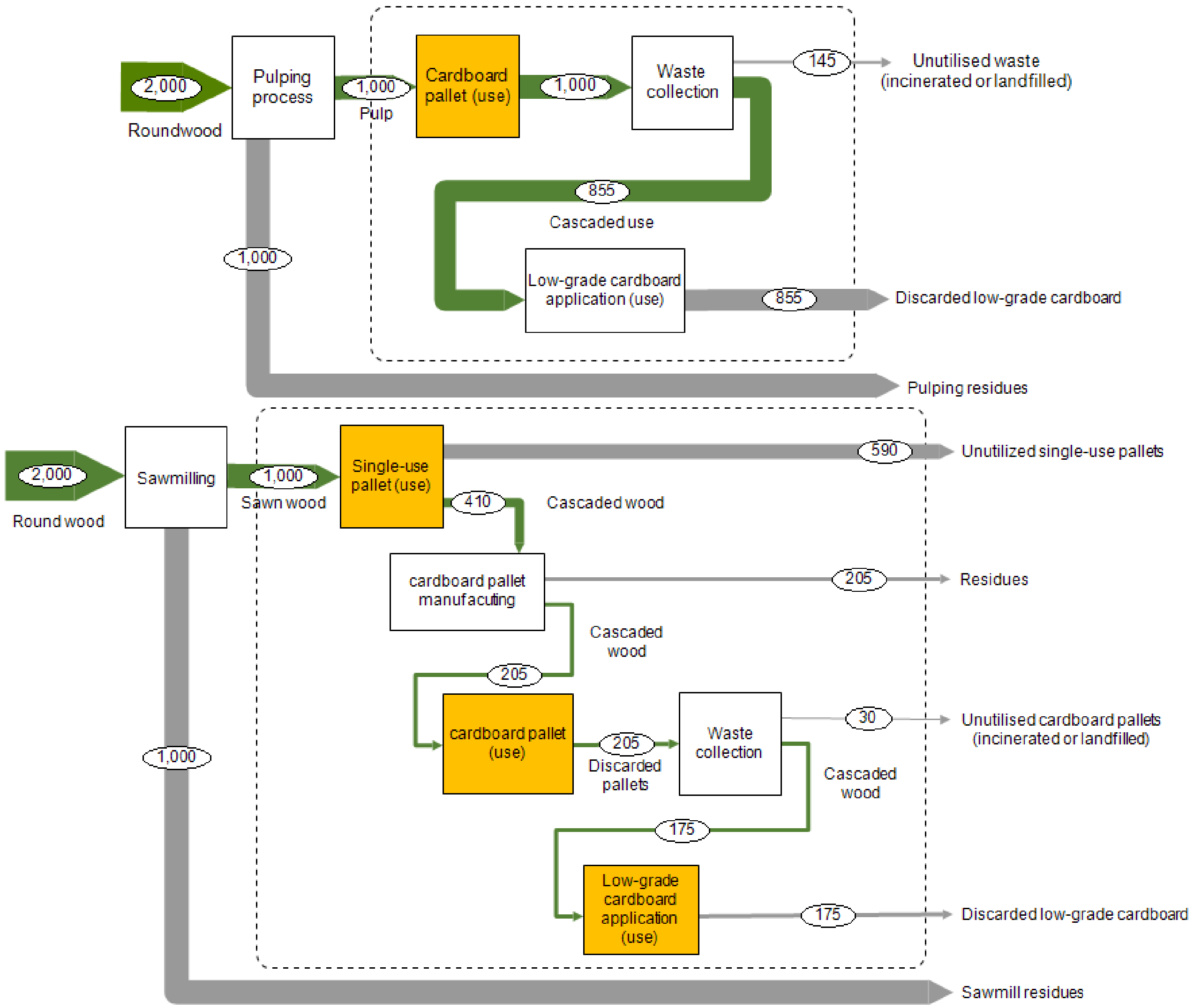


Figure 4.4: Material flow analysis for system using 1000 kg (extracted) wood in the four systems

From top (a) multiple-use pallet (b) single-use pallet (c) cardboard pallet from virgin wood (d) cardboard pallet from recovered wood. All flows are shown in Sankey , which means that the thickness of the arrows is proportional to the flow values. The flow values (shown as a number on the flow) indicate the amount of wood present in the product/flow (with unit kg). The length of the process box for use phase of products indicate the time in use of the product

For solid-wood pallets production, the sawn wood is reduced to planks of desirable dimensions, assembled into pallets using nails and staples, and delivered to the consumer for use. The average lifetime of multiple-use pallets is ten years (Deviatkin et al., 2019; Gasol et al., 2008). Of the total wood input (1000 kg) for multiple-use pallets, 25% is attributed to repair during the use phase (Gasol et al., 2008). The pallets, when discarded, are cascaded into particleboards (Vis et al., 2016, 2014). The disposal rate of these pallets is assumed to be distributed normally with the mean at the average product lifetime, and the standard deviation is one-third of the average lifetime, as done by Brunet-Navarro et al. (2018, 2016). Due to a complex supply chain, only 41% of wood pallets are recovered and recycled in Europe (EU27; Eurostat, 2017). Cascading 1000 kg of pallets produces 328 kg of particleboards (with 35% losses during particleboard production, which are incinerated for industrial heating). The remaining 59% are either not recovered (could be present in hibernating stock), landfilled or incinerated (Vis et al., 2016). The destination of this fraction is not known. The statistical entropy (RSE) for this material flow is assumed to be 1 (maximum) as it does not have any potential downstream material functionality.

The MFA of single-use pallets is similar. The single-use pallets (or lower reuse-intensity – in W_s) are typically reused a few times within their lifetime of approximately two years (Bengtsson and Logie, 2015; Gasol et al., 2008). As no repair is involved, the wood requirement is only for pallet production. The recovery and recycling rates and the application to which they are recycled are not separately known for single-use and multiple-use pallets. Hence, the recycling rate for these pallets is also assumed to be 41%, and the cascading application also is particleboard. The number of particleboards produced is thus the same in both cascading systems.

The cardboard pallets (in C_v) are made by compressing the pulp of harvested wood (KraftPal Technologies Ltd., 2020). Cardboard pallets often are used only once but have a higher recovery and recycling rate of 85.5% (Eurostat, 2017). Cardboard pallets are first recycled into new cardboard products and downcycled to lower-grade applications as fibres degrade. Cardboard is recycled 6-7 times before being incinerated (European Environment Agency, 2006). The data on the in-use time of cardboard pulp is not available. Cote et al. (2015) give a range of 2 to 8 years as the in-use lifespan for cardboard products. As a conservative approach, the assumption is that cardboard is used for two years for high-grade cardboard applications (i.e. pallets) and another two years on average for low-grade cardboard applications, e.g. packaging boxes, before being incinerated.

Currently, post-consumer wood is not used for cardboard production. However, this is assumed to be the case for the hypothetical scenario C_r to evaluate the benefit of using recovered instead of virgin wood for making cardboard pallets. The assumption is that the wood is used first for a high-value application before being recycled into cardboard pallets. The most prevalent higher-value applications are in the construction, furniture and packaging sectors. The first functional life for the virgin wood in this scenario is chosen to be a single-use pallet. The discarded single-use pallets are cascaded into cardboard pallets -

first in high-grade cardboard pallets, then in low-grade cardboard packaging applications, and ultimately incineration.

SEA is performed on the four systems to compare the extent to which each system preserves the material quality over time and over a series of functional applications. The stock of products for each year is determined, for each cascading system, based on the contextual information described above – i.e. resource input to the system (1000kg wood – sawn wood for solid-wood pallets and pulp for cardboard pallets), the lifespan of pallets and wood-based other products, and system parameters such as recycling rate. RSE was calculated per year based on the stock of products and the statistical entropy of each product. One can then observe statistical entropy evolution for different cascading systems and specify the pathway that maximally preserves the material quality over time, being this the core objective of materials management in a CE. The change in RSE over cascade lifespan is aggregated into a single score to ease the comparison between cascades.

4.3. Results and discussion

The results in Figure 4.5 show the evolution of the statistical entropy in the four cascading systems – Multiple-use solid-wood pallet (W_m), Single-use solid-wood pallet (W_s), cardboard pallet from virgin wood (C_v) and cardboard pallet from recovered wood (C_r). Figures 4.5 a & b show the statistical entropy over different life cycles of wood applications in cascading, assuming all the products reach the end of their service life altogether (i.e. at the end of the average lifetime). On the contrary, in figures 4.5 c & d, product disposal is spread over time. The product disposal rate is normally distributed (with the mean at the average lifetime). So, only a fraction of the products is discarded each year, which is why the graph shows a gradual change and extends beyond the average cascade life of 20 years. The result without normalised lifetime showcases (Fig. 4.5 a & b) the statistical entropy distinctly for different applications of wood cascading – with the different shades of the same line in the graph representing the different material applications within a cascade system.

The system boundary for the study includes the use phase over multiple service lives. For W_m and W_s, the initial use is solid wood pallets. The system boundary starts with wood used as solid-wood pallets and recycling of the discarded pallets recycled into particleboards. The system boundary for C_v includes the cardboard pallets made from virgin wood, and extends to recycling the discarded cardboard pallets, initially into new cardboard pallets, then in low-grade cardboard applications. The system boundary for the hypothetical scenario C_r starts with the wood used input being first for single-use pallets, cascaded into cardboard pallets - first in high-grade cardboard pallets and then in low-grade cardboard applications.

For RSE calculated based on the substance distribution (RSE_c; Fig. 4.5 a & c), the value at year 1 is zero only for cardboard pallets from virgin wood (in C_v) because the wood is in its most pure form (cellulosic pulp). It remains zero along the value chain as the cardboard pallets are recycled into new cardboard products, which are also pure cellulosic pulp. In all the other cascades, this value is higher than zero because of the contaminants in the pallets. Although multiple-use solid-wood pallets (W_m) use a higher amount of nails and paint per pallet compared to single-use solid-wood pallets (W_s), the RSE_c of the former is lower than the latter (at year 1) because the relative share of those contaminants per pallet is lower as the volume of wood used per pallet is higher.

In year 1, RSE_c is the same in the cascade W_s and C_r because wood is in the form of solid-wood pallets in both these cascades. But it varies with time. The RSE_c increases in W_s while decreases in C_r. The nails and staples are separated from the pallets during the waste treatment process, and then the pallets are shredded. In scenario C_r, the wood chips are used for cardboard production without needing any additive. In W_s, however, the woodchips are blended with additives for particleboard production, increasing the statistical entropy through the additional input of materials. The multiple-use wood pallet cascade (W_m) shows a more gradual increase - due to the long lifetime of the product, a smaller amount of pallets are discarded every year. The RSE_c increases because of repair activities during the use phase and is followed by recycling the pallets into higher statistical-entropy particleboards. The high statistical entropy results from the high share of contaminants in the product.

The RSE evolution due to the change in the dimensions of wood components (RSE_s developed with mass as a proxy for size) exhibits a differing trend (Fig. 4.5 b & d). The RSE_s value starts with zero for cascade W_m - the wood is in the form of planks which is the maximum possible size in the system under consideration. RSE_s for W_s and C_r are above zero despite the wood being planks because the planks are smaller in single-use pallets as they require comparatively lower durability and strength. RSE_s is highest for C_v since wood is reduced to cellulose fibres for cardboard production. Cardboard pallets are recycled into new cardboard products. The fibre length decreases in the recycling process. Hence, RSE_s increases with time and cascading use. It is maximum (close to 1) when the fibres are too degraded to be recycled. In the case of cascade C_r, wood is initially used as solid-wood pallets and then cascaded into cardboard pallets. The statistical entropy is lower for C_r than C_v because of the discarded wood pallets that remain unutilised.

RSEs for C_r and W_s are equal at year one but evolve differently with time as wood pallets is cascaded into different products in the two systems. Wood pallets are cascaded to particleboard in the former and to cardboard in the latter. Particleboards are made from woodchips and have lower statistical entropy than cardboard pallets, which are made of fibres of a much smaller size. So, RSE increases to a lower extent in W_s than Cr. The multiple-use wood pallet cascade (W_m) shows a consistent and gradual increase in RSE also in the analysis based on size. The statistical entropy increases with time because pallets are discarded in the waste stream and are mechanically reduced to woodchips for particleboard production (Saravia-Cortez et al., 2013).

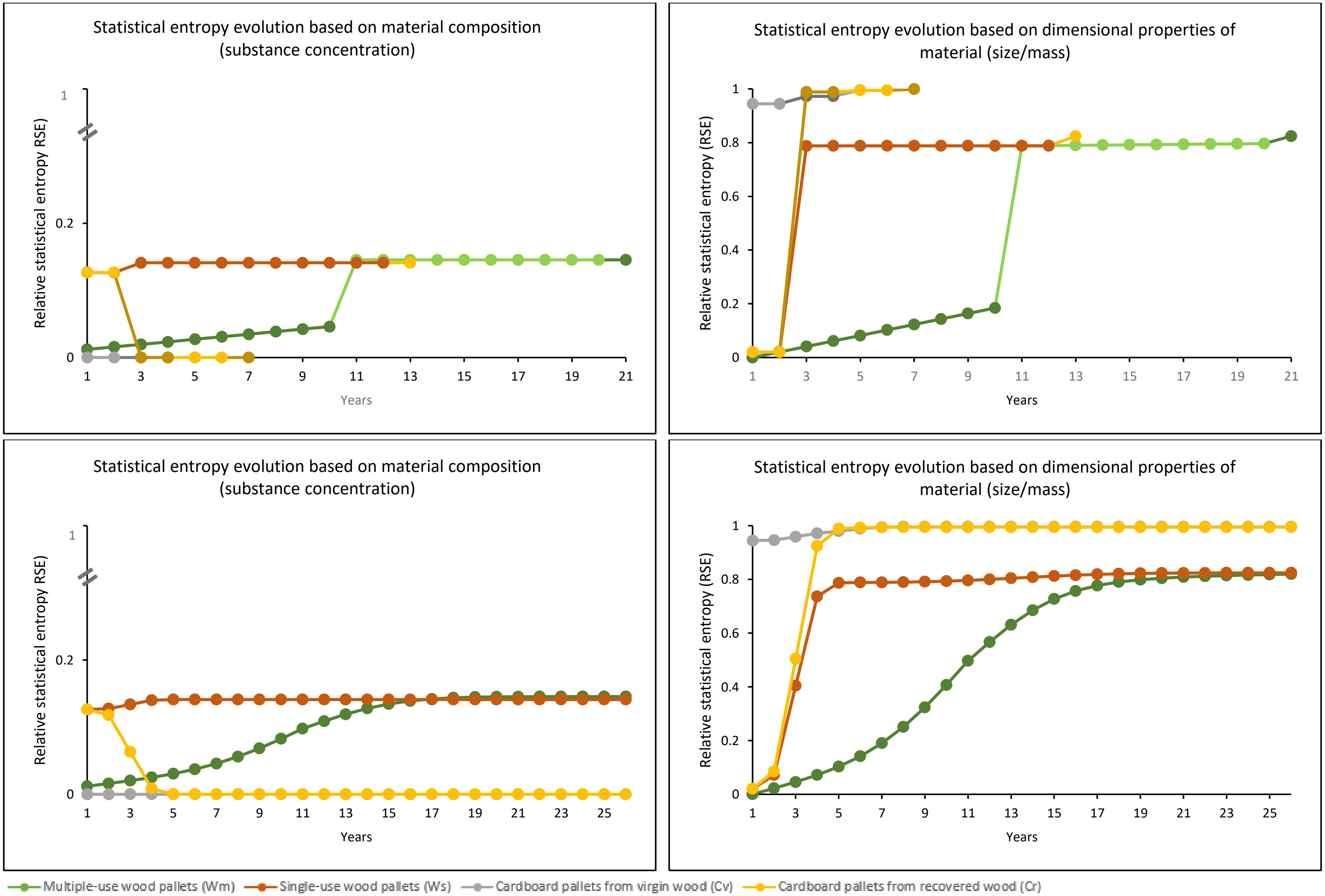


Figure 4.5: Evolution of relative statistical entropy for the four scenarios

Top left (a) Statistical entropy calculation based on substance composition. Right(b) Statistical entropy calculation based on material dimensional property (mass). The different shades in the same line indicate different material application of the cascade. Bottom left (c) and right (d) are assuming normalised distribution of end-of-life of the products

Comparing the RSE value of two cascade systems at a point indicates the difference in material quality between the two systems - with quality based on the size (of wooden components) and purity (or constituent substance distribution). Lower statistical entropy in terms of size indicates higher material value as it suggests wood use in higher value applications (applications that utilise its structural and physical properties) and that wood can still be reused in a larger number of applications. Similarly, lower statistical entropy in terms of purity indicates higher cascading potential. RSE trend (i.e. change in RSE over time) can be a measurement of cascading, i.e. the extent of preservation of product functionality (or material quality) over time. So, the flatter the RSE curve, i.e. lower the statistical entropy for a longer duration, the greater the degree to which that cascading system maintains material value over time. Hence, the RSE trend with the highest area above the curve represents the most circular cascading system.

The single score (Table 4.2), based on the area above the RSE evolution curve (considering Fig. 4.5 a & b), indicates that the material value derived from the available resource is maximum in the multiple-use pallets scenario. That is the optimal use of wood and should be promoted. The material value can be increased in this scenario by extending further their lifetime. The results also suggest that using virgin wood for making cardboard pallets, although assumed to be 'eco-pallets', should be avoided. Wood is degraded by shredding, limiting the possibility of harvesting its maximum potential value.

Table 4.2: Single score for SEA for different pallet types and management strategies
The green indicating the best-case scenario with the highest value and red indicating worst-case scenario with the lowest value for the area above the curve

	Statistical Entropy based on	
Systems	**Material composition (contamination)**	**Dimensional properties (size/mass)**
Wood multiple-use pallet (W_m)	**18.19**	**10.74**
Wood single-use pallet (W_s)	10.33	3.68
Cardboard pallet from virgin wood (C_v)	**4**	**0.16**
Cardboard pallet from recovered wood (C_r)	5.81	1.50

Returning to the initial research question: are the multiple-use pallets more resource-effective than the alternatives? Which of the two - wood or cardboard pallets - are preferable for single-use (or lower-intensity use)? The multiple-use pallets are evidently the most resource-effective packaging solution. For single-use, the wood pallets are better than the cardboard pallets assuming that the wood pallets are cascaded to particleboard. Comparing the two cardboard pallets cascades, C_v and C_r, cardboard pallets from recovered wood must be preferred as lower grade wood is used instead of virgin wood for cardboard pallet production.

It is not only the product itself but also the prior use of that wood and the choice of the products to which it is subsequently cascaded that determines the overall effectiveness of the system in using resources. Recycling solid-wood pallets into cardboard pallets result in a higher increase of entropy than recycling into particleboard. Hence, the discarded solid-wood pallets must be preferably used for making particleboard (or other lower entropy products) instead of cardboard. Cardboard pallets could be made from a more degraded quality of waste wood that has already served a long service life, and then the cardboard pallets could offer an optimal second life option for single-use pallets if produced from lower-quality waste wood. This way, cardboard pallets could effectively satisfy the part of the market demand for single-use pallets, thereby sparing the virgin wood for higher-value applications instead of the solid-wood pallet. Another hotspot for entropy increase is the recycling process itself, wherein the solid wood pallets are shredded to process the wood into particleboard or cardboard products. Reusing the planks from the pallets instead of shredding them and losing their structural properties offers a way to avoid the RSE increase in the first place.

The absolute values of RSE are influenced by the assumptions made in the case study, among others as a consequence of the lack of data. The increasing popularity of this methodology will drive the need for gathering relevant data. But more than the absolute values, the RSE evolution provides crucial insights – both at a product (or stage) and system (value chain) level. The assessment of product quality – considering the size of the wooden component, material composition (contaminant concentration), and lifetime – provides guidelines for improving product design for more resource-effective recycling. In this case study, the results suggest that solid-wood pallets and particleboard could be designed to provide functionality with lesser contaminants to increase recyclability. At a systems level, the results highlight the hotspots of quality (and value) loss. Secondly, the methodology shows the extent to which the system harmonises material quality with what the task demands. Sirkin and Houten (1994) stated this as one of the principles of cascading resources utilisation, the principle of appropriate fit, which means that the quality of the utilised resource matches the quality demand of the task to be performed. High-quality material should not be used for an application that could be provided with lower-grade material. For example, in the presented case study, cardboard pallets should be preferred over solid-wood pallets if they both provide the same function, and they could be made from low-grade waste wood instead of virgin wood.

Note that the functionality provided by each of the four cascades differs. Multiple-use pallets last longer and carry more load than single-use pallets. Multiple-use pallets thus deliver more service per unit than single-use pallets. Cardboard pallets and single-use pallets are functionally equivalent, but cardboard pallets are much lighter than single-use pallets and so require less wood for the same function. The functional value of the different pallet types is not equated in this analysis because the focus was on evaluating the change in material quality over time in different cascading pathways with 1000 kg of wood as input. So, the functional unit (and the factor constant across the different cascades) is simply 1000 kg of wood input. This way, the analysis identified the cascade that maximally retains the material quality over time from a fixed input, in line with the cascading and CE economy objective to maintain functionality and maximise the material value from the available resource. An alternative analysis is described in Chapter 7, which evaluates entropy change when all the cascades deliver the same functionalities with the same input. The system then considers that multiple-use or cardboard pallets require less wood than single-use pallets to provide the same service. The multiple-use and cardboard pallet cascade will thus have surplus wood.

The study includes this within the system boundary, assuming that such excess wood remains unutilised and could be available for other applications or left behind in the forest for other ecosystem services.

4.4. Economic valuation

As already discussed earlier, the objective of cascading is to maximise the material value, which is to maximise the utility or functionality obtained from the material. Material's inherent quality (i.e. physical and chemical properties) provides the required functionality. So, preserving the material quality over time maximises the extracted material value. The study analysed whether the market value (instead of material quality) can be an indicator of material value and whether maximising the economic value would automatically translate to a maximum material value per unit of time over a certain period. It is noted that market prices have their disadvantages as they fluctuate and are affected by internal and external market dynamics.

Table 4.3: Market values (from the year 2022) and functional value (i.e. material value or utility) of an individual pallet of each type

Product	Market value	Functional value
Multiple-use pallets	26 €/pallet	5400 t*km
Single-use pallets	13 €/pallet	300 t*km
Cardboard pallets	12 €/pallet	180 t*km

Firstly, the analysis compared the market value (price from the year 2022) and material value (i.e. functional value or utility) of different types of pallets (Table 4.3).

- **Multiple-use pallets** have a load-bearing capacity of 1500 kg. Each pallet is used on average 24 trips (Deviatkin and Horttanainen, 2020; Gasol et al., 2008; Kočí, 2019; Mazeika Bilbao, 2011; Vis et al., 2014). So, the functional value of an individual pallet is 5400 t * km (assuming the transport distance in each trip is 150 km). The price of a pallet on the market is 26€ (Pallet Centrale, 2022a; Pallet Plaza, 2019).
- **Single-use pallets** have a load-bearing capacity of 400 kg and are used on average five times (Bengtsson and Logie, 2015; Gasol et al., 2008; Vis et al., 2014). Hence, the functional value of a single pallet is 300 t * km (with a travel distance of 150 km) and has a price of 13€ (Pallet Centrale, 2022b). The functional value of single-use pallets is lower than that of multiple-use pallets. The single-use pallet's price is also lower than that of the multiple-use pallet, but not to the same extent.
- **Cardboard pallets** can transport up to 1200 kg load and are used only once. So, the functional value of an individual pallet is 180 t * km assuming these pallets are used for the same travel distance and the market value is 12€ (Pallet Centrale, 2022c).

Single-use and cardboard pallets have a lower functional value than multiple-use pallets. Their market price is also lower provides. Amongst the cardboard and single-use pallets, both have almost the same functional value and price. In this case, market price accurately represents material value. However, not the material quality. The market price depends on the demand and supply of a service and so correctly indicates the material value (which is the function provided). But, material quality (most relevant for cascading assessment) is not only the utility of the current product but also the number and type of options left open at the end of life for cascaded use, and with that in mind, solid wood pallets have a higher material quality than cardboard pallets. Statistical entropy value, assessing the material composition and physical properties, is lower for multiple-use pallets than for single-use pallets, which is lower than that of cardboard pallets. The cascading potential of wood is also in that order. Hence, the statistical entropy value (as a proxy for the material quality) might be a better reference for material quality than market price. That is verified by extending this analysis from individual products to the entire value chain.

Table 4.4 shows the total market and functional value produced in four cascades each with 1000kg wood input. These values are calculated based on the amount of each product produced in these cascades (Fig. 4.3), and their market and functional value. It is, however, challenging to compare the functional value of two products providing different types of functions. The cascades W_m and W_s on the one hand, and C_v and C_r on the other hand, have comparable functional values. When comparing W_m and W_s, it is observed that W_s offers a lower functional value but has a higher market price. Between C_v and C_r, C_v produces a higher functional value but has a significantly higher market value.

Table 4.4: Market value and functional value of each scenario

Cascading scenario	Product	Amount	Market value	Weight of each pallet	Total market value	Total functional value
Scenario W_m	Multiple-use pallets	740 kg	26 €/pallet	25 kg	770 €	160 * 10^3 t*km
	Particleboards	267 kg	0.5 €/kg		133 €	267 kg particleboards
	Total				**873 €**	**160 * 10^3 t*km & 267 kg particleboards**
Scenario W_s	Single-use pallets	1000 kg	13 €/pallet	15 kg	866 €	20 * 10^3 t*km
	Particleboards	267 kg	0.5 €/kg		133 €	267 kg particleboards
	Total				**999 €**	**20 * 10^3 t*km & 267 kg particleboards**
Scenario C_V	Cardboard pallets	1000 kg	12 €/pallet	4.5 kg	2666 €	40 * 10^3 t*km
	Cardboard boxes	855 kg	7.3 €/kg		6256 €	
	Total				**8922 €**	**40 * 10^3 t*km & 855 kg boxes**
Scenario C_r	Single-use pallets	1000 kg	10 €/pallet	15 kg	666 €	20 * 10^3 t*km
	Cardboard pallets	205 kg	12 €/pallet	4.5 kg	546 €	8.2 * 10^3 t*km
	Cardboard boxes	176 kg	7.3 €/kg		1287 €	
	Total				**2499 €**	**28.2 * 10^3 t*km & 176 kg boxes**

The market value is highest in scenario C_v. However, this is also the scenario with the shortest cascade lifespan and the fastest change of statistical entropy, indicating a rapid loss of material quality. Whereas, the multiple-use pallet scenario has the longest lifespan and the slowest change of statistical entropy. However, the market value is low. It is evident from these results that total market value does not necessarily reflect the total material value and, at the same time, is unrelated to the cascade lifespan and to the ability of the cascade to preserve quality, as intended in a CE. So, the market value might not be suitable to evaluate the material quality aspect when assessing cascading.

4.5. Benefits and limitations

SEA based on physical or dimensional properties (considering the size of wooden components) gives meaningful results. It broadens the applicability of SEA by allowing accounting for characteristics other than compositional complexity. The current study considered mass as a proxy for the size of wooden components. However, statistical entropy can define other dimensional characteristics, such as volume or length. The analysis must consider the one that dictates the quality and limits the utility of the material under consideration. For example, fibre length is one of the key factors influencing the quality of cotton textile, wool or plastics.

Wood cascading aims at keeping the material quality as high as possible for as long as possible. Material quality here refers to the intrinsic (i.e. physical and chemical) material properties that provide the required functionality and utility. The study considered that the two major factors that influence the quality of (virgin and waste) wood are dimensional properties (size and volume) and purity (presence of non-wood substances). The dimensions refer to the size of the individual wood components assembled into the final product – the wood planks in the case of a pallet, wood chips for particleboards, or cellulose fibre for paper – which affect the utility. SEA adaptations in this study assess these two dimensions of wood quality. However, besides these, several other physical properties influence the wood quality and utility, such as wood type (softwood or hardwood), species, density, granularity, irregularities (or defects) or moisture content (Marques et al., 2020). In addition, the chemical properties and ash content also have an influence. Evidently, the current SEA only partially assesses the wood quality and further work on SEA is needed to include other aspects.

Nevertheless, the current assessment is still sufficient to analyse wood cascading. The goal is not to evaluate the absolute wood quality but to observe the change in quality over time (over multiple uses) because the aim is to find the optimal utilisation pathway for the available resource. In SEA, virgin roundwood has minimum entropy (RSE = 0). The change in statistical entropy is calculated with reference to this virgin wood to see the quality degradation of this wood. The only physical property of wood that changes with use is dimension and purity (or contamination). The other characteristics (wood type, species and density) do not and evaluating these might not be essential for assessing cascading. Note that moisture content is another property that varies with time and use. However, moisture content most often decreases with time and use (except in humid locations) and is desirable for most wood products as it reduces the energy needed to dry wood for those purposes. Still, this aspect of wood quality and the need to evaluate it in cascading assessment context need further investigation.

Another benefit of SEA is that it provides both micro and macro-level information. Micro-level details are available when observing the entropy change at each cascading stage. It shows the quality loss during wood use or processing – highlighting the processes or product designs that drive quality loss, which are hotspots for improvements. Macro-level details can be gathered from the single score derived from the area above the entropy evolution curve. This score integrates the various dimensions of resource use – material quality conservation & lifetime extension and supports making decisions by identifying the highest value material-use pathway. It might also guide in tackling trade-offs between the two – lifetime extension and value preservation. This macro-level information also provides an insight into the factors contributing to quality loss giving an overview of the unused material potential. For instance, if a high material-quality material is used for a low-quality application. These insights would stimulate a quest for innovative applications that could benefit from this unutilised material potential. Cascading could thus enable value creation, going beyond merely the cascading objective of value retention. That supports the bioeconomy in its pursuits for newer bio-based applications to substitute the current demand for fossil- or inorganic resources. SEA, therefore, is not only an analysis tool but also a design tool – designing better wood cascaded by assigning feedstock for appropriate downstream application with minimum quality loss. SEA has been presented in this study using simplified case studies. But can be applied to more complex material flows. Analysing wood flow at a national or regional level could assist optimise wood use and stir innovation for technologies and applications. The proposed method could thus help develop and monitor policies.

The macro-level assessment using SEA can be a tool to compare the wood use of different countries. Currently, Sankey diagrams are the best way to compare wood flows across countries. However, they only illustrate the quantity of (virgin and waste) wood flows in a region and misses the quality aspect. It fails to inform how effective is the cascaded use. SEA could fill that gap. Additionally, SEA evaluates quality change with respect to the harvested roundwood. So, when the harvested wood in different countries varies in quality, it is worthwhile to study wood quality change, instead of wood flows as in Sankey diagrams, to compare the effective wood use in different countries.

It is valuable to identify the current limitation of these methods, which will lay the ground for further research on this topic. SEA based on physical or dimensional properties (size and volume) can only analyse the value chain of a particular material as these properties are material-specific. It cannot compare systems containing different materials. For instance, current SEA can compare wood cascading systems, but cannot be used to compare the wood value chain to the value chain of another material. Similarly, it can compare two types of wood products providing the same service but not two products from different materials. For example, wood pallets cannot be compared to plastic pallets. Although, it might be possible to compare cardboard to plastic pallets as both are fibre based. Cardboard and plastic fibres have different material properties. However, when comparing cardboard to plastic pallets, the fibre length in each product is normalised to the maximum and minimum fibre size possible in that category, and by doing so, analyse the quality loss during cascaded use of that material.

Another limitation of SEA is that, while evaluating quality based on substance composition, it does not consider the type of bonds (physical vs chemical impurities) or the degree of mixing (impregnation vs coating) between wood and non-wood substances. Impregnation is treating wood with chemicals that diffuse in the cavities of the cell wall. Coating is an external application (such as paint) on wood. In addition, the toxicity of those impurities might differ. These factors are not reflected in SEA but affect wood's cascading potential. As the statistical entropy value is calculated based on the mass of contaminants in wood, it will be the same irrespective of whether it is a physical impurity (nail), chemical non-toxic impurity (paint) or toxic impurity (creosote), and irrespective if they coated or impregnated. Including these factors in SEA is essential for SEA to be a methodology that accurately assesses cascading.

4.6. Conclusion

This work presents an initial approach to adapting SEA to account for material quality besides material composition, i.e. the concentration of substances in material flow. The adapted method, describing material quality based on dimensional properties – volume and size – is demonstrated using a wood cascading case study. In the case of wood-based pallets, the results highlight that the entropy evolution varies significantly for different types and different management strategies of pallets. Multiple-use pallets are the most effective resource use pathway. Other than identifying the optimal resource use pathway, the results stress the need to consider the entire system – previous lives and the choice of the products to which wood is subsequently cascaded – as it tells the extent to which the quality of waste wood supply aligns with that demanded. The system could expand cascaded applications for high-quality wood (in this case, discarded solid-wood pallets) and use lower-quality wood for applications that do not necessarily require high-quality wood (in this case, cardboard pallets) to improve overall effectiveness in resource use.

SEA integrates the different dimensions of cascading use – quality degradation, lifetime extension, multiple life cycles & multiple material streams – into a single metric. The positive effect of extending the lifetime and conserving the material quality over several product life cycles is reflected meaningfully in the SEA results. Hence, SEA could be a powerful tool for assessing cascading. The study demonstrates SEA using simplified case studies in this study. However, it could support analysing more complex scenarios, such as analysing the complicated structure of material flow in a country or region, involving several potential feedstocks and varied applications for each stream, and requiring matching the demand with available supply. It could stir technological innovation, expand applications, utilise the unused resource potential and optimise the current wood use.

Chapter 5: Statistical entropy analysis to assess material circularity of bio-refinery

Abstract

Bio-refineries strive to increase biomass resource efficiency, i.e. increasing output chemicals from the available biomass inputs. That also reduces the residues or wastes generated in the process. Secondly, reducing (or separating) the impurities in the output chemicals as much as possible. That enables the use of these chemicals for high-value applications that usually require high purity. The resource use is optimised also by reducing complexity and heterogeneity in the output chemicals, i.e. a lower number of distinct molecular properties (and thus chemical properties). Mixtures containing fewer compounds are easier to purify than a more heterogeneous mixture. Lastly, distinct molecular properties ease the separation process. Additionally, this paper emphasises that, following the circularity and cascading principle, the bio-refinery ought to valorise the native molecular properties of the building blocks (oligomers) and reduce additional steps of separations and depolymerisation.

Existing tools, like LCA and TEA, assess the environmental impact and economic feasibility of bio-refineries. No assessment methodology evaluates bio-refineries based on the inherent material (or chemical) properties – purity, heterogeneity and molecular structure – of the chemicals produced by the bio-refinery. In the previous chapter, SEA has already been used to assess the material quality of products in wood cascading based on the compositional- and physical complexity. This chapter investigates if SEA could assess the compositional complexity and the molecular properties of the output mixture. This study demonstrates this by evaluating two biorefineries, the conventional kraft pulping process and *lignin-first* reductive catalytic fractionation (RCF) technology. SEA results show that RCF is more effective as the output chemical mixture is purer and less heterogenous, increasing the valorisation potential. The study also evaluates the different RCF bio-refinery configurations producing different output chemicals and identified the one that maintains the molecular properties to the greatest extent, proving that SEA could be a tool to assess the material circularity of RCF. With that, cascading assessment framework could evaluate cascading strategies, not only when the wood is in a solid-wood state but even at a molecular level.

5.1. Introduction

"It is much easier to put existing resources to better use, than to develop resources where they do not exist"

George Soros

Overdependency on fossil resources and their environmental impact has driven the need to explore sustainable alternatives for energy, fuels and chemicals. Wood can be a feedstock to produce these products – it is a (potentially) CO_2-neutral and renewable option for the current petrochemical routes. Woody biomass is mainly composed of cellulose, hemicellulose and lignin. The traditional biorefineries primarily focus on the carbohydrate fraction, e.g. paper and pulp or bio-ethanol production. Lignin fraction has a strong tendency towards irreversible degradation and is thus harder to valorise. Various organic and inorganic impurities and a non-uniform structure make it more challenging to valorise lignin. So, most of the lignin currently recovered as a by-product in conventional wood fractionation processes (most commonly kraft process) is degraded and thus incinerated for energy recuperation (Van den Bosch et al., 2018).

However, lignin is an aromatic polymer consisting of interlinked phenolic units making it a promising feedstock to replace current fossil aromatic chemicals. Recent efforts in biorefinery research focus on *lignin-first* approaches in contrast to carbohydrate-centred biorefineries. In the *lignin-first* refineries, wood is fractionated into lignin oil (ready to upgrade to high-value chemicals) while retaining the pulp as a solid fraction for further processing. Lignin oil, produced through this process, has a higher degree of purity (lesser contaminants). The complex lignin structure is broken into low-molecular-weight monomers and dimer and high-molecular-weight oligomer compounds. Monomers are already functionalised chemicals. They can be easily separated from the lignin oil mixture and used in high-value applications, which demand a higher degree of purity. Moreover, there are only a few monomeric components (high selectivity) whose chemical structure is well known and is not very complex. They can be functionalised and defunctionalised depending on the intended application. But dimers and oligomers consist of a relatively large variety of types of molecules and have a more complex chemical structure. Like monomers, they can be functionalised and defunctionalised depending on the envisioned application. But likely do not achieve the same level of purification, limiting their potential application.

The objective of any biorefinery is the optimal valorisation of these building blocks to be economically and environmentally beneficial. Bio-refineries produce a mixture of output chemicals. Increasing biomass conversion efficiency – i.e. increasing the amount of biomass converted into valuable products – is the primary step for biorefineries to become economically competitive. The next step is reducing the contamination and enhancing the purity of the output chemicals to enable their use for high-value applications. Furthermore, reducing the complexity and heterogeneity of the output chemicals to ease their separation into purer streams. Mixtures containing fewer compounds are easier for purification than ones with several chemicals with varying molecular properties. Secondly, compounds having distinct physicochemical and thermodynamic properties are easier to separate. Complex mixtures containing many components may not be separable or require considerably higher energy input for separation (Arts et al., 2021).

Van Aelst et al. (2020) describe the output of different bio-refinery configurations. Figure 5.1 shows on the x-axis the molecular weight of constituent chemical components and on the y-axis the quantity of that chemical. The bio-refinery produces a heterogeneous mixture of refined lignin oil, which is separated further into pure (monomeric, dimeric, etc.) components using solvent extraction with varying compositions of the extracting solvent(s). The pristine lignin oil (before extraction) contains a wide range of polymers with not very distinct molecular weight (F_{oil}) and hence properties. Varying compositions of the extracting solvent result in different outputs. F_{H100} (enriched 4-propyl content), F_{H80} and F_{H60} (enriched 4-propanol content) result in enriched monomeric content, which is more desirable as the monomers can be easily separated.

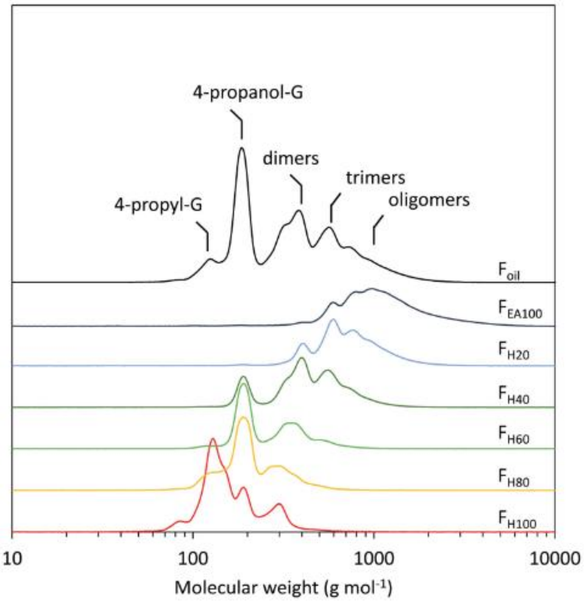


Figure 5.1: The molecular weight distribution of RCF resulting from different extraction steps
These are results presented by Van Aelst et al. (2020)

Bio-refineries thus strive for high purity (i.e. lower contamination) and lower heterogeneity in output chemicals (i.e. lower number of chemicals with distinct molecular properties). So, in a theoretical example shown in Figure 5.2, a mixture containing fewer chemicals (as in Fig. 5.2b) or with chemicals having distinct properties (as in Fig. 5.2c) is more desirable than a mixture containing a large number of chemicals with slight differences in molecular properties (as in Fig. 5.2a).

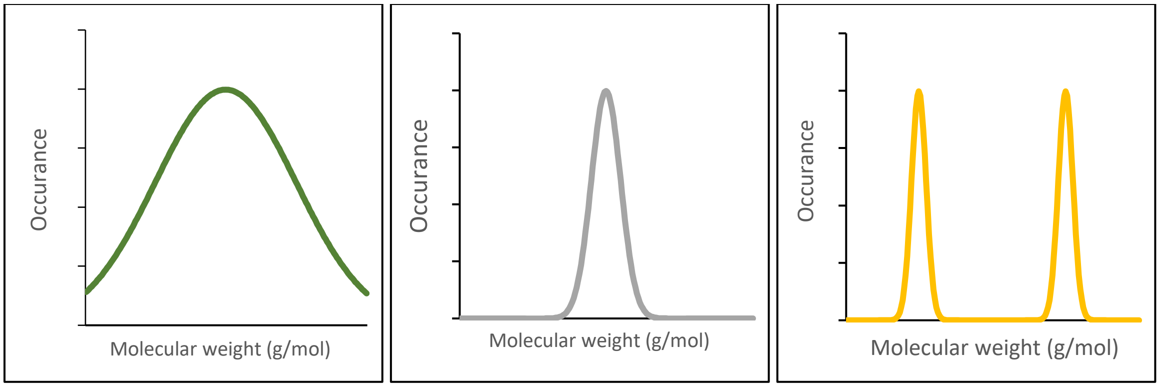


Figure 5.2: Theoretical example of molecular distribution of output mixtures

Left(a) represents a heterogeneous (high-entropy) mixture containing a large number of compounds with varying molecular weights. Centre (b) represents a mixture with lower variability(lower entropy). Lesser number of compounds and lower variation in molecular properties Right (c) Multiple sets of compounds with distinct molecular properties.

Besides that, bio-refineries aim for high monomeric yields as the monomeric fraction is highly depolymerised and can be easily polymerised to a high molecular weight functional building block. These blocks have a wide range of applications, which gives bio-refineries flexibility in choosing the application that maximises the economic gains. Oligomers, on the other hand, have limited application. Oligomers – a heterogeneous mixture with a complex molecular structure – cannot be easily polymerised for a particular application. They are separated into building blocks (such as dimers and trimers). Depolymerisation of these blocks is difficult, if not impossible, due to the strong chemical bonds between the monomeric units of these compounds. Another approach to enhancing the valorisation potential of the biorefineries would be to utilise the molecular function of these polymers. Thereby, oligomeric compounds are used as-is for material applications, avoiding the need for separation, depolymerisation and polymerisation. Change in molecular structure at each of these stages needs energy input. So, using these polymers as-is would also avoid the energy input in these steps. Limited valorisation of the oligomeric fraction is also because of little understanding of this fraction at the molecular level, which also needs improving (Dao Thi et al., 2022). The bio-refineries have focused on producing (drop-in) chemicals from lignocellulosic biomass to substitute the existing high-value chemicals produced so far from fossil-source. Novel chemicals that utilise the fundamental properties of the lignocellulosic compounds must be developed because, firstly, these drop-in chemicals have the same structure as their fossil counterparts and often do not solve the environmental challenges posed by fossil-based products (such as non-biodegradability). Secondly, using the inherent molecular properties of chemicals would reduce the need for modification of molecular structure and hence avoid the energy and resource input needed for those steps. Thirdly, this is in line with the principles of CE and cascading to maintain and valorise the material value of substances. Understanding the molecular structures of these oligomers and valorising their inherent properties is pivotal for developing novel applications utilising these polymers without having to separate, depolymerise and polymerise them.

The biorefinery performance has been evaluated mainly using techno-economic assessment (TEA) and LCA (Arts et al., 2021; Ubando et al., 2020). These assessments tell the economic viability and environmental impact of the bio-refinery. So far, evaluating circularity – maintaining the value of substances – has not been a concern. Additionally, both assessment methodologies depend on detailed process simulations – process flow diagrams and mass and energy balances. The reliability of the results of these methods depends highly on the accuracy of the process model, which is insufficiently known for emerging biorefinery technologies (at lower technology readiness levels). Moreover, as described in Chapter 4, these assessments are affected by the background system, regions or available technologies. Market dynamics influence economic feasibility. Environmental impact is affected by the energy mix (anticipated to change with the move towards renewable energy sources) and resource scarcity or availability in a given location. It also makes it difficult to compare the results of different bio-refinery studies or extrapolate them to other background systems. The assessment guiding biorefineries (designing bio-refinery process and output chemical configuration) should be based on the molecular properties to maintain the value of these polymers, enhance the material use potential and have an objective evaluation.

As demonstrated in Chapter 4, SEA is a method to quantify material quality based on purity and compositional complexity. The results also proved that SEA assesses material quality based on the complexity in physical characteristics. It can be a tool to evaluate a bio-refinery based on the composition and molecular properties of the output chemical mixture, allowing comparison of different bio-refinery or resulting from different bio-refinery configurations based on the material quality of chemicals produced. The present study aims to validate this hypothesis.

In summary, the bio-refineries strive to produce output chemical mixtures with (1) lower impurities, (2) a lower number of distinct chemical compounds and (3) compounds with distinct molecular properties. Additionally, this study emphasised that, following the circularity and cascading principle, the bio-refinery should valorise the high-molecular-weight functionalised compounds as-is without having to separate, depolymerise & polymerise them. The aim is to illustrate how SEA can assess the extent to which the bio-refineries achieve these objectives - by quantifying the complexity (purity and heterogeneity) and the diversity in molecular properties of the output mixture. This study demonstrates this by evaluating two biorefineries (1) the conventional kraft pulping process and (2) a specific type *of lignin-first strategy*, namely reductive catalytic fractionation (RCF).

5.2. Material and method

5.2.1. Statistical entropy analysis

Statistical entropy analysis evaluating material quality based on purity and compositional complexity

The existing statistical entropy calculation can describe the purity and compositional complexity of the output chemical mixture of bio-refineries. Thereby, it evaluates the extent to which the bio-refinery achieves its first two objectives, i.e. lower impurities and a lower number of distinct chemical compounds.

Statistical entropy (*H_c*) is calculated for each chemical output of the bio-refinery based on the concentration of constituent substances in that chemical (Eq. 5.1). The statistical entropy function (*H_c*) thereby quantifies the purity of each fraction, which is normalised to *RSE* (Eq. 5.2) by dividing it by the maximum level of statistical entropy (*H_{max}*). The statistical entropy is maximum when all the substances are present in an equal concentration in different flows and are maximally diluted (Eq. 5.3). *H_c* of each fraction is aggregated to derive *RSE* for the output mixture (*RSE_{total}*) using the mass-weighted average of the two fractions (Eq. 5.4).

The output mixture is not necessarily a distinct set of chemical compounds. As seen in Figure 5.1, it is a continuous distribution. Statistical entropy can be measured for the mass distribution function by calculating *H_c* for every point on the x-axis (*i*) using the value on the y-axis that describes the occurrence of each chemical (*c_i*).

$$H_{c(i)} = -\sum_{\mathrm{j}=1}^{n} c_{ij} * \log_2(c_{ij}) \qquad \textit{Equation 5.1}$$

Where c_{ij} is the concentration of constituent substances j in flow i

j in this study is primary constituent (pulp or lignin) and contaminants (so, n = 2) in each flow 'i' (carbohydrate pulp and lignin oil)

$$RSE_{(c)i} = \frac{H_c}{H_{max}} \qquad \textit{Equation 5.2}$$

$$H_{max} = \log_2(N) \qquad \textit{Equation 5.3}$$

Where N is the number of substances in that material flow

$$RSE_{(c)total} = w_1 * RSE_{(c)1} + w_2 * RSE_{(c)2} + \cdots + w_i * RSE_{(c)i} \qquad \textit{Equation 5.4}$$

Where w_i is the relative weight of the streams i

Statistical entropy analysis evaluating material quality based on the molecular weight

Statistical entropy can be defined using molecular weight distribution. SEA can thus evaluate the extent to which the bio-refinery achieves its latter two objectives, i.e. producing chemical compounds with distinct molecular properties and prioritising the high-molecular-weight functionalised compounds. So, the bio-refinery configuration that valorises the high-molecular-weight compounds and minimises the overall change in molecular weight (and statistical entropy) can be considered more desirable.

Statistical entropy – in terms of molecular weight of compounds – is calculated the same way as done to express statistical entropy based on the mass of wooden elements (Section 4.2.2). In that study, statistical entropy is defined based on the relative weight of wooden elements. Analogous to that – statistical entropy is defined, in this study, using the relative molecular weight (M_w) of each chemical compound (Eq. 5.6). The statistical entropy (H_{mw}) is calculated for individual molecules of each chemical compound based on its relative molecular weight (in g/mol). Mw_{ij} is the relative molecular weight of a single molecule j of the chemical i, and k is the total number of molecules of that particular chemical. The relative molecular weight is the weight in proportion to the benchmark (Eq. 5.5), which is the maximum molecular weight in the system under study. Determining the value of k is not essential. The probability of occurrence of an individual molecule depends on its molecular weight. But, the summation of this probability for all the molecules in a chemical is 1. Hence, Equation 5.6 simplifies to Equation 5.7.

$$Mw_{ij} = \frac{molecular\ weight\ in\ the\ chemical\ compound\ j\ (in\ \frac{g}{mol})}{maximum\ molecular\ weight\ for\ the\ specific\ case\ (in\ \frac{g}{mol})}$$

Equation 5.5

$$H_{Mw(i)} = -\sum_{j=1}^{k} Mw_{ij} * \log_2\left(Mw_{ij}\right)$$

Equation 5.6

Where s_{ij} is relative mass of a individual molecule of a chemical compound in the mixture

k is the total number of molecules of a chemical compound (i.e. the normalised fraction of a chemical compound i)

$$H_{mw(i)} = -\log_2\left(Mw_{ij}\right) \sum_{j=1}^{k} Mw_{ij}$$

Equation 5.7

$$H_{mw(i)} = -\log_2\left(Mw_{ij}\right)$$

Because:

$$\sum_{j=1}^{k} Mw_{ij} = 1$$

$$RSE_{(mw)i} = \frac{H_{mw}(i)}{H_{max}}$$

Equation 5.8

$$RSE_{(mw)total} = w_1 * RSE_{(mw)1} + w_2 * RSE_{(mw)2} + \cdots + w_i * RSE_{(mw)i}$$

Equation 5.9

Where w_i is the relative weight of individual chemical compound i

RSE is calculated using Equation 5.8 for each chemical compound to standardise the statistical entropy (H_{mw}) value to range between 0 and 1. It is calculated by dividing H_{mw} for a chemical by the maximum statistical entropy (H_{max}) for the specific system, which is the value of H_{mw} for the compound with the minimum molecular weight in the case study. RSE is 0 for the chemical with the molecular weight highest in the study ($M_w = 1$, $H_{mw}=0$) and is 1 for the chemical with the molecular weight lowest in the study ($H_{mw} = H_{max}$). All the other chemical compounds will have a H_{mw} value between these extremes. The aggregated $RSE_{(mw)total}$ for the set of output chemicals is calculated based on the mass-weighted average of each chemical (Eq. 5.9).

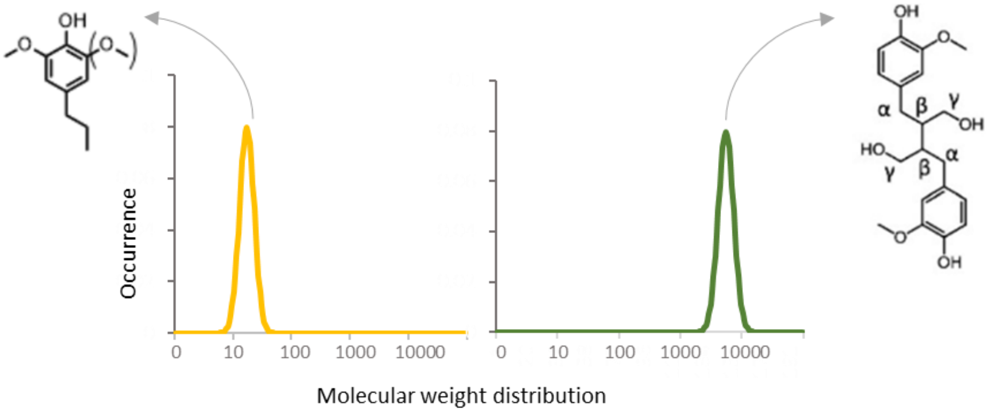


Figure 5.3: Molecular distribution of theoretical output of two bio-refineries

Left (a) The output contains a set of chemical with lower molecular weight. Right (b) The output contains a set of chemicals with comparatively higher molecular weight

The reason for defining statistical entropy based on the molecular weight is explained using a theoretical example. Figure 5.3a is a bio-refinery output containing a chemical mixture with low molecular weight (for instance, a bio-refinery output abundant in monomers), and Figure 5.3b is a chemical mixture with comparatively higher molecular weight (a bio-refinery output containing mainly dimers and oligomers). The two scenarios display the same mass distribution. They will give the same results of statistical entropy with conventional calculations, i.e. defining statistical entropy based on the mass distribution (the methodology described in the previous section). However, RSE for scenario 2 (Figure 5.3b) with relatively higher molecular weight would be comparatively lower when the entropy is defined based on molecular weight distribution.

5.2.2. Case study description

Kraft pulping process

In the kraft pulping process, wood chips are digested at elevated temperature and pressure in 'white liquor', a water solution of sodium sulphide and sodium hydroxide. White liquor chemically dissolves the lignin that binds the cellulose fibres together. The liquor is then separated from the pulp. Pulp, containing the cellulose fibres, proceeds through various stages of washing, possibly bleaching, before being pressed and dried into the finished product (United States Environmental Protection Agency USEPA, 1995). The collected liquor, containing most of the lignin fraction and called kraft lignin, is highly impure (mainly sulphite and ash; Bajwa et al., 2019) and polymerised (high molecular weight lignin). That hampers its exploitation as a platform for high-value chemical products (Van Aelst et al., 2020). This stream – also called black liquor – is used to burn on-site to provide heat and electricity for the pulping process. Table 5.1 provides the simplified mass balance for the kraft pulping process, and Tables 5.2 and 5.3 provide details of the composition of the two output streams – pulp (primarily cellulose) and liquor (primarily lignin), values estimated using the data from Alén (2015).

Table 5.1: Simplified mass balance for kraft pulping process

	Type	Amount
Input flows	Woody Biomass	1000 kg
Output flows	Pulp	400 kg
	Black Liquor	600 kg

Table 5.2: Composition of biomass pulp (by percentage weight; Alén, 2015)

Type	Amount
Cellulose	0.65
Hemicellulose	
Lignin	0.25
Extractives	0.03
Other	0.07

Table 5.3: Composition of black liquor (by percentage weight; Alén, 2015)

Type	Amount
Lignin	0.3
Aliphatic carboxylic acid	0.7
Inorganics	
Other organics	

Reductive catalytic fractionation

A novel type *of lignin-first strategy* is reductive catalytic fractionation (RCF) which yields a refined and stable lignin oil and solid cellulose-rich pulp. During RCF, lignin is released from the wood matrix and depolymerised by 'cooking' wood at elevated temperatures in a solvent (mixture). It is a promising technology to valorise lignin. The refined lignin oil has a low molecular weight and is a highly depolymerised mixture of chemicals – containing lignin monomers, dimers and oligomers – which can be functionalised to a large variety of bulk and fine chemicals (Sun et al., 2020). The co-product of RCF – the cellulose-rich pulp – is also amenable for downstream processing (Van den Bosch et al., 2018). For example, it can be fermented to bio-ethanol.

Table 5.4 provides the simplified mass balance for the RCF process, and Tables 5.5 and 5.6 provide details of the composition of the two output streams: pulp and refined lignin oil. This data has been collected from experimental work, combined with process simulation in Aspen HYSYS modelling software based on the earlier work of Liao et al. (2020) and Bartling et al. (2021).

Table 5.4: Simplified mass balance for Reductive catalytic fractionation process

	Type	Amount
Input flows	Woody Biomass (softwood)	1000 kg
Output flows	Pulp	840 kg
	Refined lignin oil	160 kg

Table 5.5: Composition of biomass pulp (by weight percentage)

Type	Amount

Cellulose	0.774
Hemicellulose	
Lignin	0.225
Ash	0.01

Table 5.6: Composition of refined lignin oil (by percentage weight)

Type	Amount
Lignin	0.79
Aliphatic carboxylic acid	0.21
Inorganics	
Other organics	

The study compares the kraft pulping and reductive catalytic fractionation (RCF) process to identify which of the two effectively separates and sustains the quality of biomass components – cellulose and lignin. Both bio-refineries produce two main outputs – carbohydrate pulp and lignin oil. But the outputs differ in their purity and heterogeneity. The substances under consideration are the main output (pulp or lignin) and extractives (contaminants or undesirable components in the product). However, lignin oil is a heterogeneous mixture containing a variety of phenolic monomers and oligomers. The composition of the lignin fraction can be subdivided further into lignin monomer, dimer, oligomers etc. The SEA based on the lignin composition, as in Table 5.6, would account only for purity in the output. Whereas SEA based on the classification of lignin into its subcomponents would quantify the compositional complexity one step further, accounting for the polymeric heterogeneity in the mixture (i.e. presence of various polymers). This detailed classification is available for lignin oil from RCF but not for kraft lignin, so, not included for a fair comparison.

SEA based on polymeric heterogeneity is demonstrated using different configurations of RCF bio-refinery. Figure 5.4 shows the process flow diagram for the RCF bio-refinery. The RCF produces mainly carbohydrate pulp and lignin oil (stage 1 in Fig, 5.4). The quality and utility of crude lignin oil depend on its composition. The crude lignin oil can be used directly without modifications if exploited well. However, most RCF research has focused on defunctionalising native lignin and separating depolymerised monomers from the crude lignin oil mixture for their application in high-value products. Monomers – a low-molecular-weight fraction of lignin oil – are selectively isolated from the mixture (the separation process in Fig. 5.4) and defunctionalised into bulk chemicals, like phenol and propylene (as shown by Liao et al. 2020). Oligomers have high functional content and high molecular weight and are complex. Converting them for downstream applications is difficult and are thus used for low-value applications, such as the resin (Van Aelst et al., 2021) and varnish used in printing inks (Liao et al., 2020) or polyols for polyurethanes (Huang et al., 2018). Oligomers could be further separated to derive dimer from the mixtures to extract a higher value. Like monomers, dimeric products have a potential application as polymer precursors for high-value applications. The value derived from the chemicals increases with further separation of oligomers. The heterogeneity in the remaining mixture also decreases further, and the average molecular weight increases. However, each step requires energy input. Hence, bio-refineries face a trade-off and struggle to find the balance between an increase in the total value derived with further separation and an increase in energy and resource input (and corresponding cost) with each step. The detailed information on the monetary value and mass & energy input – is not known for emerging technologies. SEA could be a preliminary assessment with the change in statistical entropy indicating the environmental and economic impact. Bio-refineries may then strive to reduce the net statistical entropy change at each stage.

Different process configurations lead to different output mixtures. Dao Thi et al. (2022) and Van Aelst et al. (2020) studied the separation of refined lignin oil into oligomeric compounds (monomers, dimers etc.) using solvent extraction with a solvent mixture of heptane and ethyl acetate in different proportions. The results show that varying composition of the solvents results in different yields. Table 5.7 provides a mass balance and molecular weight of the output chemicals in different scenarios. Statistical entropy is applied to compare different process configurations to determine the one having the lowest change in the overall entropy. The statistical entropy is calculated for each stage of RCF for each scenario. The calculations focused on only the lignin fraction to compare the different valorisation pathways of lignin components. The carbohydrate pulp has not been included.

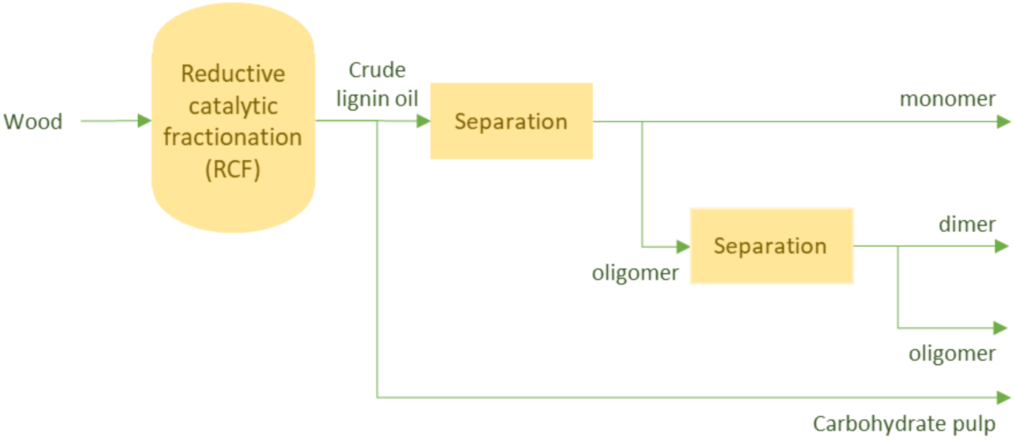


Figure 5.4: RCF biorefinery process for chemicals production from wood (Liao et al., 2020)

Table 5.7: The mass -balance of input and outputs at each stage of the RCF bio-refinery with different solvent extraction configuration

Stage	Input	F$_{H100}$ (100% Heptane)		F$_{H80}$ (80% Heptane & 20% ethyl acetate)		F$_{H60}$ (60% Heptane & 40% ethyl acetate)	
		Mass (kg)	Molecular weight (g/mol)	Mass (kg)	Molecular weight (g/mol)	Mass (kg)	Molecular weight (g/mol)
Stage 1 – Input to RCF	Wood chips	6250	7000	6250	7000	6250	7000
Stage 2 – Output of RCF	Crude lignin oil	1000	1052	1000	936	1000	984
Stage 3 – Output of 1st separation process	Lignin monomer	440	100	540	200	510	200
	Lignin oligomer	560	1800	460	1800	490	1800
Stage 4 – Output of 2nd separation process	Lignin monomer	440	100	540	200	510	200
	Lignin dimer	50	400	90	400	160	400
	Lignin oligomer	510	2000	370	2140	330	2500

Stage	Input	F_{H40} (40% Heptane & 60% ethyl acetate)		F_{H20} (20% Heptane & 80% ethyl acetate)	
		Mass (kg)	Molecular weight (g/mol)	Mass (kg)	Molecular weight (g/mol)
Stage 1 – Input to RCF	Wood chips	6250	7000	6250	7000
Stage 2 – Output of RCF	Crude lignin oil	1000	1500	1000	1000
Stage 3 – Output of 1st separation process	Lignin monomer	170	200	500	200
	Lignin oligomer	830	1800	500	1800
Stage 4 – Output of 2nd separation process	Lignin monomer	170	200	500	200
	Lignin dimer	340	400	100	400
	Lignin oligomer	490	2800	400	2800

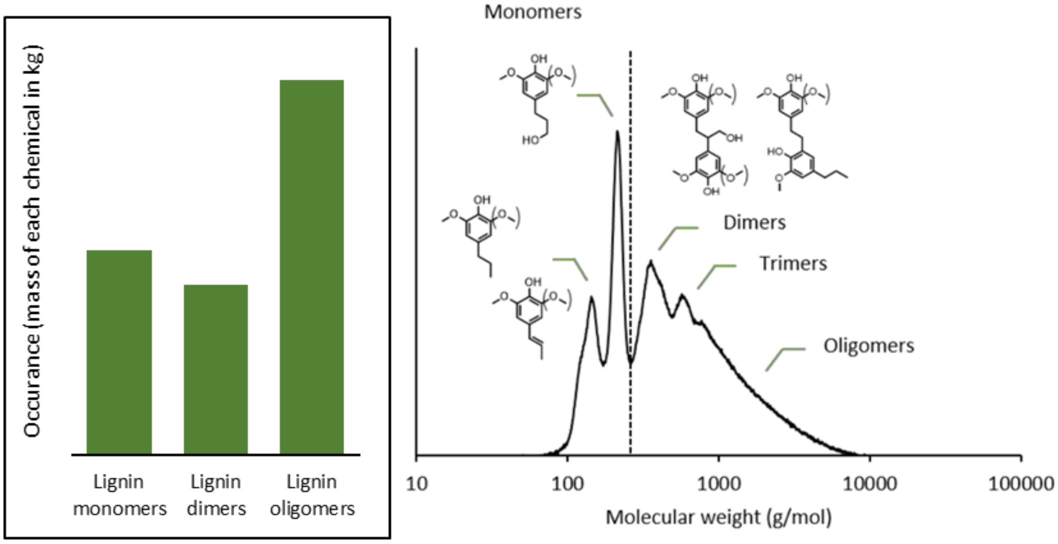


Figure 5.5: Description of a (theoretical) output of a RCF process.

Left (a) the simplified assumption that the RCF output contains three distinct chemicals. Right (b) the realistic molecular weight distribution of a RCF-derived lignin oil (Renders et al., 2019)

The output mixture of bio-refineries is not a distinct set of chemicals, as described in Table 5.6, but a range of chemicals with varying molecular properties – represented by the distribution function (like in Fig. 5.2 and Fig. 5.5b). The output mixture is assumed to contain distinct chemicals (Fig. 5.5a) for simplicity of demonstrating the application of methodology. The next step in detailing the result is calculating the statistical entropy based on the continuous distribution function, as in Fig. 5.5b, firstly by calculating H_{mw} for every point on the x-axis (i). The x-axis gives the molecular weight (Mw). Secondly, RSE is calculated for each point on the x-axis (i.e. i) and then aggregated using their weighted average with the value on the y-axis providing their relative occurrence (w_i).

5.3. Results and discussion

5.3.1. Evaluating material quality based purity and compositional complexity

Figure 5.6 shows the relative statistical entropy for the output chemical for the two bio-refineries – kraft pulping and RCF – with the same input. Kraft pulping process has comparatively a higher statistical entropy for both the output fractions – carbohydrate pulp and lignin fraction – and thus a higher overall statistical entropy for the output mixture. A higher statistical entropy for these fractions is due to the higher level of contamination and lower separation efficiency. Despite the focus of the kraft pulping process being the extraction of pulp (cellulose and hemicellulose), the pulp fraction contains a high share of lignin. On the other hand, RCF separates the two fractions to a greater extent. The pulp fraction has a comparatively lower amount of lignin, and the refined lignin oil has a lower amount of (hemi-)cellulose. So SEA results confirm that RCF produces more pure chemical compounds increasing their valorisation potential.

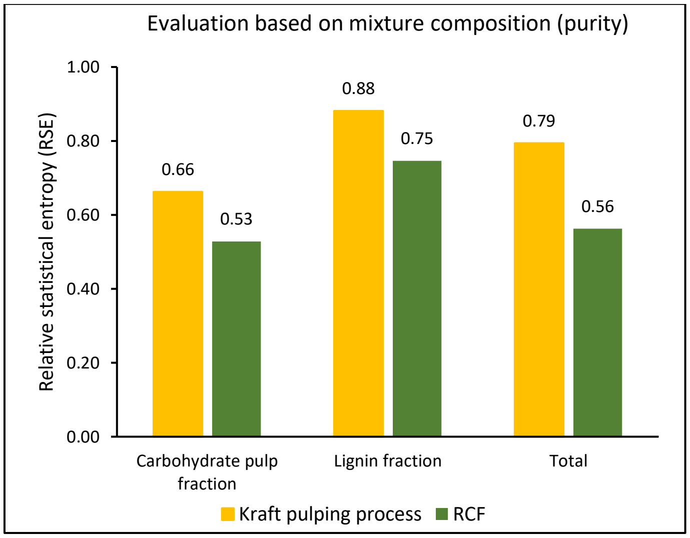


Figure 5.6: Statistical entropy of individual chemical components and the output mixture for the kraft pulping and RCF processes

It is a simplified analysis of the two processes, limited by time and available data. The results are intuitive and simplistic. However, the goal was to showcase the application of the methodology for assessing bio-refineries and not necessarily to derive indicative results. The next step in this research is detailing the composition of the output chemicals for a more comprehensive assessment and exploring cases where this gives results that are not obvious without calculation.

5.3.2. Evaluating material quality based on the molecular structure

Figure 5.7 shows the evolution of relative statistical entropy (*RSE*) through the different stages of the RCF process. Statistical entropy is defined using the molecular weight of polymeric fractions of lignin oil – monomeric, dimeric and oligomeric fractions. The fractionation process separates the native lignin from cellulose and hemicellulose fraction and efficiently depolymerises it. The molecular weight of lignin decreases as reflected by an increase in statistical entropy at stage 2. The statistical entropy at this stage is different for different scenarios because of the different molecular weights of the crude lignin oil. The separation step parts the low-molecular-weight monomers from the mixture (stage 3), causing an increase in the statistical entropy. On the same line, further separation of dimers from the oligomeric mixture increases the statistical entropy.

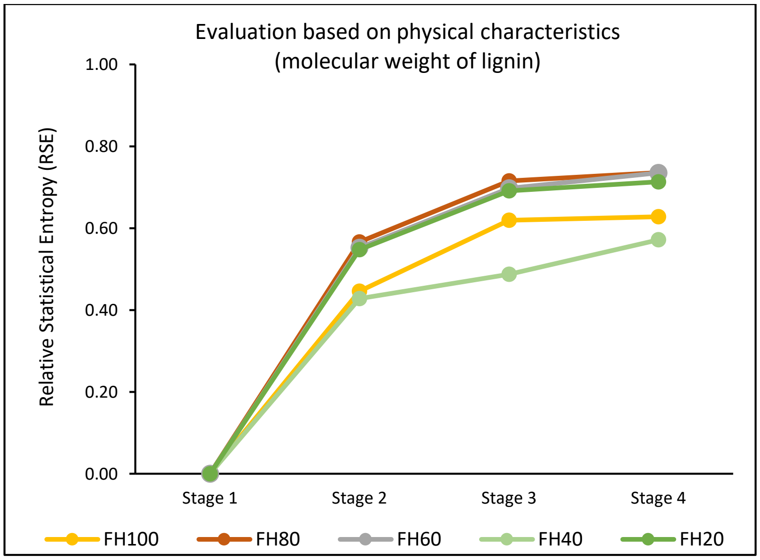


Figure 5.7: The evolution of relative statistical entropy (RSE) through the different stage for different extraction scenarios

The statistical entropy increase is the least in the F_{H40} scenario because of a low monomeric yield and a high molecular weight for the residual oligomeric fraction. The statistical entropy increase is highest in the F_{H60} for the same reason, i.e. high monomeric yield and low molecular weight for the residual oligomeric fraction. Based on entropy evolution, F_{H40} must be preferred. However, that contrasts with the current priorities of bio-refineries, in which a high monomeric yield scenario is desirable since monomeric compounds can be valorised in high economic-value applications.

The objective of this study was to demonstrate the applicability of SEA to evaluate material circularity in bio-refineries. Currently, bio-refineries target chemicals that maximise economic gains and not necessarily material circularity. Hence, they do not necessarily aim for low entropy situations, which may result in high entropy situations and then lower it with the effort required for each step. However, with the increasing knowledge of molecular properties of different oligomeric polymers and their potential functionalities, novel products and technologies are being developed with a growing focus on material circularity. Entropy evolution would then be an indicator or guiding tool for biorefineries. Having a clear understanding of the correlation between molecular weight and the functionality or utility of the polymers would further contribute to establishing the SEA methodology as a bio-refinery assessment tool.

This study assumes that the bio-refinery output mixture contains monomers, dimers and oligomers. It is a simplification for a comprehensive description of the calculations of statistical entropy and to demonstrate the applicability of the methodology. Statistical entropy must be calculated for the continuous molecular distribution function to accurately evaluate the complexity. Instead of for three components in Fig. 5.5a, statistical entropy (H_{mw} and RSE) is calculated for each point on the x-axis of molecular distribution (For example, in Fig. 5.5b) based on its molecular weight. The mass-weighted (value on the y-axis) average of the RSE of each point on the x-axis gives the aggregated RSE (RSE_{total}).

5.4. Conclusion

This chapter tests the hypothesis that SEA could be a tool for assessing material circularity in bio-refineries, i.e. to evaluate the purity, heterogeneity, distinctness in molecular properties in the output mixture, and the extent to which the molecular properties of the native building blocks are maintained and valorised. The traditional statistical entropy definition, assessing the compositional complexity, can evaluate the first two aspects. But it does not consider the molecular weight of the output chemicals. This chapter presents the adaptation of the current SEA method by describing statistical entropy definition based on molecular weight distribution, thereby allowing assess the latter two aspects of material circularity of bio-refineries. The SEA adaptations are demonstrated by comparing different bio-refineries and different bio-refinery configurations. Comparing the conventional kraft pulping process and lignin-first RCF technology shows that RCF is more effective as the output chemical mixture is purer and less heterogenous, increasing the valorisation potential.

The study also evaluates the different RCF bio-refinery configurations producing output chemicals with varying molecular weight distribution. SEA with statistical entropy definition based on molecular weight distribution identifies the one that maintains the molecular properties to the greatest extent. SEA results show that the scenario with a lower monomeric yield and a higher molecular weight for the residual oligomeric fraction is desirable as it causes the least statistical entropy. That is contrary to the current bio-refineries principles that aim for high monomeric yield, which has the highest economic valorisation potential. Currently, material circularity is not a priority for the design of bio-refinery. However, with better novel products and technologies and a better understanding of the correlation between molecular weight and functionality or utility, bio-refineries will aim for maintaining the molecular weight to maximise the functional value. SEA-based tool, with necessary adaptations, would be available to assess that. Additionally, it will form a generic tool to assess the material circularity of cascading – not only in solid wood applications but also in molecular-state applications.

Chapter 6: Life cycle assessment to evaluate environmental impact of wood

Based on: Navare, K., Arts, W., Faraca, G., Bossche, G. Van den, Sels, B., Van, K., 2022.
Environmental impact assessment of cascading use of wood in bio-fuels and bio-chemicals. *Resources, Conservation and Recycling*. 186, 106588.
https://doi.org/10.1016/J.RESCONREC.2022.106588

Abstract

Cascading keeps wood in products for a longer duration and delays the embedded biogenic carbon emission. Carbon is kept out of the atmosphere for longer, giving forests – cleared for wood harvesting - time to regrow and sequester an equivalent amount of carbon. The storage period and time needed to sequester the same amount of carbon affects the carbon balance – an aspect often overlooked in LCA. This study explicitly includes this temporal information of biogenic carbon flows to examine if it significantly influences the net GWP of cascading systems. The case study chosen combines the traditional uses in the construction and furniture industry and a novel application in fuels and chemical production. By including the latter, the study aims to verify the environmental benefit of using waste, instead of fresh wood, for the bio-refinery. The results confirm that the GWP decreases with an increasing number of cascade steps. Benefits arise by substituting energy-intensive materials with wood, which become more pronounced when considering the temporal information – highlighting that current carbon accounting may underestimate the climate benefits of cascading. While comparing the bio-refinery products with their fossil-based counterparts, the GWP of bio-refinery products depends on their feedstock. GWP is lower when using waste wood, which has served a long time, instead of virgin wood. Benefits enlarge by extending the application lifetimes of these products.

6.1. Introduction

"Quit counting time and start making the time count"
Zig Zaglar

Several studies evaluating cascading systems observed the environmental benefits of cascading use. Sathre and Gustavsson (2006) categorised four mechanisms via which wood cascading has climate benefits. They are cascade, substitution, land-use intensity, and time effect. The *cascade effect* is when recovered wood is used instead of virgin wood for an application. The benefits are because of the differences in the physical properties of the virgin and recovered wood and the logistics needed to supply them. Virgin wood is comparatively larger in size than recovered wood and has a higher moisture content, resulting in higher energy demand for drying and treating it. Also, growing, harvesting, and transporting virgin wood often require more resources than recovering, sorting and treating waste wood. The *substitution effect* is when wood substitutes fossil- or mineral-based materials, which are often more energy-intensive (Sathre and Gustavsson, 2009) and could lead to a net climate benefit. *Land-use intensity effects* are because cascading of wood allows providing multiple functions with the same resource, and since the land is a scarce resource, cascading reduces the land required to serve those applications or makes available the surplus resource for other applications. *The time effect* is by keeping the carbon stored in harvested wood products (HWP) for longer and delaying the emissions resulting from the eventual incineration or decomposition of wood. The carbon is kept out of the atmosphere for longer, giving forests – cleared for wood harvesting - time to regrow and sequester an equivalent amount of carbon.

6.1.1. Effect of carbon storage

However, most studies showcasing the environmental benefits of cascading use focused mainly on the cascade and substitution effects. The contribution of delaying emissions - by keeping carbon stored in products in cascading - is often disregarded. Only a few LCA studies of cascading considered the storage period and time of emission (Faraca et al., 2019b; Garcia et al., 2020; Mehr et al., 2018). Sathre and Gustavsson (2006), who categorised the factors contributing to the carbon balance of wood cascades, also only analysed the cascade, substitution and land-use effects. The justification for disregarding the time effect is that the stock of HWP will stabilise over time. Then, the rate of virgin wood entering the wood products pool (i.e. the rate of harvesting) will equal the rate of wood leaving the pool (i.e. the rate of incineration or decomposition). In this case, the rate of carbon dioxide (CO_2) released into the atmosphere will equal the rate of CO_2 uptake by plant growth. At this point, the prolonged carbon storage in HWP does not affect the atmospheric CO_2 concentration any further. The carbon embedded in biomass, termed biogenic carbon, is thus assumed to be carbon neutral.

This carbon neutrality assumption is not valid for evaluating wood cascading, considering that the wood is cascaded precisely to increase the stock of HWP. Pingoud et al. (2003) and Mason Earles et al. (2012) show that the HWP stock is growing in the major wood-producing countries like Canada, Finland, Germany, Sweden and the United States. The rate of combustion or decomposition of wood is lower than that of harvesting virgin wood. So, accounting for the temporal aspects of carbon storage and emissions is essential for accurately evaluating the climate impact of wood cascading systems.

Additionally, the rate of carbon uptake in the forests from where the wood is sourced also influences the carbon balance. Biomass with a fast growth rate can lead to a higher carbon reduction potential because the carbon is sequestered more rapidly. Thus, CO_2 stays in the atmosphere for a shorter duration and lower cumulative radiative forcing is created in the considered time horizon (Cherubini et al., 2011; Guest et al., 2013).

This study aims to account for the storage period and rate of carbon uptake while evaluating the GWP of alternative wood cascading scenarios – to validate whether the time or rate of biogenic carbon flows significantly impacts the carbon budget of cascading systems.

6.1.2. Cascade use of wood in the bio-refinery

An increasing number of scientific studies have highlighted the potential benefit of wood cascading. The concept is also becoming a political ambition in European bio-economy policy. However, in practice, the cascading use of wood is still in its infancy in Europe. Today, particleboard is one of the few established practices for cascading post-consumer wood (Vis et al., 2016). Most of the available studies also evaluated particleboard as the primary cascading option for the recovered wood.

At the same time, novel recycling technologies and applications are emerging for biomaterials, which provide an opportunity to develop more effective and efficient wood cascading pathways. Wood as feedstock for the production of fuels and chemicals is gaining traction and is seen as a solution to tackle the environmental impact of fossil resources. Wood is a carbon-rich material composed of cellulose, hemicellulose and lignin. Various compounds are produced already from the (hemi)cellulose fraction – prominent examples are paper, pulp, and ethanol. But most of the lignin, currently recovered as a by-product in conventional wood fractionation processes such as Kraft pulping, is in degraded form and is suitable only for incineration for energy recuperation. However, lignin is an aromatic polymer made of interlinked phenolic units making it a promising feedstock to replace fossil aromatics.

As mentioned in Chapter 5, recent efforts in biorefinery research focus on *lignin-first* approaches, in contrast to conventional carbohydrate-centred biorefineries. In the *lignin-first* refineries, wood is fractionated into lignin oil (ready to upgrade to high-value chemicals) while retaining the pulp as a solid fraction for further processing. RCF bio-refinery yields a refined and stable lignin oil and solid cellulose-rich pulp. During RCF, lignin is released from the wood matrix and depolymerised by 'cooking' wood at elevated temperatures in a solvent mixture. Given that the lignin fragments formed during the solvolytic depolymerisation are prone to re-polymerise, a redox catalyst and hydrogen source (in the form of pressurised hydrogen gas or other donors) are added to the reaction mixture to stabilise the lignin-derived phenolics (Arts et al., 2021; Liao et al., 2020; Sheldon, 2020; Van Den Bosch et al., 2015). It is a promising technology to valorise lignin. Refined lignin oil is a highly depolymerised mixture and can be functionalised to a large variety of bulk and fine chemicals (Sun et al., 2020). It contains chemical substances that have structural similarities to phenol and phenol-derived chemicals and could, therefore, (directly or indirectly) substitute fossil-based phenol in the production of downstream phenolic chemicals – such as bisphenols (Koelewijn et al., 2018, 2017), polycarbonates (Koelewijn et al., 2017), phenolic resins (Liao et al., 2020) and epoxy resins (Van Aelst et al., 2021). Its applicability goes beyond the phenol value chains – for example, in polyurethanes as polyols substitutes (Huang et al., 2018; Vendamme et al., 2020). The co-product of RCF – the cellulose-rich pulp - can be fermented to bio-ethanol, which is used as a fuel additive for gasoline bio-enrichment today. Bio-ethanol can also substitute ethylene currently produced by energy-intensive steam cracking of fossil resources.

RCF research has primarily focused on virgin biomass as a feedstock. However, recovered wood (i.e. residues and post-consumer streams) also forms an attractive alternative feedstock for RCF (Tschulkow et al., 2020; Van Den Bossche et al., 2021). Following the cascading principle, virgin wood should be used first for higher material value applications (such as construction material); and could be used for chemical production after losing its structural properties. A chemical application could add an extra cascade step in the value chain before incineration, further lengthening the cascaded chain and the carbon capture time. Refined lignin oil could, in fact, be used to produce thermoplastics or thermosets that form part of the ‘synthetic materials’ value chain, wherein it might be further recycled multiple times before being incinerated.

However, waste wood is more heterogeneous than virgin wood. It is a mixture of different types of wood (softwood and hardwood) and could contain heavy and toxic metals (Van Den Bossche et al., 2021), which impacts the overall bio-refinery yields. The recovered wood needs treatment (such as sorting and cleaning) to effectively use it in the RCF without affecting the quantity and quality of the output chemicals compared to virgin wood. The yields and treatment process influences the environmental impact of the RCF process using the waste wood. This study has included this novel technology as a potential cascading pathway applied to waste woods to investigate whether it could be environmentally beneficial to use current waste instead of virgin wood for RCF.

6.1.3. Research objective

This study aims to evaluate the net carbon balance of alternative wood cascading scenarios to produce lignocellulosic products and investigate if using waste wood instead of virgin wood lowers the GWP of the bio-refineries. The study also examines the contribution of carbon storage (and delaying emissions) to decreasing the GWP of the system. The biogenic carbon sequestration and emissions are considered using different carbon accounting methods: Firstly, using the traditional accounting method that assumes carbon neutrality and secondly, including time and rate of carbon sequestration and emissions. The objective is to evaluate whether there is a significant difference in the GWP when calculated with two accounting methodologies and consequently highlight the importance of considering the temporal details of biogenic carbon flows.

6.2. Material and method

6.2.1. Goal, scope, functional unit and scenarios description

The carbon balance of alternative cascading scenarios is assessed using the LCA methodology, following the ISO 14040/14044 standards. The functional unit for the system chosen is the **sequential use of 1m^3 (450 kg) of virgin sawn wood** harvested from the **softwood forest to produce refined lignin oil and bio-ethanol.** The time horizon considered for the assessment is 100 years. A short time horizon is chosen because carbon storage in biomass is more crucial for short-term climate mitigation goals and becomes less significant at a longer time horizon of 500 years, as confirmed by Guest et al. (2013) and Faraca et al. (2019b). Figure 6.1 is a simplified illustration of the system boundary of the cascading scenario. The detailed system boundary, including all the secondary wood flows, is available in Annexe D.1. In scenario 1, virgin wood is used as a feedstock for RCF in the form of wood chips to produce refined lignin oil and carbohydrate pulp. The carbohydrate pulp is further hydrolysed and fermented to bio-ethanol. The cascading scenarios are built upon scenario 1 to evaluate the environmental benefit of wood cascading and using waste wood instead of virgin wood for RCF. In scenario 2, fresh (or virgin) wood is used initially for higher material value application, and post-consumer wood is used for RCF. The high-value application chosen is construction material (the representative product under consideration is Glued Laminated timber [GLT] with a lifetime of 50 years; Petersen and Solberg, 2002). The generated post-consumer wood is then used as a feedstock for the RCF process. In scenario 3, another cascading step is added. Fresh wood is used for construction material (GLT as the representative product). The recovered wood from construction is used as a feedstock first for particleboard production (with a lifetime of 10 years; Faraca et al., 2019b), and then the post-consumer particleboards are used as feedstock for the RCF process. The system boundary is the cradle to the factory gate of the individual sub-systems. The study does not include transport between the sub-systems because the aim is not to determine the net GWP of alternative cascading scenarios but to assess the contribution of delaying emissions to the GWP. The transport emissions result from burning fuels (i.e. no carbon storage in a product or delayed emissions) and do not affect the analysis. They were thus not included.

The material functions provided by the various systems should be equivalent when comparing their environmental impact. Multiple sequential uses of resources is a characteristic of cascading, so different cascading systems invariably provide varying functions. In the case under consideration, scenario 1 provides RCF products (i.e. refined lignin oil and carbohydrate pulp, which is fermented to produce bio-ethanol), scenario 2 provides GLT and RCF products, while scenario 3 provides GLT, particleboard and RCF products. Additionally, the amount of each product is also different in the different cascading scenarios. The material losses at each cascading step imply that the amount of valuable products produced reduces the further downstream the application is. For instance, in the case study under consideration, the amount of refined lignin oil and carbohydrate pulp produced in scenario 3 is lower than in scenario 2, which is lower than in scenario 1. The ISO standard recommends system expansion to solve system inequalities. Following the guidelines of system expansion, each cascading scenario is credited for the products substituted as it avoids the environmental impact of the production of those products.

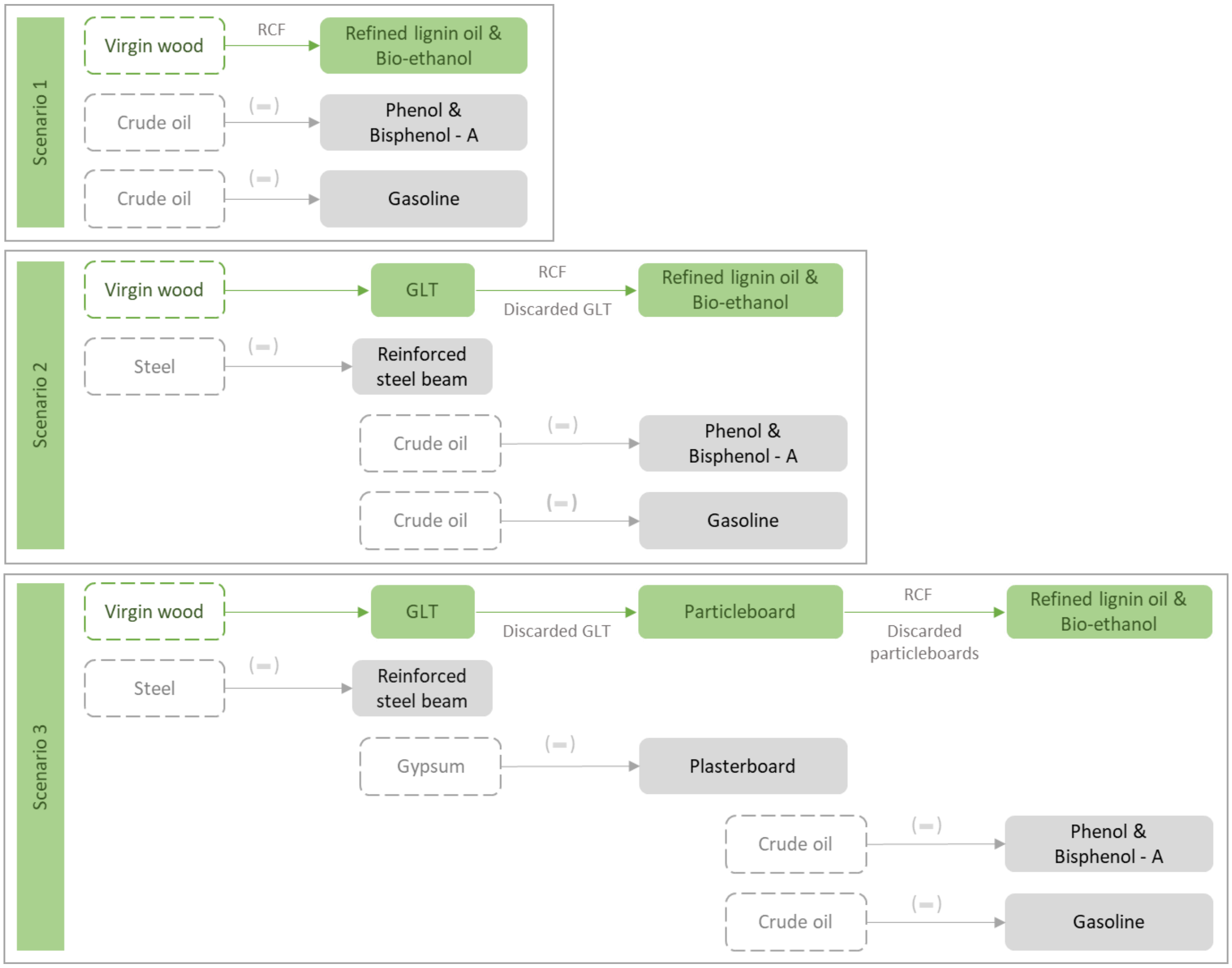


Figure 6.1: The system boundary of alternative cascading systems
Green boxes represent the service life of wood in different products. Grey boxes represent the credit received by the system for substituting non-wood products. The dotted lines show the primary resource used for different products.

The products produced in the cascading system are assumed to substitute the functionally equivalent non-wood (fossil- or mineral-based) products with the same service life. The assumption here is that the wood availability is limited. So, in the absence of cascaded use of wood, the material functions are fulfilled by non-wood materials (grey boxes in Fig. 6.1). GLT substitutes steel beams, and particleboards replace plasterboard panels made of gypsum. The RCF produces refined lignin oil and carbohydrate pulp. Refined lignin oil consists of phenolic monomers and oligomers. The monomer components have structural similarities to phenol (i.e., the aromatic ring with hydroxyl-group attached) and, hence, are assumed to substitute phenol produced from fossil-derived benzene (and propylene) via the Hock process. The oligomer components are assumed to be substitute bisphenol A - derived from benzene-originated phenol, as the chemical structure of the oligomers resembles that of bisphenol A and the oligomers could potentially serve in similar applications further downstream of the phenol value chain. The carbohydrate pulp fermented to bio-ethanol replaces gasoline from crude oil. The details of the products and the amounts of that product substituted are available in Annexe D.4. The latter is determined by equating the amounts of the two products required to provide the same function. However, the amount substituted in reality is known only by analysing market dynamics and performing consequential LCA. But it was not considered in this study as functional equivalency was sufficient to achieve the objective. Additionally, it might appear that the outputs are provided at times in different scenarios. However, the assumption is that there is a stable supply of virgin and waste wood. So, for scenarios 2 and 3, the waste wood supplied in year 0 is used for the bio-refinery. All outputs are thus provided at the same time (year 0). However, understanding market dynamics and including the changes in resource supply by performing consequential and dynamic LCA would give a more accurate picture.

6.2.2. Life cycle inventory

The main processes within the life cycle of the three cascading scenarios are GLT and particleboard production (from fresh and waste wood), RCF process and conversion of pulp to bio-ethanol. The data for RCF were collected from laboratory experiments combined with process simulation. Whereas, for the remaining processes, data was from the scientific literature. Data for the secondary processes (such as waste wood chipping and treatment and residue incineration) and production of substituted products (such as steel beam and plasterboard) is from the inventory databases (Ecoinvent). The sources of LCI data are summarised in Table 6.1. LCI was modelled using the GaBi software (Professional version 10.6). It is modelled for the European context, i.e. the background processes were specific to Europe as far as possible. But when the dataset for the European context was unavailable, data on the global scale had to be used. Table D.7 in Annexe D specifies the geographical applicability of each of the processes used for modelling the LCI.

The laboratory experiments for the RCF process were performed with virgin softwood and recovered (post-consumer) wood to produce refined lignin oil and carbohydrate pulp. Fresh wood was the feedstock for scenario 1. Grade I and II waste (or waste wood A) was considered the feedstock for scenario 2, and Grade III waste (or waste wood B) was feedstock for scenario 3. Annexe D.5 provides the details on the categorisation of waste wood and the reason for choosing them as feedstock for each scenario. The mass balance obtained from these experiments was upscaled to an industrial scale by the process simulation, from which a net mass and energy balance of the RCF process was obtained (Annexe D – Table D.5). The simulation was modelled in Aspen HYSYS based on the earlier work of Liao et al. (2020) and Bartling et al. (2021).

Table 6.1: The source of data for modelling LCI of different processes within the three scenarios

Products/process	**Source for the LCI of the product**	**Details**
GLT production (from virgin wood)	Risse et al. (2019)	Annexe D (Table D.2)
Particleboard production (from virgin and waste wood)	Kim and Song (2014)	Annexe D (Table D.3 provides LCI for particleboard production from fresh wood and Table D.4 is for particleboard production from waste wood). Particleboard from 100% waste wood is currently not produced in Europe but is part of the study to assess the cascading effects.
RCF Process for the production of refined lignin oil and carbohydrate pulp	Experimental work, combined with process simulation in Aspen HYSYS.	Annexe D – Table D.5 provides the net mass and energy balance of the RCF process used for LCI modelling
Conversion of carbohydrate pulp to bio-ethanol by hydrolysis and fermentation processes	Modelled based on a Sebastião et al. (2016)	Sebastião et al. (2016) provide the process inventory of paper sludge to bio-ethanol, which was adjusted to suit the conversion of pulp to bio-ethanol. The modification was based on the comparative difference in sugar content in the carbohydrate pulp and the sludge of the paper and pulp industry. The detailed mass and energy balance for the process is specified in Annexe D - Table D.6.
Secondary process (such as waste wood chipping, treatment and residues incineration)	Ecoinvent Database (version 3.7.1)	The datasets from the Ecoinvent database, selected for each background process, are documented in Annexe D (Table D.7).
Background processes (such as sawn wood production and virgin and waste wood treatment)		
Production of substituted products (such as reinforced steel beam and plasterboard)		

6.2.3. Assessment method

The environmental impact is examined using the global warming potential (GWP) midpoint indicators from the ReCiPe 2016 (Hierarchist). GWP is first calculated for the bio-refinery (scenario 1) to evaluate the environmental performance exclusively of the production of the lignocellulosic products. Subsequently, the GWP is calculated for the cascading scenarios (scenarios 2 and 3) to assess the benefits of wood cascading and compare the environmental performance of bio-refinery using waste wood instead of fresh wood. In each case, the GWP is calculated from cradle to gate with and without including the emissions of the carbon embedded in products. The assessment without embedded carbon emissions provides the impact of production processes themselves and isolates it from the benefit of using biomass in products. The analysis including the embedded carbon emissions is performed to assess the benefits of wood cascading. The embedded biogenic carbon is traditionally accounted for in LCA by completely excluding biogenic carbon (known as the 0/0 approach) or giving a value of +1 to biogenic carbon emissions and -1 to carbon uptake (known as the -1/+1 approach). This study additionally assesses the impact of embedded carbon by considering the rate of biogenic carbon uptake during tree growth, carbon storage period and delay in biogenic carbon emissions resulting from cascaded use of wood and avoiding fossil-based products emissions.

In summary, the different accounting methods considered in this study are cradle-to-gate emissions excluding biogenic carbon (method 1a), cradle-to-gate emissions including biogenic carbon with -1/+1 accounting (method 1b), cradle-to-gate and embedded carbon emissions excluding biogenic carbon (method 2a), cradle-to-gate and embedded carbon emissions including biogenic carbon with -1/+1 accounting (method 2b) and cradle to gate and embedded carbon emissions including biogenic carbon by considering the rate of carbon sequestration and time of emissions (method 2c).

Embedded carbon accounting

The CO_2 behaves the same in the atmosphere irrespective of the origin of the CO_2 (biogenic or fossil). However, it should be accounted for differently to incentivise the appropriate use of the resources. The fossil-based CO_2 emissions are a net addition to the atmosphere. In contrast, the biogenic carbon is sequestered from the atmosphere during plant or tree growth and is released back to the atmosphere later when biomass decomposes or is combusted. These two biogenic carbon flows – from and into the atmosphere – are assumed to be equal and considered to cancel each other out. Hence, the biogenic carbon flows are regarded as carbon neutral and accounted for by completely excluding them (0/0 approach) or assigning -1 for carbon uptake and +1 for carbon emissions (-1/+1 approach; Garcia and Freire, 2014; Hoxha et al., 2020). However, these accounting methods do not consider the time needed for carbon sequestration and the period over which carbon is stored in HWP. A theoretical example demonstrates the influence of these temporal factors on the net carbon balance (Fig. 6.2). The wood is harvested at year 0 and remains stored in HWP for a certain period. At the end of this storage period, CO_2 is emitted back to the atmosphere as the wood in these products decomposes or is incinerated (represented by the orange, yellow and green lines in Fig. 6.2 for three different storage periods). The forestland cleared for wood harvesting is assumed to be revegetated immediately after harvesting with the same biomass species. The biomass regrowth starts sequestering carbon, which creates a net debt in atmospheric CO_2 concentration (Represented by the grey line in Fig. 6.2). By the end of the rotation period, forest regrowth captures the same amount of CO_2 as that harvested from the forest. The dotted lines represent the net CO_2 in the atmosphere resulting from carbon emission and sequestration, and GWP is proportional to the area under this curve.

The biomass stored for a short life in HWP has a relatively higher GWP because the emissions at the end of life spend more time in the atmosphere within the considered time horizon (Represented by the orange line in Fig. 6.2). The GWP of biogenic emissions from short-lived products could be climate positive. The biomass needs to remain stored in HWP for a certain time for the biogenic carbon emissions to be carbon-neutral. The longer the biomass is stored, the higher the climate benefits. So, the GWP (proportional to the area under the dotted curve) is negative for the long-life cascade (i.e. green curve) in the theoretical example in Figure 6.2.

Additionally, biomass from a shorter rotation period forest (or fast biomass growth rate, such as in Fig. 6.2b) will be carbon neutral earlier in time, as carbon is sequestered more rapidly. Cherubini et al. (2011) used this reasoning and developed characterisation factors (CFs) for biogenic CO_2 emissions considering the rotation period of biomass. These factors are the impact of biogenic CO_2 emissions relative to the same amount of fossil CO_2 emissions. Guest et al. (2013) extended it by considering the time delay in biogenic CO_2 emission due to carbon storage in the harvested wood products over a period before its eventual combustion.

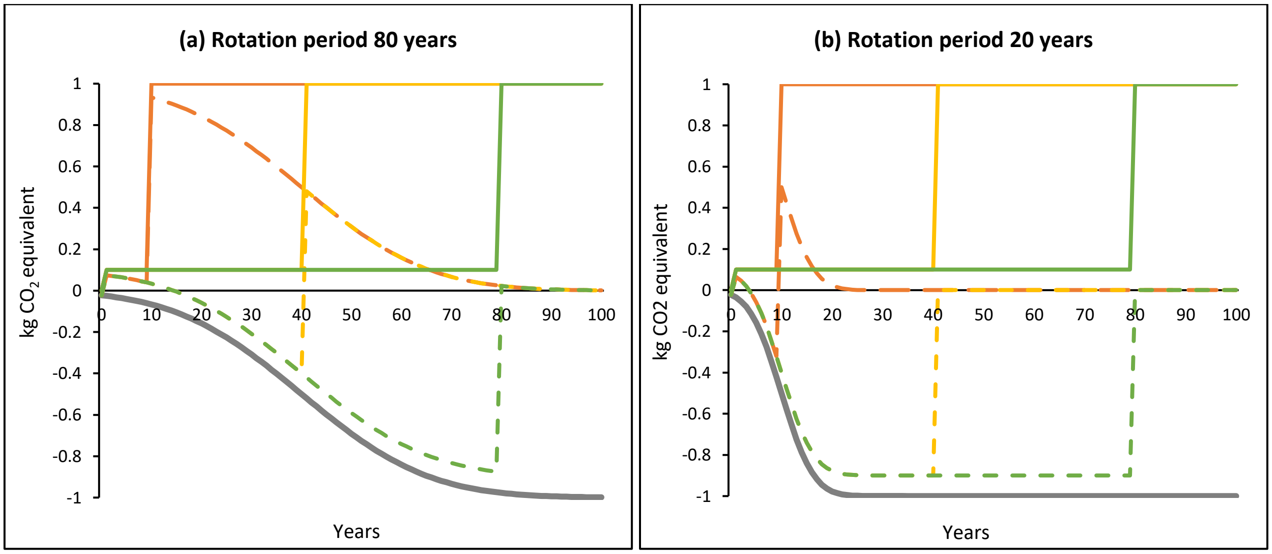


Figure 6.2: Theoretical description of net biogenic CO_2 emissions

When the wood is sourced from the forest with rotation periods 80 (a) and 20 years (b). Grey represents the amount of CO_2 accumulated by forest growth. Solid lines represent biogenic CO_2 emissions in the short (orange), medium (yellow), and long (green) service-life cascades. Dotted lines represent the net CO_2 fraction remaining in the atmosphere for the short (orange), medium (yellow), and long (green) service-life cascade. Note that this is a theoretical presentation of the net reduction of biogenic carbon emissions due to biomass growth. Uptake by oceans and terrestrial biosphere is not included.

This study used the CFs for GWP provided by Guest et al. (2013) to account for the carbon storage and rotation period. The wood is assumed to be harvested from the European softwood forests with an average rotation time of 60 years (Biermayer, 2020; Nabuurs et al., 2014). Table 6.2 lists the CFs for different storage periods corresponding to 60 year rotation period. The underlying assumption for these CFs is that the tree is cut only at the end of its rotation period (i.e. at the optimal harvesting age). The same species is planted in its place, which is also allowed to grow until its rotation length and captures the same amount of carbon that was harvested from the forests. So, the net carbon in forests remains constant over time. Also, CFs are derived assuming only a single rotation period, and a possible loss of carbon in forests after repeated harvest is ignored.

The contribution of biogenic carbon to GWP for the three cascading scenarios is calculated by multiplying the biogenic carbon emissions occurring in a particular year by the CF corresponding to that year. A disclaimer required here is that the CFs for GWP developed by Guest et al. (2013) consider the storage of harvested wood for a particular period and subsequent emission of biogenic carbon as CO_2 pulse. However, the system boundary of this study does not include the end-of-life of the final products. The biorefinery products are chemicals (like the refined lignin oil that are precursors for material applications) with potentially varied end-of-life treatment options and fuel (i.e., bio-ethanol) combusted for energy production. A simplified assumption made for the study is that all the biogenic carbon embedded in the biorefinery products is emitted as CO_2 in a single pulse at the end of the cascade service lifetime. It is a conservative assumption, and the GWP will only decrease with any possible delay in biodegradation of the carbon embedded (in case the products are landfilled or further recycled). The same assumption is made to the carbon-based substituted products, i.e. gasoline, phenol and bisphenol A products. These emissions are fossil-based and accounted for as a net addition of CO_2 to the atmosphere (i.e. CF = 1).

Table 6.2: Biogenic carbon GWP characterisation factor (CF) values corresponding to the 60-year rotation period (using a 100-year time horizon; Guest et al., 2013)

Embedded carbon storage period (in years)	**Characterisation factor (rotation period 60 years)**
0	0.25
10	0.17
20	0.09
30	0.01
40	-0.07
50	-0.16
60	-0.26
70	-0.36
80	-0.47
90	-0.59
100	-0.75

In scenario 1, virgin wood is used as a feedstock for RCF to produce refined lignin oil and carbohydrate pulp. Refined lignin oil can potentially substitute phenol-based products with wide final material applications having varying lifetimes. An average of these products' lifetimes is considered for this study, which is 10 years (Geyer et al., 2017). The co-product of RCF, carbohydrate pulp, can be fermented to bio-ethanol and used as a gasoline fuel additive. The fuel is combusted for energy, so the biogenic carbon contained in the bio-ethanol is assumed to be emitted at year 0 itself. The amount of biogenic carbon embedded in these products is multiplied by the CF corresponding to their lifetime (i.e. 0.25 for bio-ethanol and 0.17 for refined lignin oil). In scenario 2, wood is used as construction material (GLT) for 50 years (Petersen and Solberg, 2002; Sandin et al., 2014). Residues produced during GLT manufacturing are combusted for industrial heating. So the biogenic carbon in the residues is considered emitted at year 0, applying CF 0.25. The end-of-life waste is then used as feedstock for RCF to produce the carbohydrate pulp and refined lignin oil. Similar to scenario 1, refined lignin oil is used in phenol-based products for another

10 years. Biogenic carbon is stored for 60 years in this scenario, so the CF applied is -0.26. The service life of wood used in bio-ethanol from the carbohydrate pulp ends at year 50 (CF = -0.16). Scenario 3 has an additional service life of 10-year, because of the intermediate use of wood as particleboard. Wood is initially used as construction material (GLT) with a lifetime of 50 years. The end-of-life waste from the construction industry is used for particleboard manufacturing with a lifetime of 10 years. The residues produced during GLT and particleboard production are combusted for industrial heating. The combustion of residues of GLT production is considered to be at year 0 (CF = 0.25), and that of particleboard production is considered at year 50 (CF = -0.16). The post-consumer particleboard is a feedstock for RCF, extending the service life of a part of the biomass by 10 years as phenol-based products. The CFs applicable in this scenario for biogenic carbon in refined lignin oil and bio-ethanol are -0.36 and -0.26 respectively. The values are aggregated for each scenario to derive the net GWP.

Scenario analysis

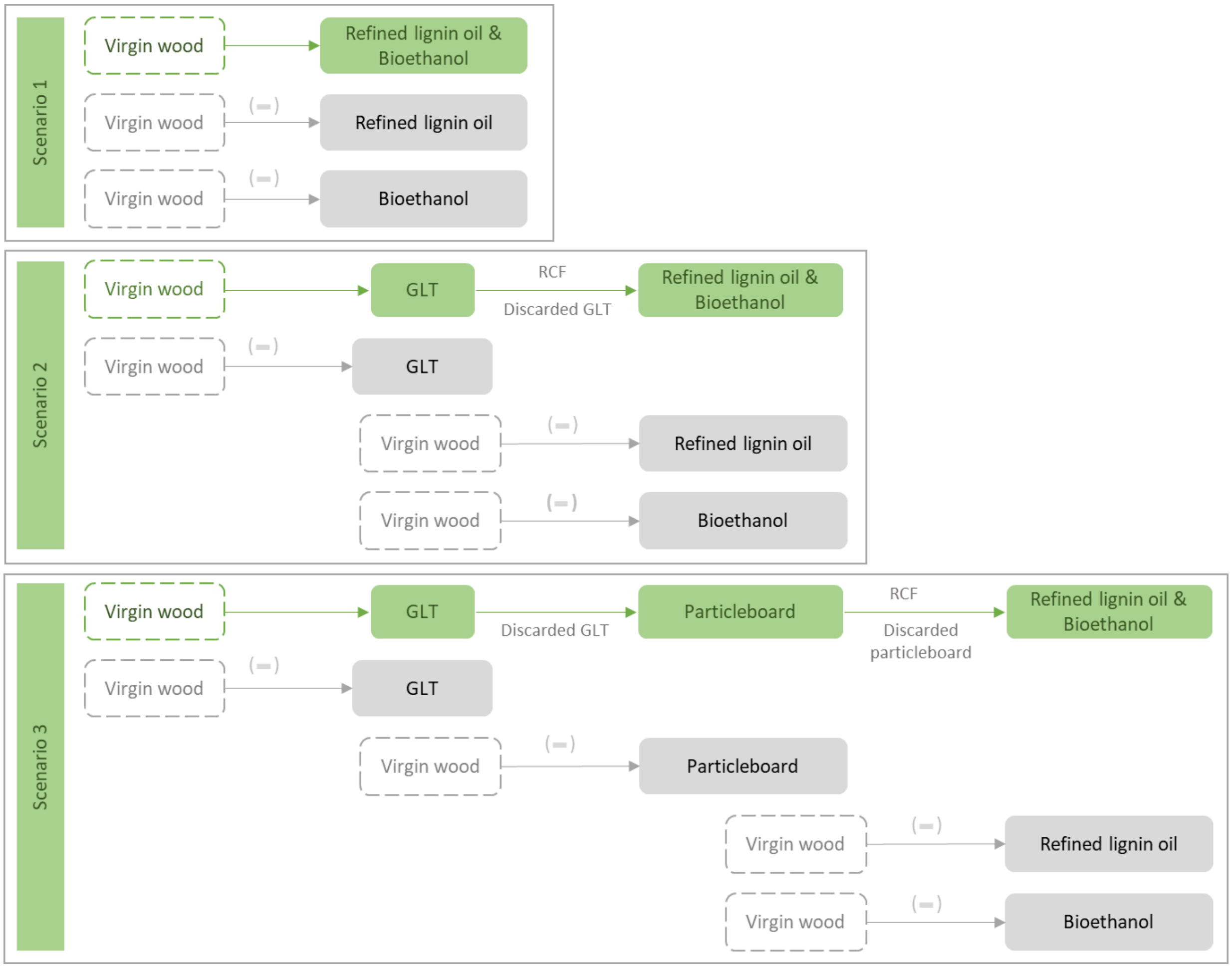


Figure 6.3: System boundary of alternative cascading scenarios

The green boxes represent the service life of wood in different products. The grey boxes represent the use of wood without cascading. The dotted lines show the primary resource for different products.

The study also analysed the case when wood supply from forests is not constrained. So, in the absence of wood cascading, all the products are made from virgin wood. The (simplified) system boundary of the cascading scenario is in Figure 6.3 and the detailed system boundary is available in Annexe D.1. The net GWP of each scenario is assessed based on the impact of producing wood products in cascading and the benefit of avoiding the production of equivalent material functions from virgin wood. This analysis contributes to understanding whether cascading of wood is beneficial even without considering substitution.

Sensitivity analysis

The data collected from scientific literature shows a high degree of variability. Annexe D (Table D.9) shows the values for the input parameter from different sources. To choose a particular data set for building LCI, a conservative approach was followed (Table D.1 lists the assumed values). The parameter values that result in the highest GWP are selected so that the results showcase the worse situation. The GWP will be lower than the LCA results of this study with any other data in the literature. Additionally, sensitivity analysis is performed to see the effect of change in input data on final LCA results.

Sensitivity analysis is performed on the two parameters for which literature provides the most diverse values - substitution rate and storage time. In addition to the variety in values for the lifetime of wood products (i.e. GLT, particleboard), refined lignin oil also has wide final material applications in diverse industries, further increasing the variability in lifetime values.

The uncertainty and variability in substitution rate and product lifetime could affect the LCA results. Hence, sensitivity analysis is carried out on these parameters to test the robustness of the LCA results to the variation in values. The value of each parameter is increased by 10% in a one-at-a-time approach – one parameter is varied while keeping all other parameters fixed at their baseline values. The sensitivity ratio is calculated (using Eq. 6.1) for each parameter to determine the degree of change in results with a variation in the parameter value.

$$Sensitivity\ ratio = \frac{\frac{\Delta results}{Initial\ results}}{\frac{\Delta parameter}{Initial\ parameter}} \qquad \textit{Equation 6.1}$$

6.3. Results and discussion

6.3.1. Global warming potential of the bio-refinery (scenario 1)

Figure 6.4 shows the net GWP for scenario 1 with different carbon accounting methods. GWP is positive when the system boundary is cradle-to-gate (method 1a) because the production of fossil-based fuel and chemicals (i.e. phenol, bisphenol-A and gasoline) have a lower GWP than the production of an equivalent amount of the bio-based products (i.e. refined lignin oil and bio-ethanol) in the bio-refineries. The difference is partly because biorefinery processes are immature and unoptimised compared to the high technology readiness level of the Hock and crude oil refining processes to produce phenol, bisphenol-A and gasoline. Biomass conversion technologies need monitoring and further innovation to lower their GWP, which remains a challenge today. So, substituting fossil-based fuel and chemicals with these biobased products could be regarded as environmentally detrimental with the current state-of-the-art technology.

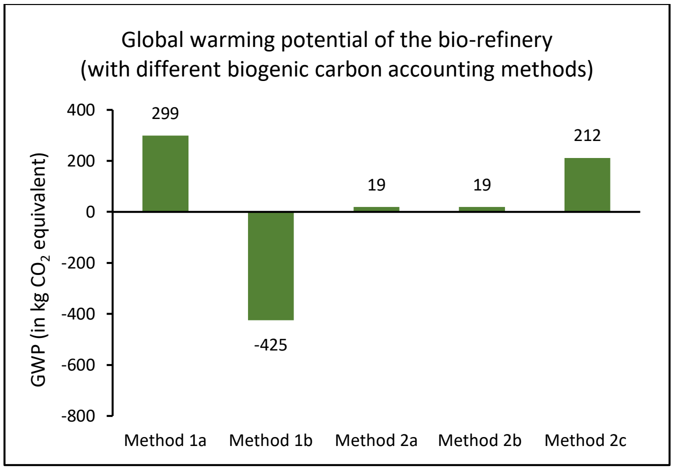


Figure 6.4: The GWP of scenario 1 with different accounting methods (all values rounded to the nearest integer)
***Method 1a**: Cradle to gate emissions (excluding biogenic carbon),*
***Method 1b**: Cradle to gate emissions (including biogenic carbon: -1/+1 accounting),*
***Method 2a:** Cradle to gate and embedded carbon emissions (excluding biogenic carbon: 0/0 accounting method),*
***Method 2b:** Cradle to gate and embedded carbon emissions (including biogenic carbon: -1/+1 accounting),*
***Method 2c:** Cradle to gate and embedded carbon emissions (including biogenic carbon: with CFs).*

However, when comparing bio-based chemicals and fuels with petrochemical ones with a ‘cradle to gate system boundary’, the bio-based alternatives must receive credit for embedded biogenic carbon - as demonstrated by Pawelzik et al. (2013) and prescribed by European Commission (2009). Since, at the end of life, petrochemicals emit CO_2 that increases the net atmospheric GHGs, while bio-based materials do not. They emit CO_2 already sequestered during plant regrowth (carbon neutrality assumption). Net GWP of scenario 1 becomes negative (method 1b) with this credit. The carbon embedded in the products for the functional unit is 816 kg CO_2 equivalent, resulting in the net GWP of -425 kg CO_2 equivalent (i.e., 299 – 816 = -517, the GWP is higher than -517 because of the biogenic carbon emission during the production processes – refer Fig. 6.5). The bio-based materials – refined lignin oil and bio-ethanol – are thus better than an equivalent amount of phenol and gasoline in terms of GWP. This result is in line with earlier studies which observe that bio-based products have a lower GWP than their fossil-based counterparts (Bartling et al., 2021; Liao et al., 2020). However, this assessment method is limited to the production processes and omits the potential impact of the carbon embedded in the products.

When considering the emissions of carbon embedded in the products, the net GWP of the system decreases from 299 to 19 kg CO_2 equivalent. The system receives credit for avoiding fossil-based carbon emissions (Fig. 6.4 & 6.5 method 2a). The inclusion of biogenic carbon content does not affect the results when the system boundary includes the end-of-life emissions (Fig. 6.4 & 6.5 method 2b). This accounting still ignores the rate of carbon sequestration and emission, which is accounted for in this study by multiplying the carbon embedded in bio-based products with the CF corresponding to the lifetime of those products, *viz.* 0.25 for bio-ethanol with a lifetime of 0 years and 0.17 for refined lignin oil with a lifetime of 10 years (method 2c). The net GWP increases to 212 kg CO_2 equivalent, suggesting that the carbon neutrality assumption (0/0 or -1/+1 approach) underestimates the GWP of short-lived products.

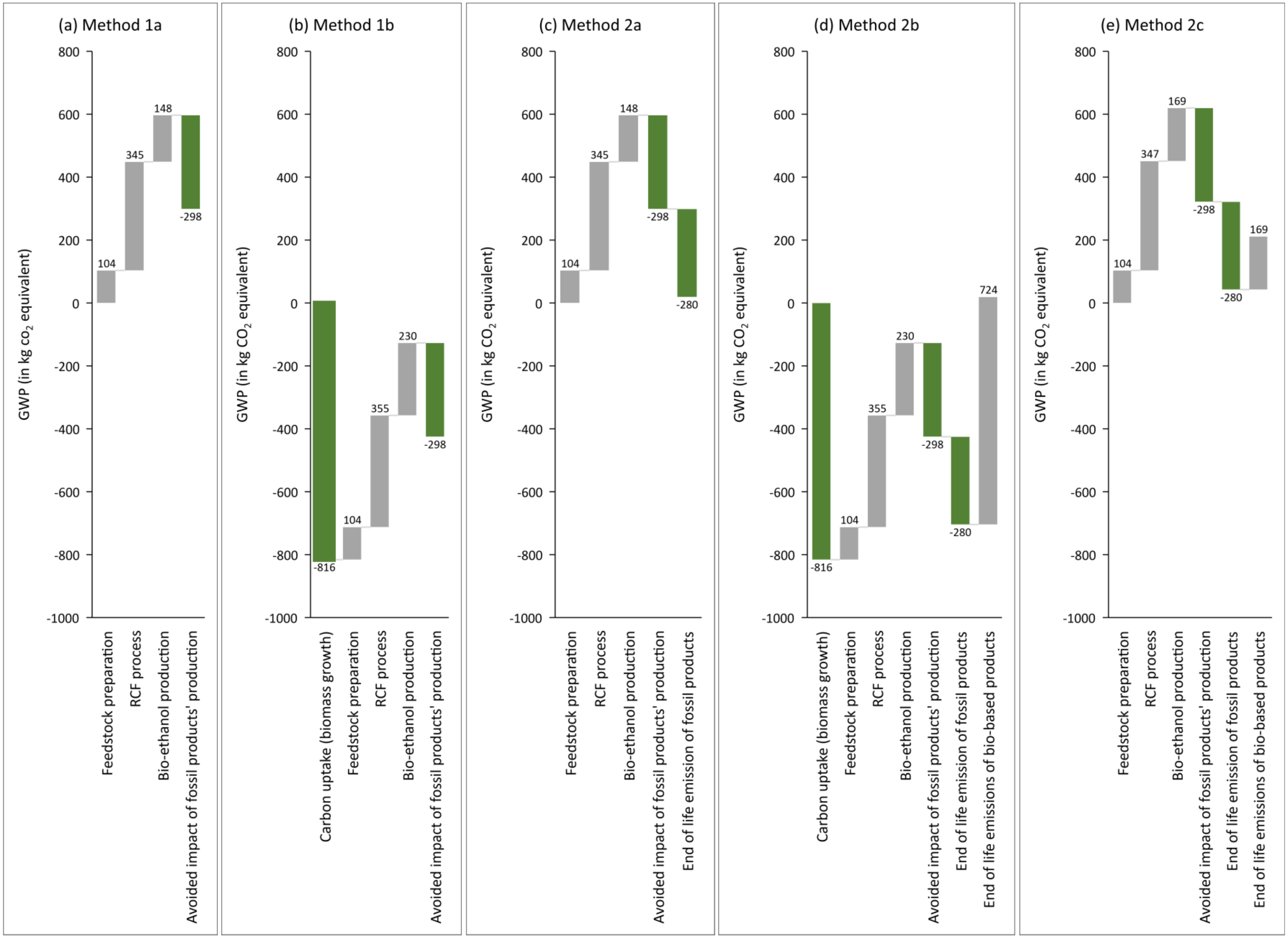


Figure 6.5: Waterfall diagram illustrating the contribution of individual processes to the overall GWP in different accounting methods (a) Method 1a: Cradle to gate emissions excl. biogenic carbon (b) Method 1b: Cradle to gate emissions incl. biogenic carbon: -1/+1 accounting (c) Method2a: Cradle to gate and embedded carbon emissions - 0/0 accounting (d) Method 2b: Cradle to gate and embedded carbon emissions - -1/+1 accounting (e) Method 2c: Cradle to gate and embedded carbon emissions with biogenic carbon CFs

6.3.2. Comparing GWP for the cascading scenarios

Figure 6.6 shows the net GWP for the different scenarios with the three accounting methods (1) cradle-to-gate process emissions – method 1a, (2) embedded carbon emission with carbon neutrality assumption – method 2a and (3) embedded carbon emission with CFs – method 2c. Method 2b is discarded from subsequent analysis because method 2a (0/0 approach) and 2b (-1/+1 approach) give the same results when the end-of-life emissions are included. The GWP is highest for scenario 1 and decreases with the increasing number of cascading steps. Annexe D.7 (Table D.10) provides detailed calculations, and Figure 6.7 illustrates the contribution of individual stages and processes to the net GWP for each scenario. Negative GWP for scenarios 2 and 3 in method 1a are primarily due to the savings from substituting the energy-intensive products (steel beams and gypsum fibreboard) with the wood-based products (GLT and particleboard). The residues (e.g. sawdust, wood chips) produced during GLT and particleboard production are burned for industrial heating, adding to climate benefit by avoiding the need for burning natural gas, which has a substantial GWP. These results align with other LCA studies that showed that wood-based products outperformed other functionally equivalent materials in terms of GWP (Sathre and Gustavsson, 2009). Wood use in cascading increases the availability of wood for other functional applications, thereby increasing opportunities to substitute more energy-intensive materials and adding to the substitution benefit.

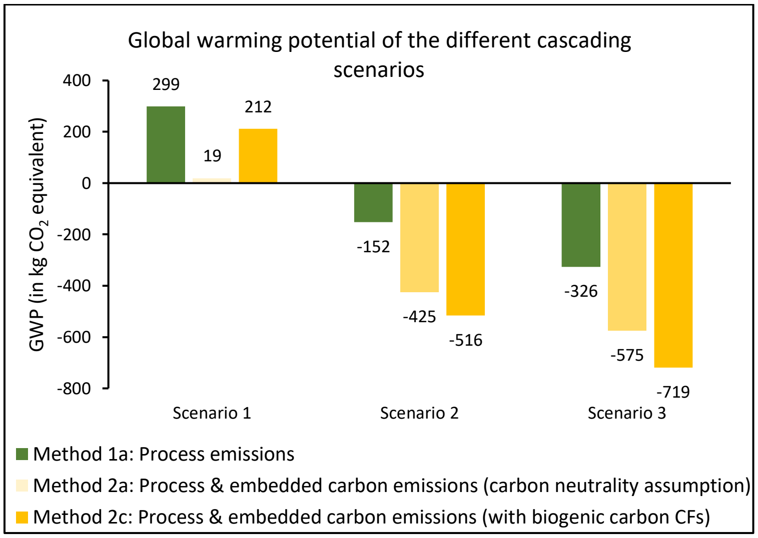


Figure 6.6: The GWP of the three cascading scenarios when wood substitutes non-wood material (all values rounded to the nearest integer)

The net GWP for the three scenarios decreases in method 2a because the systems avoid fossil carbon emissions embedded in substituted products (i.e. gasoline, phenol and bisphenol-A). In method 2c, the comparative results do not change, but the difference between the scenarios increases. The GWP of scenario 1 is higher when considering the CFs because of the short lifetime of the cascade. For scenario 2, the GWP decreases with a cascade lifetime of 60 years. In this scenario, wood is used first for construction material. Residues produced during GLT manufacturing are burned for industrial heating. The residues are climate-positive as they reach the end of their life already at year 0. But the wood contained in the construction material remains in the product for 50 years and is further used as feedstock for the RCF process, resulting in negative GWP. Scenario 3, with an additional 10-year lifetime extension, provides further CO_2 savings. The climate benefit of biogenic carbon storage increases with an increased lifetime of the cascade.

The results highlight that the current accounting of biogenic carbon (assuming carbon neutrality) underestimates the GWP for short-life cascades and overestimates it for long-life cascades. More importantly, in this study, the bio-based chemicals and fuel have a positive GWP when produced from fresh wood (scenario 1) and negative when produced from waste wood (scenarios 2 and 3) because of their respective service lifetimes. In other words, bio-based products from fresh wood of a long rotation period forests can only outperform their fossil-based counterparts in terms of GWP if their lifetimes are sufficiently long. So, virgin wood use is justified only for long-life chemicals and not for fuels or short-life chemicals such as single-use plastics. Furthermore, bio-based chemicals and fuels produced from waste wood (which has at least served a long life) are always better than those made from virgin wood and are likely to outperform their fossil-based counterparts. Therefore, considering the service life and rotation time is crucial for accurately evaluating the GWP of bio-based products.

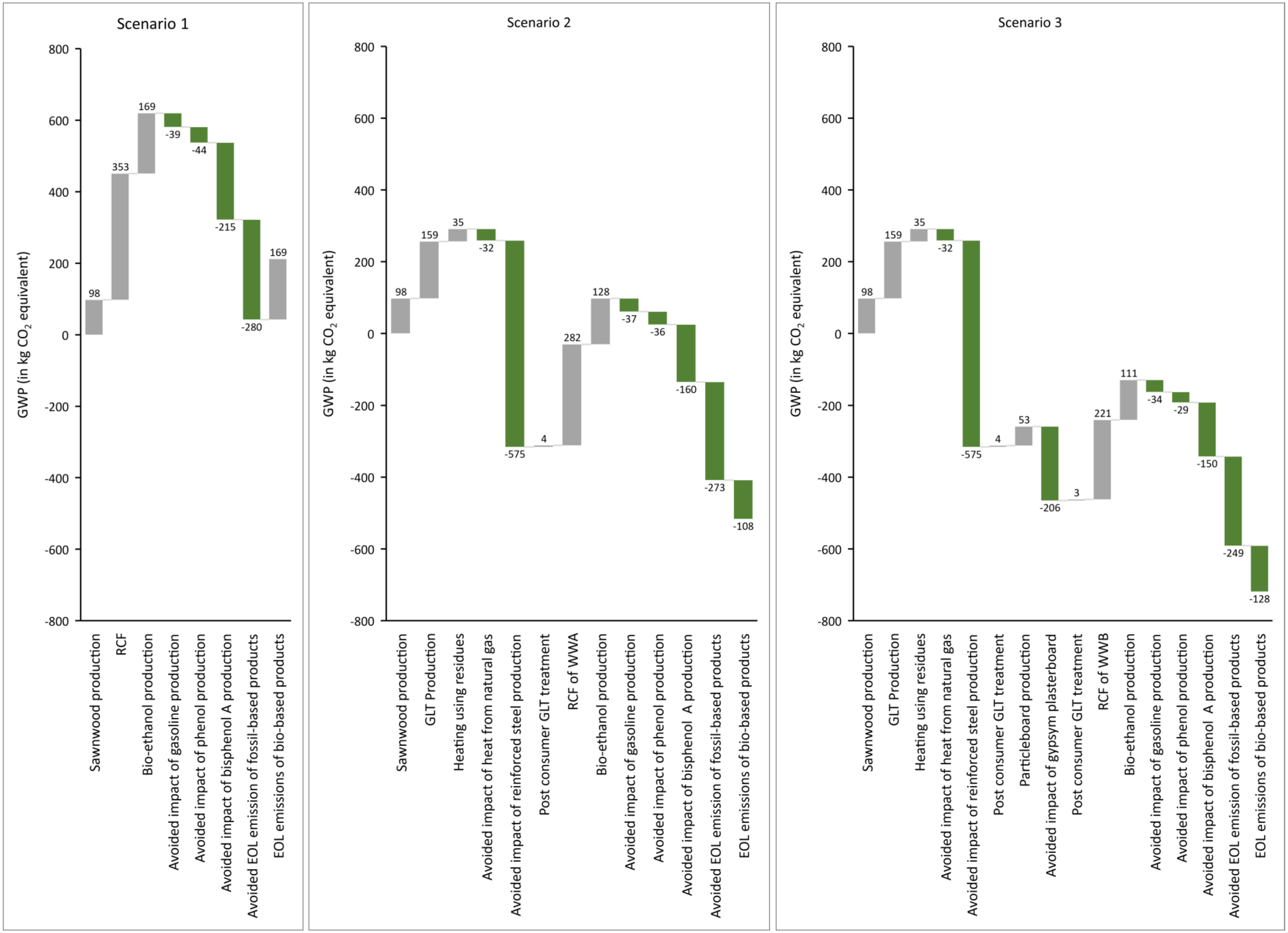


Figure 6.7: Waterfall diagram illustrating the contribution of each cascading stage and process to the overall GWP considering cradle to gate and embedded carbon emissions with biogenic carbon CFs (Method 2c)

6.3.3. Scenario analysis

Figure 6.8 shows the climate benefit when the waste wood substitutes virgin wood to provide the same material functions. The GWP of scenario 1 is zero because the wood is not cascaded in any case in the baseline scenario. For the other two scenarios, similar to the results when substituting non-wood products, scenario 3 has a lower GWP than scenario 2. Particleboard production from waste wood instead of fresh wood is the primary contributor to decreasing the net GWP. Waste wood is smaller in size and has lower moisture content than virgin wood, which lowers the energy required for chipping and drying processes in particleboard production. The GWP of RCF is comparable in the three scenarios. However, the absolute GWP value of the RCF process in scenario 3 is lower than in scenario 2 because the amount of wood available reduces the further downstream the process is in the cascading chain due to material losses in the intermediate stages. So, lower CO_2 is emitted in RCF in scenario 3 than in scenario 2 (refer to Annex D.8 for the GWP of individual stages and processes).

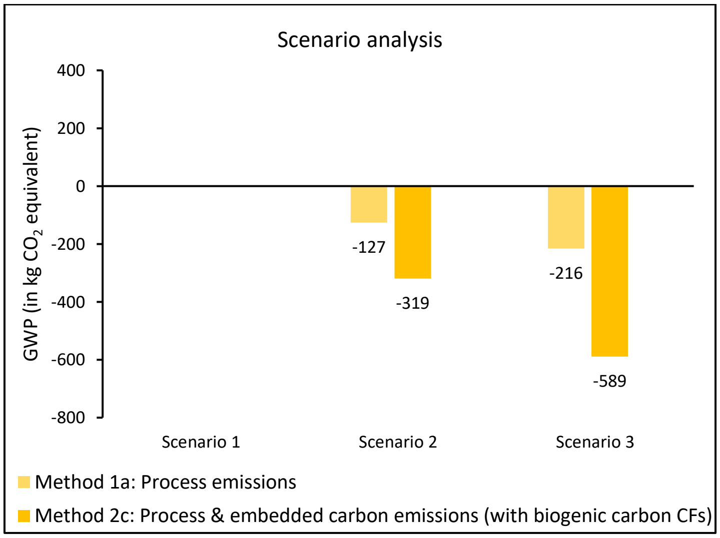


Figure 6.8: The GWP of the three cascading scenarios when waste wood substitutes fresh wood to provide the same functions (all values rounded to the nearest integer)

The results highlight that the substitution effect is more significant than the cascading effect, confirming the findings of Sathre and Gustavsson (2006). However, this analysis also demonstrates that cascading use could be beneficial by itself – even without substituting wood products for non-wood products, supporting the findings of Hoglmeier et al. (2014).

The contribution of carbon storage to net GWP is relatively much higher when waste wood substitutes virgin wood (Method 2c) – primarily because cascaded systems avoid multiple short-life cascade chains with a net positive climate impact. The effect is highest for scenario 3 because producing particleboard & RCF products from virgin wood is avoided, which has a net positive climate impact because of the short product lifetime. Cascading can thus accumulate climate benefits as the production of short-life products from virgin wood is avoided with each cascading step.

6.3.4. Sensitivity analysis

Sensitivity to the substitution rate

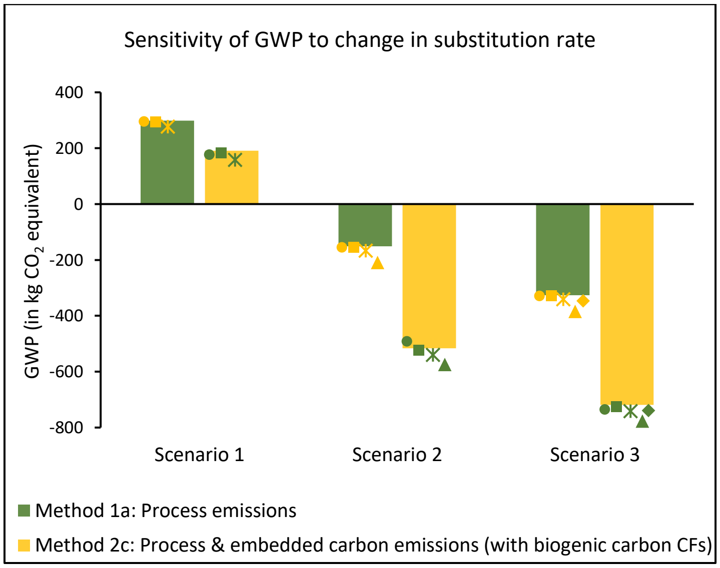


Figure 6.9: The change in the GWP of the three cascading scenarios with the increase in substitution rate by 10% (circle – bio-ethanol, square – monomer, star – oligomer, triangle – GLT and rhombus - particleboard)

The GWP for each scenario is recalculated after increasing the substitution rates of the products by 10% (Fig. 6.9). GWP decreases with an increase in the substitution rate. The overall comparative results and ranking of scenarios are not affected. The LCA model appears robust to the change in substitution rates of bio-ethanol, refined lignin oil monomer and particleboards as the difference in GWP is not significant. It increases by less than 1% (Annexe Table D.12). The results are sensitive only to the change in the substitution rate of GLT and refined lignin oil oligomer components, for which the sensitivity ratio is greater than 1%. Hence, the precise value of the substitution rate for these products should be known to accurately estimate the GWP for the different scenarios of the case study under consideration.

Sensitivity to the products' lifetime

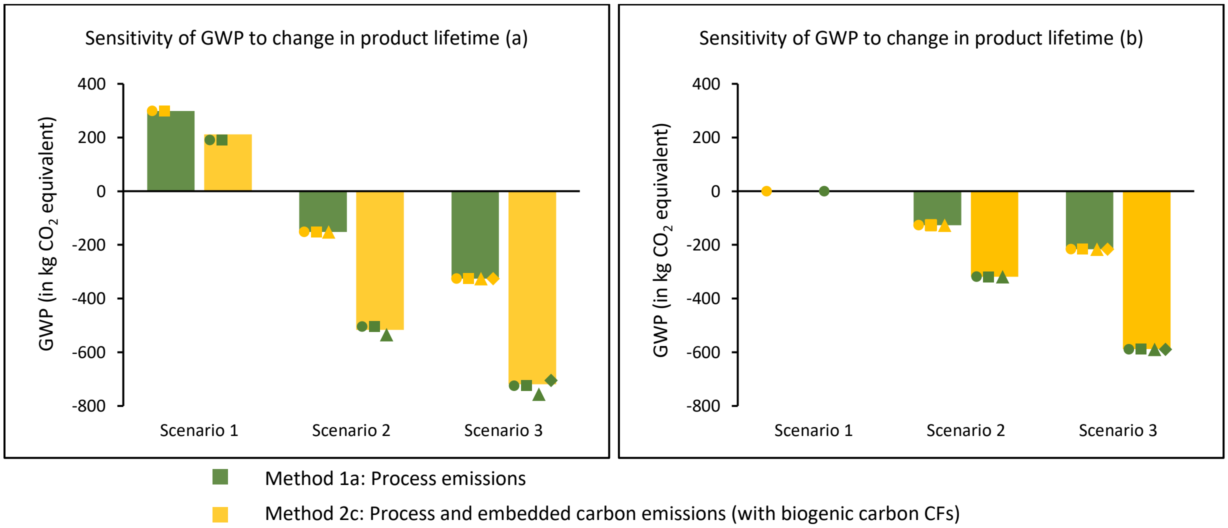


Figure 6.10: Change in GWP of the three cascading scenarios with an increase in the lifetime of products by 10% when *(a) wood substitutes non-wood products (b) wood substitutes wood products (circle – monomer, square – oligomer, triangle – GLT and rhombus - particleboard)*

Similar to the sensitivity analysis results for the substitution rate, the GWP (including the biogenic carbon) decreases with an increase in the product lifetime (Fig. 6.10). The overall comparative results and ranking of scenarios are unaffected. The LCA results appear robust as the difference in GWP is not significant in most cases, except in scenario 2 when wood products substitute non-wood products (Annexe D – Table D.13 &D.14 provides the sensitivity ratios).

6.4. Conclusion

The LCA results comparing different wood cascading scenarios confirm that cascaded use is advantageous - the GWP of the system decreases with an increasing number of cascading steps. When assessing the GWP excluding biogenic carbon, the climate benefits are primarily a result of substituting energy-intensive materials with wood. Wood cascading provides an opportunity to replace more non-wood products, every time adding to the substitution benefit. The analysis also affirms that cascading use is beneficial by itself even without considering the effect of substituting non-wood products – lowering the GWP when the material functions are provided by cascaded use of wood instead of from fresh (or virgin) wood. These results are more pronounced when including the temporal aspect of biogenic carbon, i.e. the time of biogenic carbon emissions and the rate of biogenic carbon uptake. This conclusion is valid in both cases – with and without considering the substitution effect. The study highlights that, although the ranking of scenarios remains the same, the climate impacts of cascading are underestimated without accounting for the temporal details of biogenic carbon flows. Hence, the GWP of bio-refinery products depends on the feedstock - fresh or waste wood. When comparing the bio-refinery products to their fossil-based counterparts, the total carbon storage time and the rotation period (of the forests from which the wood is sourced) could influence which of the two performs better in terms of GWP. It might always be better to use waste wood that has already served a long time instead of fresh wood to produce bio-based fuel or chemicals if the bio-refinery process efficiency is the same irrespective of the feedstock. Additionally, bio-refinery products for long lifetime applications rather than single-use or energetic purposes may enhance the environmental benefits.

The results highlight the importance of considering temporal information for an accurate evaluation of the climate impact of cascading. The quote at the beginning of the chapter, ‘Quit counting time’, might hold true for everything else in life, but definitely not for evaluating the GWP of cascading.

Chapter 7: Assessment of wood cascading using SEA and LCA

Abstract

The objective of this study is to apply the complete toolbox – the combined assessment of SEA and LCA – to a single case study comparing the material circularity and environmental impact of different cascade systems. The study uses and builds on the case study from chapter 4, i.e. wood-based pallets. In the preceding SEA, the functional unit of the system was 1000 kg of wood input (the factor constant across the different cascades), wherein the aim was to evaluate the change in material quality over time in cascading systems for a certain wood input to identify the one that maximises the material value extracted from the available resource. The underlying reasoning is that the cascade that maintains quality for longer maximises the material value. The different cascading systems, however, provide different material (or functional) values - multiple-use pallets have a higher load-carrying capacity and lifetime than single-use and cardboard pallets. The functional output of the different scenarios should be equivalent when assessing their environmental impact using LCA.

This study defines the functional unit based on input and output to have it identical for both SEA and LCA. The functional unit is an input of 1000 kg of wood input (as in Chapter 4) and an output of $2 * 10^7$ kg * km transport distance and 267 kg particleboard. The multiple-use and cardboard pallets require less wood to provide the same functional unit. The surplus wood is assumed to remain unutilised and thus available for other applications to further increase the total material value of the cascade. Results of SEA and LCA suggest that the multiple-use pallet system is better than the other systems. Of the other two, the solid-wood pallet system is better than the cardboard pallet system, even though the latter uses almost 10% less wood to provide the same functions. But the difference between the two is not that large when considering the temporal details of biogenic carbon flows and surplus wood within the system boundary. The results stress that performing dynamic LCA (considering temporal details of biogenic carbon flows) and consequential LCA (i.e. considering the consequence of a change of resource use on overall resource use dynamics) is essential for accurate evaluation of cascading.

7.1. Introduction

"All models are wrong, but some are useful"

George E. P. Box

Even though there is no agreement on the definition and implementation of wood cascading, a consensus is that it aims at reducing the need for primary resources and the associated pressure on the forests. Wood cascading strategies – such as using recovered wood or residues instead of virgin wood, enhancing product durability (or product lifetime), and increasing overall resource efficiency – reduce the wood required to provide a particular functionality. The surplus wood can then remain in the forest to sustain other ecosystem services or be harvested to deliver other material or energy applications.

However, most cascading studies do not include this surplus wood (made available by cascading) in their system boundary. The studies assessing the environmental impact determine the impact of using a certain amount of wood or providing a specific function. In the former case, the functional unit for comparing different cascading scenarios is a certain amount of wood input (as in Bais-Moleman et al. 2017, Faraca et al. 2019b, Sathre and Gustavsson, 2006). There is no consideration for the reduction in wood demand resulting from cascading. In the studies that assess the environmental impact of a specific function, the functional unit is the output (as in Rivela et al., 2006b). The different cascading scenarios might use different amounts of inputs in this case. Neither of these sets of studies takes into account the surplus wood within their system boundaries. The functional unit in the previous chapters (Chapters 4, 5 & 6) is also a fixed amount (1000 kg) of wood input to different scenarios.

It is essential to investigate the destination of this surplus wood as that completes the net resource use impact of a cascading system. The cascaded use might reduce the wood input. However, it may lead to an overall increase in the demand for that product, thus not decreasing the raw material input and the corresponding environmental impact (termed rebound effect; Zink and Geyer, 2017). This surplus wood might also be used for other material applications so far not on the market, which may also increase the overall demand for wood and the corresponding environmental impact of the strategies meant to be resource-saving. The excess biomass could also be used for applications currently produced from fossil- or mineral-based (or other bio-based) sources. It will, in that case, not decrease the net resource use but might reduce the overall environmental impact by substituting energy-intensive material.

Yet another reason for including the excess wood within the system boundary of cascading studies is to receive credit for the biogenic carbon embedded in this surplus wood. Bio-based products receive credit for the embedded carbon (due to carbon uptake during tree growth), as demonstrated in Chapter 6 Section 6.3.1 (Method 1b). However, the increase in resource efficiency indicates that a lower amount of wood (virgin or waste) is required to provide the same functionalities. The product (or the system) would receive lower credit as the product contains lesser embedded carbon. The system is thus dis-credited for efficiency increase. Hence, the system must receive credit also for the surplus wood.

This chapter's objective is to test the hypothesis that excluding the surplus wood – made available by cascading strategies – within the system boundary of the study underestimates the benefits of cascading. The study uses and builds on the case study from Chapter 4, i.e. wood-based pallets. That study compared three types of pallets – multiple-use pallets, single-use pallets and corrugated cardboard pallets. Multiple-use pallets are very robust and have a much higher carrying capacity (1500 kg) than single-use pallets that can transport only a maximum load of 400 kg. Also, multiple-use pallets have a longer life. They are used for around 23 trips, while single-use pallets last for only around five journeys. So, fewer multiple-use pallets are needed than single-use pallets to transport a certain load of products and thus require much less wood to provide the same function. Similarly, cardboard pallets also need less wood than single-use pallets for the same function because, although single-use pallets and cardboard pallets are functionally equivalent, cardboard pallets are much lighter than single-use pallets.

The analysis determines the amount of wood needed for the three types of pallets – the multiple-use, single-use and cardboard pallets – to provide the same service. The remaining wood is assumed to remain unutilised. This thesis chapter demonstrates the guiding principle for defining system boundaries and functional units for cascading systems and performs the combined assessment using SEA and LCA to evaluate the material circularity and environmental impact of the three wood cascading scenarios.

7.2. Case study description

7.2.1. Baseline scenario – single-use wood pallet

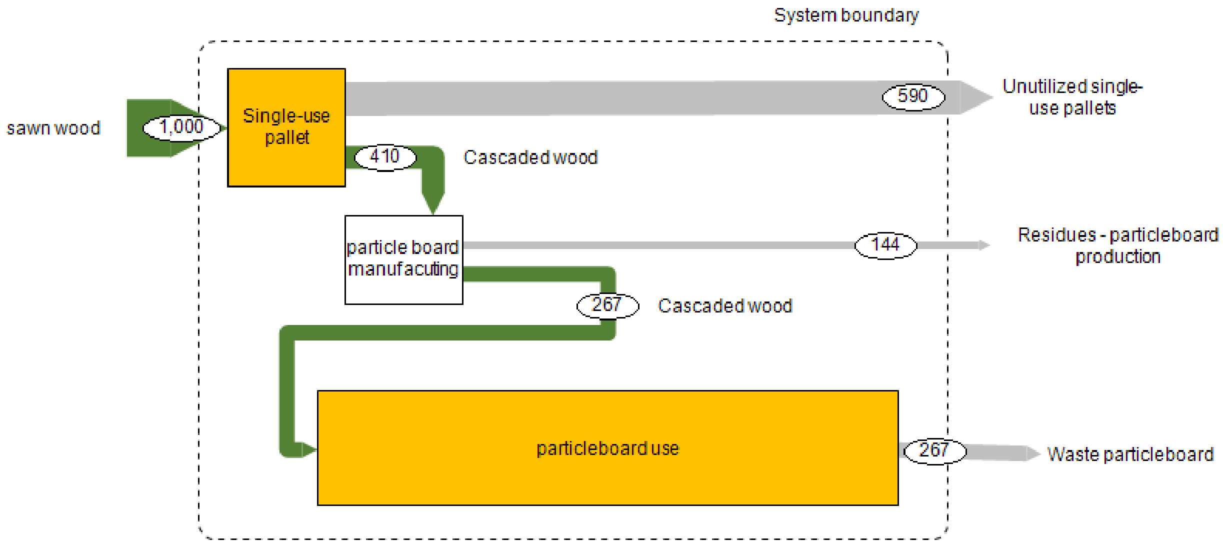


Figure 7.1: Material flow analysis for system using single-use pallet

All flows are shown in Sankey style, which means that the thickness of the arrows is proportional to the flow values. The flow values (shown as a number on the flow) indicate the amount of wood present in the product/flow.

Material flows for the single-use pallet cascading system (Fig. 7.1) are built with 1000 kg of wood (sawn wood) as input to the system. The functional value of the single-use pallet is determined based on the load carried by a pallet over a certain distance.

Although called 'single-use', these pallets are typically reused a few times before being discarded. They are thus also referred to as limited-use pallets. They are used on an average 5 times (Bengtsson and Logie, 2015; Gasol et al., 2008; Vis et al., 2014). A single-use pallet with a dimension of 1200 x 800 x 144 mm can carry a load up to about 400 kg (Kronus, 2022; Rotomshop, 2022). The service provided by a pallet would depend on the number of journeys and the distances involved. The data on the transport distances is not available and is assumed to be 150 km, as done by Deviatkin and Horttanainen (2020). Hence, the service provided by a single-use pallet is $3*10^5$ kg*km, and the total service provided by 1000 kg is $2*10^7$ kg*km assuming each pallet weighs 15 kg. Table 7.1 provides the calculation of the functional unit.

Table 7.1: Step-by-step calculation for determining the functional value provided by 1000 kg of wood using single-use pallets

Parameter	**Value/calculation**	**Reference**
Load bearing capacity of a single-use pallet	400 kg	(Kronus, 2022; Rotomshop, 2022).
Number of trips (per pallet)	5	Average of the values from the literature: 4.40 trips (Gasol et al., 2008) and 5.5 trips (Vis et al., 2014). The other value in literature, i.e. 2 trips (Bengtsson and Logie, 2015; Mazeika Bilbao, 2011), were not considered because they were not for Europe.
Distance per trip	150 km	Deviatkin and Horttanainen (2020).
Total functional value (per pallet)	**load bearing capacity * number of trips (per pallet) * distance per trip** **= 400 * 5 * 150 kg * km** **= $3 * 10^5$ kg * km**	
Weight of each pallet	15 kg	Average of the values of weight specified by Kronus (2022), Rotomshop (2022) and Vigidas Pack (2022)
Number of pallets (in 1000 kg wood)	= 1000/15 = 66.67	
Total functional value (provided by 1000 kg wood)	**= $3 * 10^5 * 66.67$** **= $2 * 10^7$ kg * km**	

Single-use pallets are cascaded into particleboards at the end of their service life (Vis et al., 2016, 2014). However, due to a complex supply chain, only 41% of wooden pallets are recovered and recycled in Europe (Eurostat, 2017). Cascading 1000 kg wooden single-use pallets produces particleboards with 267 kg wood (assuming 35% losses during particleboard production). Hence, the functionality provided by the system is $2 * 10^7$ kg * km transport distance and 267 kg particleboard, which is assumed to be the functional unit to compare different scenarios.

7.2.2.Multiple-use wood pallet

Material flows for the multiple-use pallet cascading system (Fig. 7.2) are built by first determining the amount of wood needed to provide the same function as the baseline system (i.e. single-use pallet cascade).

Multiple-use pallets are, comparatively, more robust. They have a higher load-bearing capacity and a longer service life but are heavier. These pallets are 25 kg (EPAL, 2018), support an average of about 23 journeys and last ten years (Deviatkin and Horttanainen, 2020; Gasol et al., 2008; Vis et al., 2014). Hence, the service provided by a single pallet is $51*10^5$ kg * km, assuming the distance travelled in each trip is 150 kg. So only 132 kg of wood is required to provide the functional value equivalent to that in the single-use pallet scenario (calculation provided in Table 7.2). The remaining wood is assumed to remain unutilised.

Table 7.2 Step-by-step calculation for determining the amount of wood needed for multiple-use pallets to provide the equivalent functional value

Parameter	**Value/calculation**	**Reference**
Load bearing capacity of a single-use pallet	1500 kg	
Number of trips (per pallet)	22.5	The average of the different values specified in the literature: 20 trips (Deviatkin and Horttanainen, 2020), 30 trips (Gasol et al., 2008), 15 trips (Kočí, 2019) and 25 trips (Vis et al., 2014).
Distance per trip	150 km	The distances might be different for different pallet types. However, for the lack of data, the same distances are assumed.
Total functional value (per pallet)	**load bearing capacity * number of trips (per pallet) * distance per trip** **= 1500 * 22.5 * 150 kg * km** **= $50.63 * 10^5$ kg * km**	
Number of pallets required to provide functional value equivalent to single-use pallets (i.e. $2 * 10^7$ kg * km)	**= $2 * 10^7 / 51.75 * 10^5$** **= 3.95**	
Weight of each pallet	25 kg	EPAL (2018)
Amount of wood required to produce 3.86 pallets	= 3.95 * 25 kg = 98.75 kg	
Percentage of total wood used for repair	25%	Gasol et al. (2008)
Additional wood required for repair	= 98.75 * 0.25 / 0.75	

	= 33 kg	
Total sawn wood required to provide equivalent functional value	**= 98.75 + 32.92 kg** **= 132 kg**	
Surplus wood	**= 1000 – 132 kg** **= 868**	

Multiple-use pallets are cascaded also into particleboards at the end of their life (Vis et al., 2016, 2014). The data on recovery and recycling rates did not distinguish between single-use and multiple-use pallets. Hence, the recycling rate for wooden pallets is assumed to be the same for both single-use and multiple-use pallets (i.e. 41%). The remaining 59% is either not recovered or is landfilled or incinerated (Vis et al., 2016). Cascading 54 kg of multiple-use pallets produces only 35 kg of particleboards. However, to satisfy the demand of 267 kg particleboard, which is the functional unit, the deficit (232 kg) is assumed to be provided using virgin sawn wood. Despite the additional 356 kg of fresh wood used to produce the particleboard, 512 kg of sawn wood remains unused in this scenario.

In summary, 132 kg of wood is used to produce multiple-use pallets that provide the functional value of 2 * 10^7 kg * km transport distance and are cascaded to produce 35 kg particleboards. Additionally, 356 kg of fresh wood is used to produce 232 kg of particleboards, and 512 kg of wood remains unused.

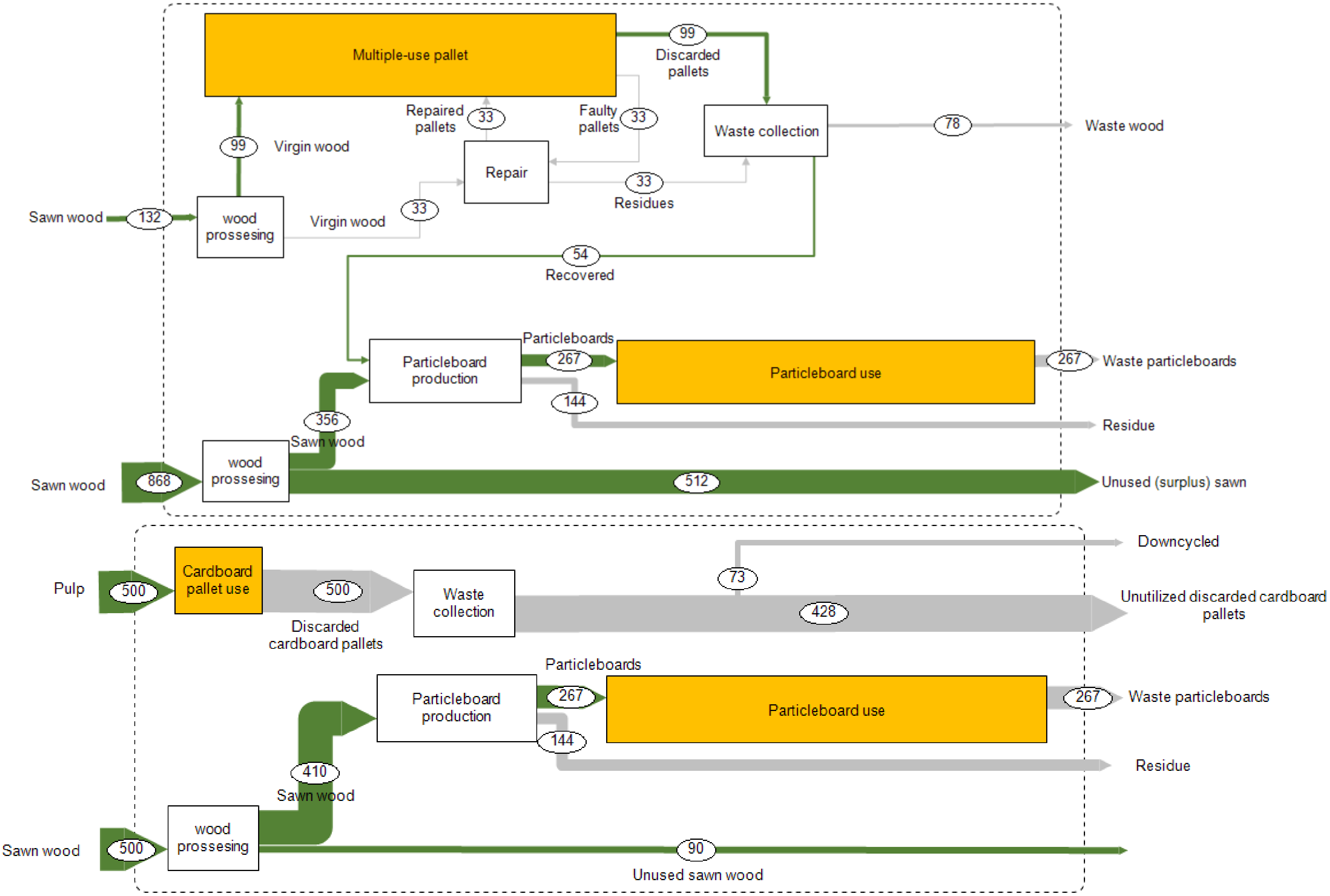


Figure 7.2: Material flow analysis for different wood cascading system

Top (a) Multiple-use pallets, Bottom (b) cardboard pallets. All flows are shown in Sankey style, which means that the thickness of the arrows is proportional to the flow values. The flow values (shown as a number on the flow) indicate the amount of wood present in the product/flow

7.2.3. Cardboard pallets

Similarly, material flows for the cardboard pallet cascading system (Fig. 7.2b) are built by first determining the amount of wood needed to provide the same function as the baseline system (i.e. single-use pallet cascade).

Cardboard pallets can transport up to 1200 kg load. But are used only once. So single-use pallets and cardboard pallets have (approximately) the same functional value. However, cardboard pallets are much lighter than single-use pallets. Thus, cardboard pallets require much lesser wood to provide equivalent functional output. It needs only 500 kg wood to deliver the functional value same as 1000 kg single-use pallets (calculation provided in Table 7.3). However, at the end of their service, cardboard pallets cannot be cascaded into particleboards as in the single-use pallets scenario. So, the 267 kg particleboard is assumed to be produced using virgin wood. Despite that, 90 kg of virgin wood stays unused in this scenario.

Table 7.3: Step-by-step calculation for determining the amount of wood needed for cardboard pallets to provide the equivalent functional value

Parameter	**Value/calculation**	**Reference**
Load bearing capacity of a single-use pallet	1200 kg	Pallet Centrale (2022c)
Number of trips (per pallet)	1	KraftPal Technologies Ltd., (2020)
Distance per trip	150 km	The distances might be different for different pallet types. However, with the lack of data, the same distances are assumed.
Total functional value (per pallet)	**load bearing capacity * number of trips (per pallet) * distance per trip** **= 1200 * 1 * 150 kg * km** **= $1.8 * 10^5$ kg * km**	
Number of pallets required to provide functional value equivalent to single-use pallets (i.e. $2 * 10^7$ kg * km)	**= $2 * 10^7$ / $1.8 * 10^5$** **= 111**	
Weight of each pallet	4.5 kg	KraftPal Technologies Ltd., (2020)
Amount of wood required to produce 3.86 pallets	= 111 * 4.5 kg = 500 kg	

7.3. Material and method

7.3.1. Statistical entropy analysis

The objective of this analysis is to evaluate the statistical entropy trend in the alternative material use cascades, which provide the same functionality with the same material input. SEA was performed for the evaluations of statistical entropy based on the material composition and physical characteristics. Using the MFA, RSE was calculated per year based on the stock of products and waste flows produced that year. The RSE change over time is aggregated into a single score to ease comparing different scenarios (using the rationale presented in Chapter 4). This analysis would identify from among the different cascading systems – that provide the same set of functionalities with available resources – which material pathway maximally maintains the material value for the longest duration and is thus the most desirable cascade from a CE perspective.

7.3.2. Life cycle assessment

The objective is to assess the GWP of alternative cascading systems providing product delivery services using different wood-based pallet types. The functional unit for the system is **delivery of 2 * 10^4 t*km transport distance with pallets and 267 kg particleboard from 1000 kg of wood** harvested from the softwood forest. The time horizon considered for the assessment is 100 years. The system boundary of the cascading systems is cradle to use, including the production and use of multiple applications in cascading. The single-use pallet cascade system includes pallets production from sawn wood and their use for transporting goods. The pallet's weight affects the energy required for transporting. So, the use phase of the pallets is included within the system boundary. The system boundary extends to cascading pallets to particleboards (i.e. waste collection, treatment and particleboard production). The system boundary of the multiple-use pallet scenario includes the pallet production, the use phase (repair and transport) and cascading them to particleboards (including waste collection, treatment and particleboard production). In this scenario, a part of the particleboards is made from fresh wood, which is within its system boundary. The system boundary of the cardboard pallet scenario contains only the pallet production as there is no cascaded use. However, the system also includes particleboard production from fresh wood. The system boundary for the latter two cascade systems includes also surplus wood.

The data for modelling the life cycle inventory (LCI) was collected from scientific literature and modelled with the help of the background process available in the Ecoinvent Database (version 3.7.1) and the GaBi software (Professional version 10.6). The LCI of solid-wood pallets was available in Gasol et al. (2008), and the cardboard pallet was available in KraftPal Technologies Ltd. (2020). The LCI of particleboard production (from virgin and waste wood) was based on the inventory data from Kim and Song (2014). The inventory used for modelling the solid-wood pallet and particleboard production is in Annexe E (Table E.1 – E.3).

The environmental impact is examined using the global warming potential (GWP) midpoint indicators from the ReCiPe 2016 (Hierarchist). GWP is estimated by excluding and including the biogenic carbon. The assessment without the inclusion of embedded biogenic carbon is to determine the impact of the production processes themselves. The inclusion is to assess the contribution of embedded carbon and the benefit of carbon stored in cascading. The GWP of embedded biogenic carbon is calculated with both biogenic carbon accounting methods - the traditional accounting method (-1/+1 approach) and the explicit consideration of the period for carbon uptake in forests and carbon storage in cascading (using characterisation factors like in Chapter 6). This carbon storage period is identified only with the time when the life of the wood comes to an end. The system boundary of this study does not include the end-of-life (disposal to landfill or waste incineration) of the last functional product in the cascade. Like in Chapter 6, the assumption is that all the biogenic carbon embedded in the products is emitted as CO_2 instantly at the end of the cascade lifespan. However, no emissions are associated with the portion of the wood that remains unused in the two cascading systems. The study assumes no emissions within the time horizon considered for the used wood. In other words, the characterisation factor for the biogenic carbon that remains embedded in wood is -1. The rate of carbon uptake is included by considering the forest rotation period. The rotation period is the time required for the forests to regrow and capture the same amount of CO_2 as that harvested from the forest. Pallets and cellulosic pulp are made mainly of pine wood. So the rotation period of European softwood forestry (60 years) is considered for the study.

7.4. Results and discussion

7.4.1. Statistical entropy analysis

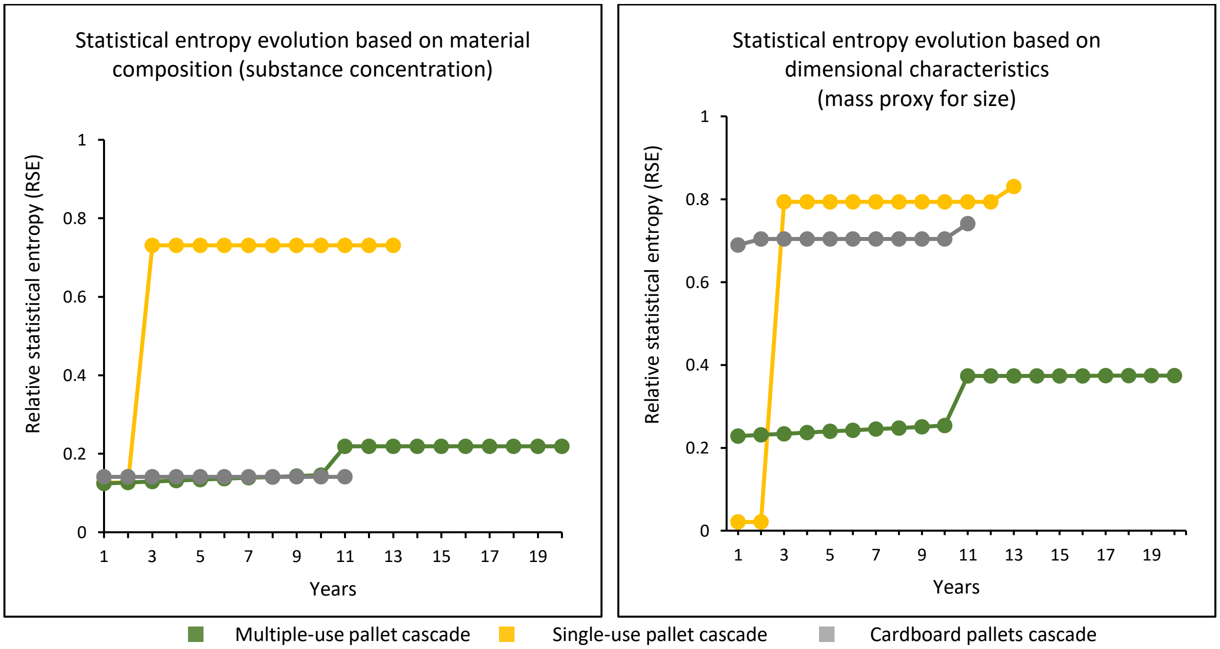


Figure 7.3: Evolution of relative statistical entropy comparing different systems providing an equivalent function using three types of product systems

Left (a) Statistical entropy definition based on material composition (considering the share contaminants), Right (b) Statistical entropy definition based on dimensional properties (mass as a measure of size).

For RSE calculated based on the material composition (Fig. 7.3a), the statistical entropy is highest for the cardboard pallets cascade system. The cardboard pallets themselves have low statistical entropy (RSE = 0) as they are made of pure cellulosic pulp. However, RSE is high because of particleboards produced from virgin wood. RSE remains constant throughout the life cycle as there is no cascaded use in this system. RSE is lowest for the single-use pallet for the first life of the wood. It increases over time because of the unutilised post-consumer pallets (with RSE = 1) and wood cascaded to particleboards. RSE for the multiple-use pallet scenario is higher than that of the single-use pallet scenario in the initial year. The statistical entropy based on material composition is lower for multiple-use pallets than single-use pallets, as seen in Chapter 4, because of the relatively lower concentration of contaminants in multiple-use pallets. RSE in the multiple-use pallet scenario (Fig. 7.3a) for the initial years is higher because of particleboards from virgin wood. The increase at the later stage is lower (than in the single-use pallet cascade) because a lower portion of particleboards is produced. Also, a lower number of pallets in this cascade means less unutilised post-consumer pallets (with RSE = 1).

RSE calculated based on the mass shows a similar trend (Fig. 7.3b), although the absolute difference between the three cascades is higher. The statistical entropy is highest for the cardboard pallets, the result of degrading wood structure to cellulose fibre (for cardboard production) and wood chips and particles(particleboard production). RSE is lowest for the single-use pallet for the first life of the wood. The factor contributing to the increase is the same as in the previous assessment (Fig. 7.3a). RSE for the multiple-use pallet scenario is higher than that of the single-use pallet scenario in the initial year. The statistical entropy of multiple-use pallets based on size is lower than that of single-use pallets because the boards are heavier in the multiple-use pallets than in single-use pallets. RSE for the initial years in the multiple-use pallet scenario (Fig. 7.3a) is due to high-entropy particleboards.

The single score (Table 7.4), based on the area above the RSE evolution curve, indicates that the multiple-use pallets are the optimal resource use of wood and are a preferable choice. For the remaining two types of products, the results differ for the two definitions of statistical entropy. However, for wood products, the dimensional characteristics impact to a greater extent their utility and recyclability. Hence, the study focuses on the statistical entropy definition based on dimensional properties. Although cardboard pallets need less wood to provide the same functionality, they are less resource effective. When a consumer seeks pallets for single (or limited) re-use, wood pallets are preferable over cardboard. However, this conclusion holds when (at least 41% of) pallets are cascaded to particleboards. The benefits are, furthermore, higher when higher fractions of pallets are recovered and cascaded and are cascaded to applications with statistical entropy lower than that of particleboards.

Table 7.4: Single score for SEA for different pallet types and management strategies
The green indicating the best-case scenario with the highest value and red indicating worst-case scenario with the lowest value for the area above the curve

	Statistical entropy based	
Scenarios	**Material composition (contamination)**	**Dimensional properties (size/mass)**
Multiple-use pallet scenario	**16.57**	**14.04**
Single-use pallet scenario	**5.07**	4.60
Cardboard pallet scenario	9.52	**3.60**

7.4.2. Life cycle assessment

Figure 7.4 shows the net GWP for the three wood cascade systems with the different biogenic carbon accounting methods and with and without including the surplus wood in the system boundary. The multiple-use pallet cascade system has the least GWP and, among the remaining two, the single-use pallet cascade is better than the cardboard pallet cascade. This comparative result stays the same. But the difference between cascade systems varies for all the accounting methods and system boundary considerations.

When excluding the biogenic carbon, the multiple-use pallet system has the least GWP (212 kg CO2 equivalent) mainly because a lower amount of resources (material and energy) are required to provide the same function. Between the other two, the GWP of solid-wood pallets cascade is less than cardboard pallets cascade, mainly because high energy demanded by cardboard pallet production. The secondary reason (although having a marginal contribution) is the production of particleboards from virgin wood in the cardboard pallet scenario, which has a higher GWP than producing them from recovered wood in the single-use pallet scenario. This factor also increases the GWP of multiple-use pallets system wherein the substantial number of particleboards produced are from fresh wood, but does not compensate for the substantially lower GWP of multiple-use pallets production.

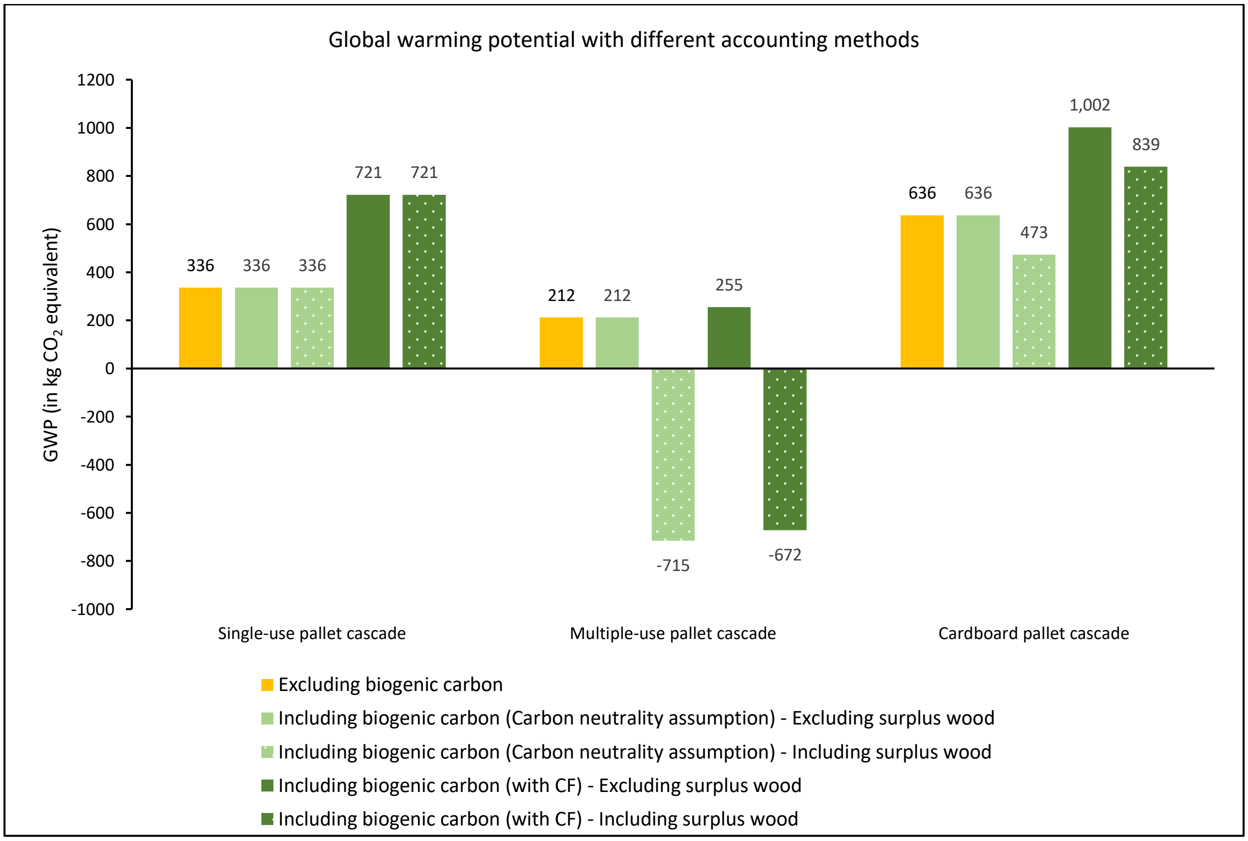


Figure 7.4: The GWP of the two pallet scenarios with different accounting methods (values rounded to the nearest integer)

When including the contribution of embedded carbon, the comparative result remains the same. However, the difference between multiple-use pallets and the other two systems increases, while the difference between the single-use and cardboard pallet systems decreases. With the carbon neutrality assumption (-1/+1 approach), the GWP is the same with and without including the biogenic carbon. The carbon, sequestered during the tree growth (CF = -1), is emitted at the end of the cascade (CF = -1). However, when considering surplus wood, the GWP decreases for the multiple-use and cardboard pallet systems because a certain amount of carbon remains embedded in (surplus) biomass (CF = -1) and is not emitted within the considered time horizon.

When considering the temporal aspect of biogenic carbon flows, the GWP increases because of the short lifetime of these cascades (Refer to the CFs in Chapter 6 Table 6.2) relative to the long rotation of the forests (60 years). For the single-use pallet system, the GWP increases 385 kg CO_2 eq. (from 336 to 721 kg CO_2 eq.). The system has a 1000 kg wood input, which accounts for approximately 1800 kg biogenic CO_2 (assuming 0.494% carbon content in wood), resulting in a GWP of 385 kg CO_2 eq. (with CF corresponding to cascade lifetime = 12 years).

GWP increase is lower in the cardboard pallet cascade than in the single-use pallet system despite the shorter cascade life. It increases by only 366 kg CO_2 eq. (from 636 to 1002 kg CO2 eq.) because lesser wood is used in the system. It uses only 500 kg wood (accounting for approx. 900 kg biogenic CO_2) for cardboard and 410 kg wood (accounting for approx. 743 kg biogenic CO_2) for particleboards. The GWP of 910 kg wood is 366 kg CO_2 eq. (with a cascade lifetime of 1 year for cardboard pallets and 10 years for particleboard). GWP increase is the least in the multiple-use pallet (an increase of only 43 kg CO_2 eq.) because of comparatively longer service life and lower amount of wood input to the system. When the surplus wood is included within the system boundary, the net GWP lowers for the multiple-use and cardboard pallet because the carbon embedded in surplus wood is not emitted within the considered time horizon (CF = -1).

Table 7.5: Difference between GWP of single-use pallet system and that of cardboard system in different accounting methods and system boundary consideration

Accounting method	**Difference in GWP (kg CO_2 eq.)**
Excluding biogenic carbon	300
Including biogenic carbon (Carbon neutrality assumption) – Excluding surplus wood	300
Including biogenic carbon (Carbon neutrality assumption) – Including surplus wood	137
Including biogenic carbon (with CF) – Excluding surplus wood	281
Including biogenic carbon (with CF) – Including surplus wood	118

In summary, the multiple-use pallet system is better than the other systems. Of the other two, the solid-wood pallet system is better than the cardboard pallet system, even though the latter uses almost 10% less wood to provide the same functions. However – importantly – the difference between the two is not that large when considering the temporal details of biogenic carbon flows and surplus wood within the system boundary. It supports the conclusion of Chapter 6 that the traditional biogenic carbon accounting methods underestimate the impact of short-life cascades such as these. Secondly, the results stress the need to redefine the system boundary of cascading systems. When observing the difference between single-use pallet and cardboard pallet systems (Table 7.5), the GWP of cardboard pallets is overestimated with the carbon neutrality accounting and not considering the 90kg surplus wood. The same is the case for multiple-use pallet systems.

7.5. Conclusion

The analysis compares the three wood-pallet cascading systems – multiple-use pallets, single-use pallets and cardboard pallets. The study evaluates which of the three cascading systems, with 1000 kg of wood input and providing functions, achieve the highest material circularity and lowest carbon balance. The functional unit for the systems is to deliver $2 * 10^4$ t*km transport distance with pallets and 267 kg particleboard from 1000 kg of wood harvested from the softwood forest. The multiple-use pallets cascading system is clearly the most optimal system – it maintains the material functionality for the longest and has a significant amount of surplus wood available for other uses. It also has the lowest GWP. Of the other two systems, the single-use pallet cascading system performs better than the cardboard pallet cascading system in terms of material value, despite requiring more wood for the same function. The GWP of the former is also lower. So, single-use pallets should be preferred over cardboard pallets.

Moreover, the LCA results highlight the importance of including the surplus wood within the system boundary, without which the system that needs less wood to provide the same function receives lower credit for biogenic carbon. Thus the current definition of the system boundary, excluding the surplus wood, discredits cascading systems for reducing the need for primary resources (or increasing resource efficiency). That can also be corrected by performing consequential LCA, i.e. considering the consequence of a change of resource use on overall resource use dynamics. The result provides a basis for defining system boundaries and functional units for cascading systems. The functional unit should specify both the resource input and functional output of the system, without which the carbon balance might be overestimated - like for multiple-use and cardboard pallet cascade systems in this study.

Chapter 8: Conclusion

> *"As I look back over my efforts, I would characterise my contributions as being largely in the realm of model building. … I perceive myself as rather uninhibited, with a certain mathematical facility and more interest in the broad aspect of a problem than the delicate nuances. I am more interested in discovering what is over the next rise than in assiduously cultivating the beautiful garden close at hand"*
>
> ***Henry Eyring***

8.1. General conclusions

Biological cycles are not necessarily circular in reality. Biotic resource use could be even environmentally detrimental and must be evaluated critically to ensure it is circular and sustainable. The circularity in the biological cycles is defined by sustainable harvesting of resources, their cascaded use, and safely returning them to the environment without affecting the ecosystem functioning, often as crucial nutrients that support ecosystem regeneration. CE principles describe circularity for biological cycles but do not adequately monitor them. CE monitors must, additionally, evaluate that the sourcing of biotic resources does not affect the functioning of the ecosystems and that closing the nutrient loop does not harm the environment and fosters ecosystem regeneration. The CE monitors must also be apt to assess cascading, i.e. determine the extent to which a cascading pathway maintains material value (i.e. quality or utility).

Biotic resource use is optimised by cascading, especially for wood, through sequential use – best utilising the remaining resource quality. The objective is to maximise material value (or utility) from available resources to reduce the primary resources needed to provide for societal needs, reducing the pressure on the ecosystems and supporting the goal of sustainable sourcing. It also makes biomass available for other applications. Since material quality (i.e. intrinsic material properties) provides the necessary utility, cascading aims at maintaining material quality through multiple applications for as long as possible. Using it for applications currently derived from energy-intensive (fossil- or mineral-based) materials could have a net climate benefit. Keeping the material value for longer (i.e. increasing cascade lifespan) also delays the emissions of carbon embedded in the products, occurring when the wood eventually decomposes or is incinerated. In a way, supporting the safe closure of the biological nutrient cycle by slowing the release of CO_2 (and other nutrients) to the environment and ensuring it does not disrupt the nutrient balance and ecosystem functioning.

Circularity monitoring must evaluate the degree to which a cascading pathway preserves material quality. For that, it must assess the material quality over time of different cascading systems to identify the one that retains the material quality for the longest time. Quality for wood is characterised by the dimensional properties of the wooden components (such as size or volume) and their purity (i.e. the presence of physical and chemical contaminants). Wood components refer to individual wooden pieces assembled to form the final product – a plank in the case of a pallet or wood chip for particleboards. The cascading strategies preserve the size of the wood and avoid contaminants as far as possible to keep the possibilities open for its cascaded use. Hence, the cascading assessment must quantify the quality of wood flows based on the size of the wooden components and the share of contaminants and evaluate it over time (across multiple applications) and across parallel streams (fresh wood, residues and post-consumer wood) to identify the optimal cascaded application for each stream. Other physical properties, such as wood type, density and species, also affect the wood quality. However, these features do not change over time and are thus less relevant when assessing the cascaded use, which is to observe the quality change in the available wood resource during use.

Existing cascading assessments primarily focus on resource use efficiency and environmental impact but lack quantitatively assessing wood quality and lifetime. SEA, a generic method that gives a measure of variance in a distribution function, has been proven beneficial for evaluating the quality of material flows by quantifying the substance distribution in the materials (i.e. constituent substances and their relative concentration). It can thus evaluate the quality of wooden components based on contaminant concentration. This PhD research proposed an adaptation to the state-of-the-art SEA to evaluate the dimensional characteristics of the wooden components. It defined statistical entropy based on the size distribution, which presented meaningful results. A beam used in the high material-value application has low statistical entropy (with narrow size distribution), and statistical entropy increases as the beam breaks into smaller pieces (and size distribution widens). It proves that SEA can quantify material quality also based on aspects besides material composition. This analysis demonstrates that SEA can aggregate the quality of multiple (parallel) flows into a single statistical entropy value. When applied over time, it shows the evolution of statistical entropy representing the change in material value with time. SEA applied to different cascading systems allows a comparison of the change in material value with time for those systems and identifies the pathway with the slowest degradation in material value (represented by the slowest increase in statistical entropy).

SEA measures the material circularity of wood cascading, i.e. quantifies material quality over time and identifies the optimal resource-use pathway that maximally preserves it. The next step is to optimise and improve the resource use of that pathway. LCA guides efficiency improvement (i.e. by reducing the overall resources required) and environmental impact reduction. However, traditional LCA does not consider the cascade lifespan. This PhD research shows that including temporal information (with dynamic LCA) is essential, without which the long-life cascades do not receive credit for delaying emissions. In addition, wood substituting energy-intensive (fossil- and mineral-based) materials contribute to climate benefits. LCA (via scenario analysis) can guide choosing an application from alternatives (if there are any) that would maximise substitution benefits. Lastly, consequential LCA, i.e. considering the consequence of a change of resource use on overall resource use dynamics, is essential for wood cascading LCA. Wood use receives credit for stored carbon. This credit would decrease with a reduction in wood use, which is often the case for cascading strategies as they come with gains in resource efficiency. To not disincentivise efficiency gains, the LCA of wood cascading must also include within its system boundary the wood that is unutilised because of the efficiency gains, which can also be done by performing consequential LCA.

The PhD research objective was to develop a methodological framework to assess the wood cascading. The results prove that complementary SEA and LCA adequately evaluate cascading. SEA measures the material circularity of wood cascading, LCA the environmental impact. However, the adaptations made to SEA (measuring the mass distribution) and additional analysis suggested for LCA (i.e. dynamic and consequential LCA and scenario analysis) in this PhD research are essential to include all the dimensions of cascading. This study thereby proposes a combined assessment of SEA and LCA, including the suggested adaptations to these methods, as a toolbox to assess the wood cascading.

8.2. Application of the framework

Macro-level application of the framework could be to assess the potential of the wood use in a country or a region, which is currently done using wood resource balance and often illustrated as a Sankey diagram (such as in Fig. 3.1). Wood Resource Balance provides a transparent summary of the wood production in forestry and its use in forest-based industries. Sankey diagram displays the source of wood (harvested, imported) and its downstream usage (domestic consumption, exports and addition to stocks). It also shows the sectors from which waste wood is recovered and the sectors to which it is directed. However, it only includes information on the volume, which is not a sufficient measure of the potential of wood - it is also the quality of the wood that counts. Calculating the statistical entropy of each mass flow in the Sankey diagram would more accurately represent the potential of wood in each flow. Additionally, regional wood use cannot be compared using the Sankey diagrams or wood resource balances because the wood quality might differ across regions. SEA performed on the Sankey diagram could be used to compare the performance of different countries. Additionally, regional LCA and input-Output LCA can provide the environmental impact of wood use. This framework could be applied to other biotic resources (such as textile and paper pulp) that are cascaded. These materials also lose their structural properties during use or processing and are cascaded down to optimise resource use.

Micro-level application of the framework could be to evaluate products or processes. There is a proposal to have a material passport for products, such as buildings, for better insights into end-of-life processing options to optimise waste as a resource. However, besides material composition, these passports should include different aspects of material quality. Statistical entropy can more accurately represent the cascading potential of buildings – as already suggested by Roithner et al. (2022). It could be considered for developing product labels (or certifications) for buildings. A low entropy building will indicate a high recyclability potential or need low effort in recycling. The more modular the design (i.e. easier to dismantle), the lower would be the product entropy. The more complex the products (with more substances), the higher the entropy. Similarly, the more structural wooden components, the lower the entropy. Low entropy would represent the higher recyclability of the products. CDW is currently the most heterogeneous waste stream, wherein clean and large-sized wood components (that are even reusable) get mixed with contaminated or lower-grade parts. The mixed stream considered contaminated is incinerated or used in a lower-grade application, highlighting the loss of material potential. A framework indicating the cascading potential of buildings would incentivise better sorting and separation and enable use in higher-value applications. In addition, the advancement in LCA suggested essential as part of this framework (i.e. dynamic and consequential LCA and scenario analysis) is crucial for the construction sector with its long lifetime and large volumes. The traditional LCA would underestimate the building's carbon impact.

8.3. Limitations of the current work

The main challenge in this work was gathering relevant and accurate data. Statistical entropy definition, based on the size distribution of the wooden elements, needs data on the mass of the different wood components. There is currently no assessment based on the wood component's mass. So, this data was not readily available. The weight of the wood plank in a wood pallet could be measured manually. However, this could not be done for the wood chips in particleboard and fibres in cardboard. The data on fibre length was available, and the mass was estimated based on that. Hence, the values of RSE are not accurate. In any case, the trend in RSE is more important than its absolute values. Nonetheless, the increasing popularity of this methodology will drive the need for gathering relevant data and enable deriving a more accurate indicator.

Another challenge was building an appropriate cascading case study that showcases the framework's benefits and brings forward novel insights. However, particleboard production and incineration are the only two established practices for cascading post-consumer wood. So, the cascading assessment framework could not be demonstrated using a sophisticated cascading scenario. One of the proposals is to perform SEA on the wood flow Sankey diagram of different countries to compare circularity in wood use in different countries. But the detailed data necessary for the analysis was not easily available. Hence, a simplified (and partially theoretical) case study had to be selected.

8.4. Pathway for future work in SEA

The current limitations of SEA set a pathway for its future development. One of the challenges facing SEA is analysing products containing more than one material. For example, wood-plastic composites – materials composed of wood and thermoplastic polymers (Carus et al., 2008; Teuber et al., 2016). They could be considered as one material as wood and polymers cannot be separated and will be cascaded or discarded as one. That would require understanding the physical properties that determine their utility and cascading potential. Another case is when the two materials constituting the product can be separated for further cascading. For example, consider a sofa made of textile glued to wood. This product forms a part of the wood and textile cascading systems. Hence, the system boundary will have to include both these material value chains, and SEA will have to be combined. That might additionally require a hierarchy of statistical entropy definitions. The first step in preserving the utility of the two materials is avoiding the mixture of materials or easing their separation. In the case of the sofa, it could be by stapling the textile onto the wood planks instead of gluing them together. The primary SEA would thus focus on material composition. The next step is preserving the utility of individual materials. So, the next level of SEA would base on the physical characteristics of the two materials – wood and textile – evaluating wood component size distribution for the wood part and the fibre size distribution for textile.

A similar challenge is when the wood itself becomes part of the value chain beyond the system boundary of wood-cascading. For instance, when wood-based chemicals (outputs of bio-refineries) are used in pharmaceuticals or plastics. They become part of another material value chain, wherein they are recycled multiple times (or cascaded) before being incinerated. That would also require the inclusion of the different material chains within the system boundary of the SEA study. This challenge is also when considering wood incineration, which is seen as an end of the cascade value chain because the utility of wood is assumed to reach its minimum. However, the incineration of wood produces ashes that also have potential use – as agricultural fertilisers (Pitman, 2006; Vance, 1996) or building material (Cheah and Ramli, 2011; Krook et al., 2004). Hence, there is a potential to expand the system boundary and adapt the SEA method to assess the utility of ashes.

Yet another challenge with SEA is that it does not differentiate between different substances. It does not consider the type of bonds between the substances. For instance, two systems with the same relative concentrations, so with the same value for statistical entropy, may differ significantly in the energy required to maintain the statistical entropy (i.e. maintain the material value or functionality). For example, the material of the glue used in a product influences the energy required to disassemble the product. Hence, the SEA must be complemented with the energy needed at each stage of change in statistical entropy for a complete assessment.

In material management, SEA has been used only for quantifying substance distribution. The adaptation to the statistical entropy put forth in this study extends it to the size distribution and opens the possibility to broaden the applicability of the methodology. SEA could be used to quantify any distribution function relevant to the system under consideration. It could describe characteristics specific to the quality of a particular material, such as fibre length for cotton textile or plastics. The next step could be to extend SEA beyond the material characteristics. For example, SEA can quantify the geospatial distribution of resources, products and materials in society to indicate the effort required to recover and utilise them. The more widespread they are (i.e. broad geospatial distribution), the more effort needed to collect and reuse them.

SEA could be developed as a generic tool to assess material circularity or to indicate the effort needed to achieve circularity. A high statistical entropy (wider distribution) indicates low material circularity or higher effort needed to functionalise the resources (or reduce the entropy). For SEA to be a generic tool, it must evaluate all the different material value chains. But as described before, different materials might differ in the physical properties that affect their utility, which would require different statistical entropy definitions. Secondly, the tool must go beyond material management to evaluate operations, business models and CE strategies. SEA could assist that by, for instance, evaluating geospatial distribution to assess the effort required to recover a particular waste. Different aspects of material circularity are indicated by different statistical definitions that might require hierarchical analysis. Hence, the next step could be to develop a hierarchical framework highlighting different layers to enable effective cascading. Considering the recycling of textiles, firstly, the effort for textile collection or recovery can be assessed by their geographical distribution. Secondly, sorting and separation depend on the heterogeneity of the waste (colours, types, and materials – cotton, polyester). Thirdly, their cascading depends on the material composition (presence of buttons and zips that can be manually separated) and substance composition (blend of different fibre types). Lastly, the recyclability potential of each material depends on fibre size. So, this SEA-based tool will need to be supported with a framework that specifies the statistical entropy(s) definitions relevant for the assessment and the hierarchy of those definitions to convey the order of precedence.

8.5. Pathway for future work in cascading assessment

As already discussed, the objective of cascading is to maximise the material value. The material value, also defined in this research as utility or functionality, is the benefit provided by a resource to humans. With an increase in the value obtained from the same resource, the primary resources needed to provide for societal needs would decrease. So, the most accurate assessment of cascading would be to quantify this material value. However, measuring this value is challenging. The material value can be determined for a specific product based on the function it provides (like the functional unit in LCA). For example, transporting a certain load over a distance is the function of the pallets. However, these values will not have the same unit for two products providing different functionalities. So, measuring material value for a cascade involving various application types is challenging. As seen in the case study in Chapter 4, it was difficult to quantify the utility value of a cascade involving pallets and particleboards and compare it with other cascade systems involving pallets and cardboard boxes (refer to section 4.4). Economic value is, most often, considered to represent the utility value. It is the most convenient method. However, the analysis in Chapter 4 (section 4.4) also describes its demerits.

With the difficulty of quantifying material value and because the inherent material quality (i.e. physical and chemical properties) provides the required functionality, the objective of maximising material value is achieved by preserving the material quality as long as possible. This PhD research assumed the dimensional property (mass of wooden components in products) as the indicator of material quality. However, other physical properties, besides dimensional properties, also influence functionality. So, cascading assessments could be improved by determining the appropriate physical parameters. A better understanding of the physical (and chemical) characteristics most relevant to the wood utility would be helpful for that. Secondly, different material properties are relevant for different wood applications. For example, mechanical properties (influenced by size) are critical for construction purposes, while the calorific value and moisture content are relevant for energetic purposes. Thus, cascading assessments must be multi-dimensional – evaluating different quality parameters as the wood resources pass through diverse applications. Knowledge of the correlation between the different quality parameters and utility needs to be enhanced. The statistical entropy is then defined based on the characteristics relevant to the applications under consideration.

The current focus of cascading is on optimising resource use and not on the sustainability of that resource use. It aims to maximise the material value from the available resources but does not validate if that use impacts the future supply. The underlying purpose of cascading is to ease the pressure on the ecosystems (by slowing/decreasing the need for wood harvest) and reduce the environmental impact (by slowing down the waste/GHG emissions to the atmosphere). So, cascading should be assessed within reference to these ecosystem boundaries. Cascading assessments must evaluate if it reduces the rate of wood harvesting to levels that are sustainable and the rate of GHG emissions to levels below the environment's absorption capacity. SEA could be a potential tool for that assessment. Statistical entropy invariably increases for wood-based products - as wood physically degrades with time, during use and waste treatment. The various cascading strategies can only slow down this increase, from cradle (wood harvest) to grave (eventual wood decomposition emitting CO2 into the atmosphere). The only process that reverses this (decreases the statistical entropy of wood use) is tree growth. Another approach to ensuring sustainability in wood usage could be maintaining (or decreasing) the overall statistical entropy in wood. The statistical entropy increase in the wood cascades could be kept in sync with the statistical entropy decrease during forest growth. The use of wood can be considered sustainable (and circular) only when entropy increases in cascade is slower than entropy decreases in forest growth.

This PhD research lays the groundwork for a better understanding of the circularity of wood usage – specifically in assessing cascading and its impact on material circularity and the environment. This PhD research systematically addresses the problem and bridges some of the many gaps open in this field. No single research can comprehensively address all the complexities and issues in this field. As this Chapter describes, several research gaps still exist. This PhD research lays ground and assists others in the field to narrow the remaining gaps that will eventually lead to more sustainable wood usage in real life. With growing concern about climate change and the degradation of ecosystems, optimising the use of wood has become more critical than ever before. It is not only for the betterment of the forests but essential for humankind's existence. Reiterating the words of Mahatma Gandhi – *"What we are doing to the forests of the world is but a mirror reflection of what we are doing to ourselves and to one another"*.

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Annex A.

A.1. Google Scholar results for search, dated May 2020, with the combination of term 'circular economy' and each of terms 'biological' and 'biobased'

Table A.1: The research papers that include the combination of the terms 'circular economy' and 'biological' or 'biobased' in title, in keywords or in abstract

Title paper	Relevance
Goggle scholar search: Circular economy and biological	
Product design and business model strategies for a circular economy (Bocken et al., 2016)	Design strategy for a biological cycle [This was in addition to the search results with specified terms. The paper did not include "biological cycle", "biological/biobased material" or "bioeconomy"/"bio-economy" in title or keywords but was considered relevant source as it explicitly defines design strategy for biological cycle]
Circular economy and the matter of integrated resources (Velenturf et al., 2019)	Proposes an alternative to the widely accepted conceptual division of technical and biological material
A Conceptual Framework for Circular Design (Moreno et al., 2016)	Business model and circular design framework for both technical and biological cycle
Transition towards a circular economy at a regional level: A case study on closing biological loops (Vanhamäki et al., 2020)	Proposes regional strategies to closing the biological nutrient loop, and emphasises use of biowaste and sewage slurry as a central aspect to doing so.
Circular business models in biological cycles: The case of an Italian spin-off (De Angelis and Feola, 2020)	Design of circular business model for biological materials
Restorative and regenerative: Exploring the concepts in the circular economy (Morseletto, 2020)	Discusses significance of terms 'regeneration' and 'restoration' in biological and technical cycles
Biological processes for advancing lignocellulosic waste biorefinery by advocating circular economy (Liguori and Faraco, 2016)	Design of biological process to support circular economy
Recent trends in green and sustainable chemistry: rethinking textile waste in a circular economy (To et al., 2019)	Describes textile economy following principles of circular economy
Goggle scholar search: Circular economy and biobased (Search included the terms – 'bio-based', 'biobased' and 'bio based')	
The Seven Challenges for Transitioning into a Bio-based Circular Economy in the Agri-food Sector	Proposes supply chain pathway in agri-food sector to achieve a zero-waste goal

(Borrello et al., 2016)	
Transforming the bio-based sector towards a circular economy - What can we learn from wood cascading? (Jarre et al., 2020)	Discuss factors influencing the realisation of wood cascading
The significance of biomass in a circular economy (Sherwood, 2020)	Discusses sustainable biomass production and treatment of biowaste as measures for circular economy is biobased sector
Bio-based circular economy in European national and regional strategies (Vanhamaki et al., 2019)	Discusses national and regional strategies for biobased economy
Bridging the Gaps for a 'Circular' Bioeconomy: Selection Criteria, Bio-Based Value Chain and Stakeholder Mapping (Lokesh et al., 2018)	Discusses methodology for identifying the most promising bio-based value chain
Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy (Mestre and Cooper, 2017)	Design for biological cycle
Soil and land management in a circular economy (Breure et al., 2018)	Importance of land and soil management to support circular economy
The circular bioeconomy—concepts, opportunities, and limitations (Carus and Dammer, n.d.)	Proposes an alternative illustration to current butterfly diagram, which goes beyond differentiation of technical and biological cycles, which cannot be held in reality. Further on, discusses synergies and differences between CE and Bioeconomy, and means to achieve circular bioeconomy
The circular economy and the bio-based sector-Perspectives of European and German stakeholders (Leipold and Petit-Boix, 2018)	Discusses the business community's view on the circular economy in bio-based sectors
On the Circular Bioeconomy and Decoupling: Implications for Sustainable Growth (Giampietro, 2019)	Critical take on circular bioeconomy – suggesting that circular bioeconomy continues to support the neoclassical economies by suggesting that resource scarcity can be substituted by technological innovation. Suggests the entropic narrative can help explore economic activity within biophysical limit.
Towards sustainability? Forest-based circular bioeconomy business models in Finnish SMEs (D'Amato et al., 2020)	Discusses business model in forest-based sectors
Let us discuss how cascading can help implement the circular economy and the bio-economy strategies	Discusses implementation of cascading strategy to improve resource efficiency and circularity

(Bezama, 2016)	
Bio-Economy Contribution to Circular Economy (Corrado and Sala, 2018)	Valorisation of Bio-Waste and Bio-Based By-Products and its contribution to circular economy
Hybridised sustainability metrics for use in life cycle assessment of bio-based products: resource efficiency and circularity (Lokesh et al., 2020)	Processes means to integrate indicators based on material circularity in LCA
A research challenge vision regarding management of agricultural waste in a circular bio-based economy (Gontard et al., 2018)	Multi-criteria assessment of agricultural waste management
Organic solid waste management in a circular economy perspective - A systematic review and SWOT analysis (Paes et al., 2019)	Analyses SWOT of organic waste management through circular economy (CE) principles
Cascading Utilisation of Wood: a Matter of Circular Economy? (Mair and Stern, 2017)	Discusses a conceptual overlap between CE and cascading use

The search aims to find studies focusing on 'circular economy' in biological cycles or for biological material. Hence, the studies that merely mentioned the terms ('biological' cycle or material, bio-based) without a particular focus of the study were excluded from the search results.

There are numerous research papers focusing on technological developments, and the only mention that to be contributing to circular economy or circular bioeconomy. These studies were not included in this particular analysis. Following are the results that focus on technology and were excluded from current analysis

1. Waste-to-energy nexus for circular economy and environmental protection: Recent trends in hydrogen energy (Sharma et al., 2020)
2. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy (Robles et al., 2020)
3. Bio-based and biodegradable polymers - State-of-the-art, challenges and emerging trends (RameshKumar et al., 2020)
4. Bio-based Plastics - A Building Block for the Circular Economy? (Spierling et al., 2018)
5. Nitrogen and phosphorus release from organic wastes and suitability as bio-based fertilisers in a circular economy (Case and Jensen, 2019)
6. Bio-based fertilisers: A practical approach towards circular economy (Chojnacka et al., 2020)
7. End-of-Life Options for Bio-Based Plastics in a Circular Economy—Status Quo and Potential from a Life Cycle Assessment Perspective (Spierling et al., 2020)

8. Impact of Bio-Based Plastics on Current Recycling of Plastics (Alaerts et al., 2018)
9. Bio-Based Compounds from Grape Seeds: A Biorefinery Approach (Lucarini et al., 2018)
10. Greening the Browns: A Bio-Based Land Use Framework for Analysing the Potential of Urban Brownfields in an Urban Circular Economy (Chowdhury et al., 2020)
11. Recent Trends in Green and Sustainable Chemistry & Waste Valorisation: Rethinking Plastics in a circular economy (Kaur et al., 2018)
12. To be, or not to be biodegradable… that is the question for the bio-based plastics (Prieto, 2016)
13. Biobased Acrylate Photocurable Resin Formulation for Stereolithography 3D Printing (Voet et al., 2018)
14. Biocatalysis and biomass conversion: enabling a circular economy (Sheldon, 2020)
15. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives (Venkata Mohan et al., 2016)
16. How Do Bioplastics and Fossil-Based Plastics Play in a Circular Economy? (Kawashima et al., 2019)
17. End-of-waste life: Inventory of alternative end-of-use recirculation routes of bio-based plastics in the European Union context (Briassoulis et al., 2019)
18. Plant-based materials and transitioning to a circular economy (Shogren et al., 2019)
19. Sustainable tetra pak recycled cellulose / Poly(Butylene succinate) based woody-like composites for a circular economy (Platnieks et al., 2020)

Table A.2: The results of the evaluation of CE monitors

	CE monitors	**Sustainable harvesting**	**Cascading Use**	**End of life: Closing ecological loop**	**Environmental Impact**	**Reference**
1	Circular economy indicator prototype	Not assessed	Not assessed	Not assessed	Not assessed	Cayzer et al. (2017)
2	Circular Economy toolkit	Not assessed	Not assessed	Explicitly but partially assessed Assess share of material **biodegradable**	Not assessed	Evans and Bocken (2014)
3	CE-enterprise-index	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed Assess output per unit **land, water and energy** consumption, **emissions** per unit output	Li and Su (2012)
4	Circular economy indicator system of China	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed Assess **energy consumption, water withdrawal**, and **emissions** per unit output	Geng et al. (2012)
5	EU Resource efficiency scoreboard	Not assessed	Not assessed	Explicitly but partially assessed Assess area under **organic farming, soil erosion, nutrient balance**	Explicitly but partially assessed Assess greenhouse **gas emissions per capita**, index of common farmland **bird species**, **land fragmentation, pollutant emissions**	European Commission (2015)
6	End-of-Life Recycling Rates	Not assessed	Explicitly but partially assessed	Not assessed	Not assessed	Graedel et al. (2011)

			Assess **functional and non-functional recycling rates**			
7	Circular Economy Performance Indicator	Not assessed	Explicitly assessed	Not assessed	Not assessed	Huysman et al. (2017)
8	Circularity Potential Indicator	Not assessed	Not assessed	Not assessed	Not assessed	Saidani et al. (2017)
9	Circular economy index	Not assessed	Explicitly but partially assessed Assess **market value**	Not assessed	Not assessed	Di Maio et al. (2015)
10	Circularity Index	Not assessed	Explicitly but partially assessed Assess **energy required for material & virgin material**	Not assessed	Not assessed	Cullen (2017)
11	Circular Pathfinder	Not assessed	Not assessed	Explicitly but partially assessed Assess share of material **biodegradable**	Not assessed	"ResCoM Circular Pathfinder," n.d.
12	Circularity Calculator	Not assessed	Not assessed	Not assessed	Not assessed	IDEAL&CO (2017)
13	Material circularity indicator	Mentioned (but not assessed) Suggests use of complementary risk indicator '**material scarcity**'	Not assessed	Not assessed	Not assessed	Ellen MacArthur Foundation (2015)
14	Indicators for Material input for CE Indicators for Eco-design for CE	Mentioned (but not assessed)	Mentioned (but not assessed)	Not assessed	Mentioned (but not assessed)	European Environment Agency (2016)

	Indicators for Production for CE Indicators for Consumption for CE					
15	Input-Output Balance Sheet	Not assessed	Not assessed	Explicitly but partially assessed Assess share of material **biodegradable**	Not assessed	Marco Capellini (2017)
16	Cradle to cradle certification program	Not assessed	Not assessed	Explicitly assessed	Explicitly but partially assessed Asses **energy and water** consumption	The Cradle to Cradle Products Innovation Institute (2014)
17	Eco-efficient value ratio	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed, using **LCA**, which is a methodology to study environmental impact. However, impact on resource depletion on ecosystem services and time-dependent carbon flows is rarely studied	Scheepens et al. (2016)
18	Resource duration indicator	Not assessed	Implicitly assessed Include **time in use** of a resource	Not assessed	Not assessed	Franklin-Johnson et al. (2016)
19	Circular economy toolbox	Explicitly but partially assessed Includes **share of resources from certified sources**	Explicitly but partially assessed Assess **closed loop and open-loop recycling rates**	Explicitly but partially assessed Assess share of material **biodegradable**	Not assessed	U.S. Chamber of Commerce Foundation (n.d).
20	Assessing circular trade-offs	Implicitly assessed Including criticality (using **resource price**) and **renewability**	Mentioned (but not assessed)	Explicitly but partially assessed Assess share of material **biodegradable**	Explicitly but partially assessed (The aspects assessed are not known)	https://www.circle-economy.com/assessing-circular-trade-offs/#.XOZYo-gzaUk
21	Sustainable circular index	Not assessed	Not assessed	Not assessed	Not assessed	Azevedo et al. (2017)

22	Circular economic value	Not assessed	Not assessed	Not assessed	Not assessed	Fogarassy et al., (2017)
23	Value-based resource efficiency	Implicitly assessed Considered **economic value** of stressed resources	Not assessed	Not assessed	Not assessed	Di Maio et al. (2017)
24	Circularity Indicator Project	Not assessed	Not assessed	Not assessed	Not assessed	Camacho-Otero and Ordoñez (2017)
25	Circular Economy Company Assessment Criteria	Not assessed	Not assessed	Not assessed	Not assessed	Camacho-Otero and Ordoñez (2017)
26	Hybrid LCA Model	Implicitly assessed LCA includes **land use change** and **resource scarcity**	Not assessed	Not assessed	Explicitly but partially assessed, using **LCA**, which is a methodology to study environmental impact. However, impact on resource depletion on ecosystem services and time-dependent carbon flows is rarely studied	Genovese et al. (2017)
27	CE indicator system	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed, measures environment damage cost based on the economic impact of **environmental pollution** (such as **air pollution, water pollution, light pollution, noise, solid waste**)	Zhou et al. (2013)
28	Evaluation for CE Development in Cities	Not assessed	Not assessed	Not assessed	Not assessed	Li et al. (2010)
29	Measuring Regional CE–Eco-Innovation	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed, using **LCA**,	Smol et al. (2017)

					which is a methodology to study environmental impact. However, impact on resource depletion on ecosystem services and time-dependent carbon flows is rarely studied	
30	Regional Circular Economy Development Index	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed Assess **water, energy** and **chemical fertilisers** consumption	Guogang and Jing (2011)
31	Evaluation of Regional Circular Economy	Not assessed	Not assessed	Not assessed	Not assessed	Jia and Zhang (2011)
32	Environmental Protection Indicators in a context of CE	Not assessed	Not assessed	Not assessed	Explicitly but partially assessed Assess **water, energy** per unit output	Su et al. (2013)
33	Super-efficiency Data Envelopment Analysis Model	Not assessed	Not assessed	Not assessed	Not assessed	Wu et al. (2014)
34	Integrative Evaluation on the Development of CE	Implicitly assessed Includes per **capita green area**	Not assessed	Not assessed	Not assessed	Qing et al. (2011)
35	Indicators of Economic Circularity in France	Not assessed	Not assessed	Not assessed	Not assessed	Ministry of the Environment Energy and Marine affairs in charge of internations relations in climate change (2017)
36	Circular Economy Indicators for India	Not assessed	Not assessed	Not assessed	Not assessed	Talwar (2017)
37	Circular Economy Monitoring Framework	Not assessed	Not assessed	Explicitly but partially assessed Assess share	Not assessed	Eurostat (2018)

				of material **biodegradable**		
38	Product-level-circularity-metric	Implicitly assessed Include the **cost of recirculated resources**	Implicitly assessed Include the **cost of recirculated resources**	Not assessed	Not assessed	Linder et al. (2017)
39	Recycling and collection rates	Not assessed	Explicitly but partially assessed Assess **closed loop and open-loop recycling rates**	Not assessed	Not assessed	Haupt et al. (2017)
40	Reuse potential indicator	Not assessed	Not assessed	Not assessed	Not assessed	Park and Chertow (2014)
41	Resource productivity indicator	Not assessed	Implicitly assessed Include **industrial added value per unit material input**	Not assessed	Not assessed	Wen and Meng (2015)
42	Material recycling index	Not assessed	Explicitly but partially assessed Assess recyclate composition	Not assessed	Not assessed	Van Schaik and Reuter (2016)
43	Zero Waste index	Not assessed	Not assessed	Not assessed	Not assessed	Zaman and Lehmann (2013)
44	Circular Impacts Project EU	Not assessed	Not assessed	Not assessed	Not assessed	Ecologic Institute (2018)
45	Economy-Wide Material Flow Analysis	Not assessed	Not assessed	Not assessed	Not assessed	Haas et al. (2015)
46	Product Circularity Indicator	Not assessed	Mentioned (but not assessed)	Not assessed	Not assessed	Bracquené et al. (2019)
47	Circulator tool	Not assessed	Not assessed	Not assessed	Not assessed	EIT RawMaterials (n.d.)

48	Eco-efficiency index	Implicitly assessed Include the **cost of raw material**	Not assessed	Not assessed	Not assessed	Laso et al. (2018)
49	Circulytics	Explicitly (and completely) Considers if the biotic resources are **sustainably sourced**	Not assessed	Explicitly but partially assessed Assess whether the outflow of material are suitable for biological cycle	Not assessed	Ellen MacArthur Foundation (2020)
50	Global resource indicator	Explicitly but partially assessed Assess the **renewability rate** while considering resource scarcity	Not assessed	Not assessed	Not assessed	Adibi et al. (2017)
51	Circularity material indicator	Not assessed	Explicitly but partially assessed Used weighted factor based on purity, quality, and recoverability of material to calculate circularity index	Not assessed	Not assessed	Pauliuk et al. (2017)
52	EU Raw materials scoreboard	Explicitly but partially assessed Considers growing stock and forest-felling (utilisation) rate	Not assessed	Not assessed	Not assessed	European Commission (2018)
53	Circular economy efficiency composite index	Not assessed	Not assessed	Not assessed	Not assessed	Ma et al. (2014)
54	Economic-Environmental Indicators to Support Investment Decisions	Not assessed	Not assessed	Not assessed	Not assessed	Fregonara et al. (2017)
55	Adjusted Raw Material Consumption	Not assessed	Not assessed	Not assessed	Not assessed	Hu et al. (2017)

56	Ease of disassembly metric	Not assessed	Not assessed	Not assessed	Not assessed	Vanegas et al. (2018)
57	Circularity loop calculator	Not assessed	Not assessed	Not assessed	Not assessed	Kingfisher (2014)
58	Circular economy measurement scale	Not assessed	Not assessed	Not assessed	Not assessed	Nuñez-Cacho et al. (2018)
59	Circularity assessment of product families	Not assessed	Not assessed	Not assessed	Not assessed	Mesa et al. (2018)

Annex B.

B.1. Definitions of cascading:

1. Cascading is a strategy for using wood and other biomass in a more efficient way by reusing residues and recycled materials in sequential steps for as long as possible, before turning them into energy (European Environmental Agency, 2018).
2. Under the cascade principle, wood is used in the following order of priorities: wood-based products, extending their service life, re-use, recycling, bio-energy and disposal (European Commission, 2013).
3. Cascading is a strategy for using raw materials or the products made from them in chronologically sequential steps as long, often and efficiently as possible for materials and only to recover energy from them at the end of the product life cycle. It is based on the use of so-called 'cascades of use' that flow from higher levels of the value chain down to lower levels, increasing the productivity of the raw material (WWF - World Wide Fund For Nature, 2016).
4. Cascading use of biomass takes place when biomass is processed into a bio-based final product and this final product is used at least once more either for materials or energy (Essel et al., 2014).
5. The cascading use of wood takes place when wood is processed into a product and this product is used at least once more either for material or energy purposes. In a *Single-stage cascading*, wood is processed into final product and this product is used once more for energy purposes. *Multi-stage cascading* is when biomass is processed into a final product and this final product is used at least once more as a material. It is only after at least two uses as a material that energy use is permitted (Essel et al., 2014; Vis et al., 2016).
6. Theoretical notion which integrates concepts of resource economy and sustainability into an operational framework for determining the efficiency and appropriateness of a given resource exploitation in a given context (Sirkin and Houten, 1994). They described resource cascading as method to enhance the efficiency of resource utilisation by a sequential re-utilisation of the same unit of a resource for multiple high-grade material applications followed by a final use for energy generation.
7. Resource-cascading is defined as the sequential exploitation of the full potential of a resource during its use and is one of the ways to improve efficiency of the raw materials use (Fraanje, 1997).
8. Multiple use of the wood resources from trees by using residues, recycling (utilisation in production) resources or recovered resources (collected after consumption). Micro-economic cascades (product cascades): Cascading use of biomass takes place when biomass is processed into a bio-based final product and this final product is used at least once more either for materials or energy - Equivalent to

single-stage cascading. Macro-economic cascades (sector cascades): Cascading use of biomass in an industrial sector takes place when residues and recycling materials are processed (Mantau, 2015).

9. Cascading use of biomass implies a linear system in which biomass progresses through a series of material uses, by reuse and recycling, before finally being used for energy extraction (Keegan et al., 2013).
10. Cascading is use of the same unit of a resource in multiple successional applications (Höglmeier et al., 2015).
11. Cascade principle implies the priority use of wood material based on the higher added value that can be potentially generated along the wood value chain (Ciccarese et al., 2014).
12. An open loop recycling system where quality degradation occurs is called a cascade recycling system (Kim et al., 1997).
13. Cascading use of a material resource as the reuse of one unit of material for several consecutive uses, which, in general, encompasses a downward trend of material quality. Cascades differ from recycling by the fact that several (more than two) different use processes follow each other in a fixed order, having a decreasing demand for material quality (Rehberger and Hiete, 2020).
14. Cascading use is the efficient utilisation of resources by using residues and recycled materials for material use to extend total biomass availability within a given system (Vis et al., 2016).
15. The use and subsequent reuse of recycled woody biomass is called cascading (Brunet-Navarro et al., 2018).
16. Cascade utilisation of biomass aims at maximising the socio-economic advantage that can be gathered from a limited amount of biomass harvested through increasing the efficiency of its use (Haberl and Geissler, 2000).
17. Cascade use is the subsequent use of biomass for a number of applications, i.e. materials, recycling of materials and energy recovery (Dornburg, 2004).
18. *Cascading in time*: Subsequent use in time to ensure a long(er) life span of the biomass. *Cascading in value*: Cascading in time can be optimised by cascading in value to ensure the highest value possible is achieved when choosing between alternatives, and the value over the whole life cycle is maximised.

    Cascading in function: production of different functional streams from a single biomass stream (by using co-products and residues), maximising total functional use (Odegard et al., 2012).
19. The Netherlands Environmental Assessment Agency defines cascading as postponing the time at which the biomass is incinerated (with the object of energy recovery) as long as possible (Odegard et al., 2012).

Annex C.

Table C.1: Characteristics of different products part of the system

Product	**Properties**	**Values**	**References & Remarks**
Multiple-use pallets	Life time	10 years	Gasol et al. (2008); Deviatkin et al. (2019); (Vis et al., 2014)
	Composition	Wood 99.75%, Physical contaminants 0.2% Chemical contaminants 0.05% (share by mass)	Gasol et al. (2008)
	Mass of the pallet	25 kg	Deviatkin et al. (2019); EPAL (2018); Gasol et al. (2008)
	Mass of each board (plank)	1.44 kg	Deviatkin et al. (2019) The reference provides weight of each board in the pallet. A weighted average was taken (as simplification) since each board in the pallet has different weight
	Payload	1500 kg	
Single-use pallet	Life time	2 years	Gasol et al. (2008)
	Composition	Wood 98.3 %, Physical contaminants 1.7 % (share by mass)	Gasol et al. (2008)
	Mass of the pallet	15 k	The reference provides wide range for this value – 20 kg (Vigidas Pack, 2022), 13.2 kg (Kronus, 2022) and 11 kg (Rotomshop, 2022). Hence, an average value was considered.
	Mass of each board (plank)	0.864 kg	Deviatkin et al. (2019) The value is estimated based on the proportion of individual board weight to the total weight in multiple use pallets
	Payload	400 kg	(Kronus, 2022; Rotomshop, 2022; Vigidas Pack, 2022)
Cardboard pallet	Life time	2 years	Cote et al. (2015) gives a range of 2 to 8 years as in-use lifespan for cardboard products. As a conservating approach, it is assumed that cardboard is used for an average of 2 years for high-grade cardboard application (i.e. pallet). This is assumed also by Zhang et al. (2020). Fortin et al. (2012) assumes average life time for pulp and paper mill products to be 2.8 years. EU framework provides reference for lifetime of paper to be 3 years (Vis et al., 2014). Ramage et al. (2017) gives <2 years as reference lifetime for paper and packaging products

	Composition	Wood-based fibres 100 %	KraftPal Technologies Ltd., (2020)
	Fibre length	2.6 mm	Teixeira (2012)
	Fibre size (estimation)	$8 * 10^{-11}$ kg	Teixeira (2012) Volume of individual fibre = $2.6 * 28 * 10^{-3}$ mm = $7.15 * 10^{-2}$ mm^3 Based on the density of the sheet (1.15 g/m3) and fibre to mass ratio to be 10% (sheet contains 10% fibre by mass). The mass of individual fibre will be at least 8 * 10-11 kg. This is not entirely accurate as the density is of the composite. But due to the lack of data, assumption is that the sheet contains 10% fibre also by volume. 1 m3 (fibre) = 1.15 gm (fibre) So, $7.15 * 10^{-8}$ m3 fiber (which is volume of 1 fiber) = $8.22 * 10^{-11}$ kg
	Payload	1500 kg	KraftPal Technologies Ltd., (2020)
Low-grade cardboard application	Life time	2 years	Cote et al. (2015) gives a range of 2 to 8 years as in-use lifespan for cardboard products. As a conservating approach, it is assumed that cardboard is used for an average of 2 years also for low-grade cardboard application
	Composition	Wood-based fibres 100 %	
	Fiber length	1.56 mm	Teixeira (2012)
	Fibre size (estimation)	$4 * 10^{-11}$ kg	Teixeira (2012) Since, the fibre length is half of that in the high-grade application, the mass is assumed to be halved
Particleboard	Life time	10 years	Faraca et al. (2019b)
	Composition	Wood 88 % , Chemical contaminants 12 % (share by mass)	Kim and Song (2014) states chemical additives are 18% by mass in particleboard. Rivela et al. (2006) states this value to be 9.7%, Wilson (2008) states it to be 10%, Wan et al. (2014) states value 8 – 10%. Astari et al. (2018) considers the values 8%, 10% and 12%. Vis et al. (2016) states this 15%. An average value of 12% was considered for the study.
	Fibre size (estimation)	$2.7 * 10^{-5}$ kg	Particle size 3.36 mm and board density (including non-wood substances) is 0.8 g/cm3 (Astari et al., 2018) which contains 89% of wood. So, the weight of particle size is estimated at = $3.36 * 3.36 * 3.36 * 10^{-3} * 0.8 * 0.89 * 10^{-3} = 2.7 * 10^{-5}$ kg

Table C.2: Parameters considered for material flow analysis

Scenario	Properties	Values	References & Remarks
Multiple-use pallet	Share of discarded pallets recycled to particleboard	41%	At European Scale, 41 % are recycled to particleboard, remaining are either not recovered

(W_s) scenario	Share of discarded pallets incinerated	59 %	or incinerated (Eurostat, 2017; Vis et al., 2016). The remaining is assumed to be incinerated as they are not recovered and are not utilised.
	Losses during particleboard production	35%	35 % of waste wood that is lost during particleboard production is incinerated (Kim and Song, 2014)
	Share of discarded particleboard recycled	0 %	The post-consumer particleboard are not recycled and are incinerated (Vis et al., 2016)
	Share of discarded particleboard recycled	100 %	
Single-use pallet (W_s) scenario	Share of discarded pallets recycled to particleboard	41%	At European Scale, 41 % are recycled to particleboard, remaining are either not recovered or incinerated (Eurostat, 2017; Vis et al., 2016). The remaining is assumed to be incinerated as they are not recovered and are not utilised. Although, it is known that the recyclability is lower for painted pallets, the data on the extent to which it is lower is not known. So, the recycling rate of single-use pallet is assumed to be the same as multiple-use pallet.
	Share of discarded pallets incinerated	59 %	
	Losses during particleboard production	35%	35 % of waste wood that is lost during particleboard production is incinerated (Kim and Song, 2014)
	Share of discarded particleboard recycled	0 %	The post-consumer particleboard are not recycled and are incinerated (Vis et al., 2016)
	Share of discarded particleboard recycled	100 %	
Cardboard pallet from virgin material (C_v)	Share of discarded cardboard pallets recycled	85.5%	The cardboard pallets are not repaired. At European Scale, 85.5 % of cardboard pallets are recycled, remaining are either not recovered or incinerated (Eurostat, 2017). The remaining is assumed to be incinerated as they are not recovered and are not utilised.
	Share of discarded cardboard pallets recycled	14.5 %	
	Share of discarded low-grade cardboard recycled	0 %	The low-grade cardboard waste is incinerated at the end of 2 years.
	Share of discarded low-grade cardboard incinerated	100 %	
Cardboard pallet from recycled material (C_r) scenario	Recycling pallets to cardboard pallets	41%	At European Scale, 41 % are recovered and recycled for material application, remaining are either not recovered or incinerated (Eurostat, 2017; Vis et al., 2016). In this scenario, the assumption is that the recovered wood is recycled for cardboard pallet production.
	Incineration	59 %	
	Recycling the cardboard pallet to low – grade cardboard	85.5%	The cardboard pallets are not repaired. At European Scale, 85.5 % of cardboard pallets are recycled, remaining are either not recovered or incinerated (Eurostat, 2017). The remaining is
	Incineration of cardboard pallets	14.5 %	

			assumed to be incinerated as they are not recovered and are not utilised
	Recycling the low – grade cardboard	0 %	The low-grade cardboard waste is incinerated at the end of 2 years.
	Incinerating the low-grade cardboard	100 %	

Table C.3:The stock of wood in different applications over time (all the amounts are in kg – rounded off to a single digit)

	Scenario W_m		**Scenario W_s**		**Scenario C_v**		**Scenario C_r**		
Year	Solid-Wood pallets	Particleboard	Solid-Wood pallets	Particleboard	Cardboard pallets	Low-grade cardboard	Solid-Wood pallets	Cardboard pallets	Low-grade cardboard
0	740	0	1000	0	1000	0	1000	0	0
1	740	0	1000	0	1000	0	1000	0	0
2	740	7	1000	267	1000	0	1000	0	0
3	740	14	0	267	0	855	0	205	0
4	740	21	0	267	0	855	0	205	0
5	740	28	0	267	0	0	0	0	175
6	740	35	0	267	0	0	0	0	175
7	740	42	0	267	0	5	0	0	0
8	740	49	0	267	0	0	0	0	0
9	740	55	0	267	0	0	0	0	0
10	740	62	0	267	0	0	0	0	0
11	0	267	0	267	0	0	0	0	0
12	0	260	0	267	0	0	0	0	0
13	0	253	0	0	0	0	0	0	0
14	0	246	0	0	0	0	0	0	0
15	0	239	0	0	0	0	0	0	0
16	0	232	0	0	0	0	0	0	0
17	0	225	0	0	0	0	0	0	0
18	0	218	0	0	0	0	0	0	0
19	0	211	0	0	0	0	0	0	0
20	0	204	0	0	0	0	0	0	0

The total amount of wood at each stage is 1000 kg. The remaining is the amount not recovered, discarded or incinerated, it is not included in the table for the lack of space

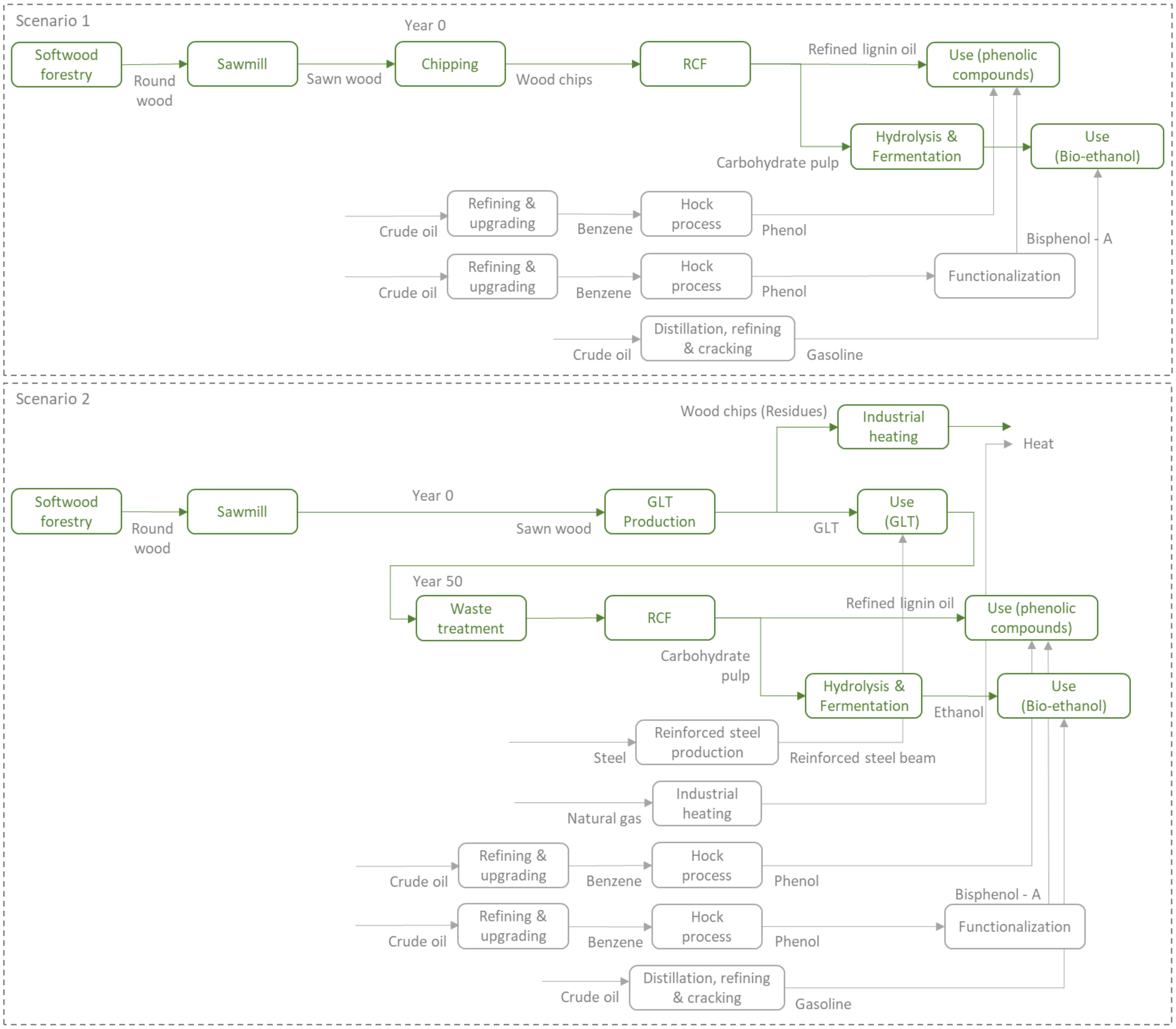
Table C.4: A step by step simplified demonstration of the calculation of relative statistical entropy for a particular year and particular scenario

Scenario	Year: 7 Scenario: W_s
Calculation of statistical entropy (H_c) and relative statistical entropy for each product is calculated based on the relative concentration of substances present in the product using the formulae:	$H_c = -\sum_{j=1}^{n} c_{ij} * \log_2(c_{ij})$ $RSE_{(c)i} = \frac{H_c}{H_{max}}$
Calculation of statistical entropy for **solid-wood pallet**	The composition of solid-wood pallet: Wood 98% and Physical contaminants 2% $H_c = -0.98 * \log_2(0.98) - 0.02 * \log_2(0.02)$ $= 0.12644$
Calculation of H_{max}	H is maximum when the two substances are in equal proportion So, $H_{max} = -0.5 * \log_2(0.5) - 0.5 * \log_2(0.5)$ $= 1$
Calculation of RSE_c	$RSE_{(c)i} = \frac{H_c}{H_{max}} = 0.12644/1$ $RSE_c = 0.12644$
Calculation of statistical entropy for **particleboard**	The composition of solid-wood pallet: Wood 88 % and Chemical contaminants 12 % $H_c = -0.88 * \log_2(0.88) - 0.12 * \log_2(0.12)$ $= 0.529$ $RSE_c = 0.529$
Aggregated relative statistical entropy	$RSE_{(c)total} = w_1 * RSE_{(c)1} + w_2 * RSE_{(c)2} + \cdots + w_i * RSE_{(c)i}$ Relative mass balance for the year 7 in the scenario W_s Solid wood pallets = 0 kg Particleboard = 267 kg Unutilised (end of life) solid wood pallets = 590 kg Residues during waste wood production = 143 kg $RSE_{(c)\,total} = (0 * 0.12644 + 267 * 0.529 + 590 * 0 + 143 * 0)/1000$ $= 0.141$ The RSE_c for the unrecovered solid wood pallets and residues is 0 because the physical contaminants (i.e. nails and staples) are separated at the waste treatment facility before further processing. As they remain unutilised or are lost, there is no contamination present in these fractions.
Calculation of statistical entropy (H_c) and the relative statistical entropy for each product is calculated based on relative size of individual wood components that form the product using the formulae:	$H_s = -\sum_{j=1}^{k} s_{ij} * \log_2(s_{ij})$ Where $s_{ij} = \frac{mass\ of\ piece\ j}{\begin{array}{c}maximum\ mass\\(for\ the\ specific\ case\ study)\end{array}}$

	The maximum mass for the case study is 1.44
Calculation of statistical entropy for **solid-wood pallet**	Mass of each board (plank) = 0.86 kg Relative mass (s) = 0.86/1.44 = 0.6 H_s = - log 0.6 = 0.74
Calculation of H_{max}	H is maximum when the wood is in the most physically degraded state (in the systems under consideration). In this case, it is in the degraded cardboard. Mass of the wood is 2 * 10^{-11} kg Relative mass (s) = 2 * 10^{-11} / 1.44 = 1.4 * 10^{-11} kg So, H_{max} = - $\log_2$ (1.4 * 10^{-11}) = 36.07
Calculation of RSE_s	$RSE_{(s)i} = \frac{H_s}{H_{max}}$ RSE_s = 0.74 / 36.07 = 0.02
Calculation of statistical entropy for **particleboard**	Mass of each fibre = 2.7 * 10-5 kg Relative mass (s) = 2.7* 10^{-5} /1.44 = 1.875 * 10^{-5} H_s = - log (1.875 * 10^{-5}) = 15.7027 RSE = 15.7 / 36.07 = 0.44
Aggregated relative statistical entropy	$RSE_{(c)total} = w_1 * RSE_{(c)1} + w_2 * RSE_{(c)2} + \cdots + w_i * RSE_{(c)i}$ Relative mass balance for the year 7 in the scenario W_s Solid wood pallets = 0 kg Particleboard = 267 kg Unutilised (end of life) solid wood pallets = 590 kg Residues during waste wood production = 143 kg $RSE_{(c)\ total}$ = (0 * 0.02 + 267 * 0.44 + 590 * 1 + 143 * 0.57)/1000 = 0.79 The RSE_c for the unrecovered solid wood pallets is assumed to be 1 because the resource is lost and has zero cascading potential. The RSE_c for the residues produced during waste wood production is calculated based on the mass of individual sawdust (the main constituent of the residues). Their mass is estimated to be 9 * 10^{-7} kg.

Annex D.

D.1. Scenario description & system boundary



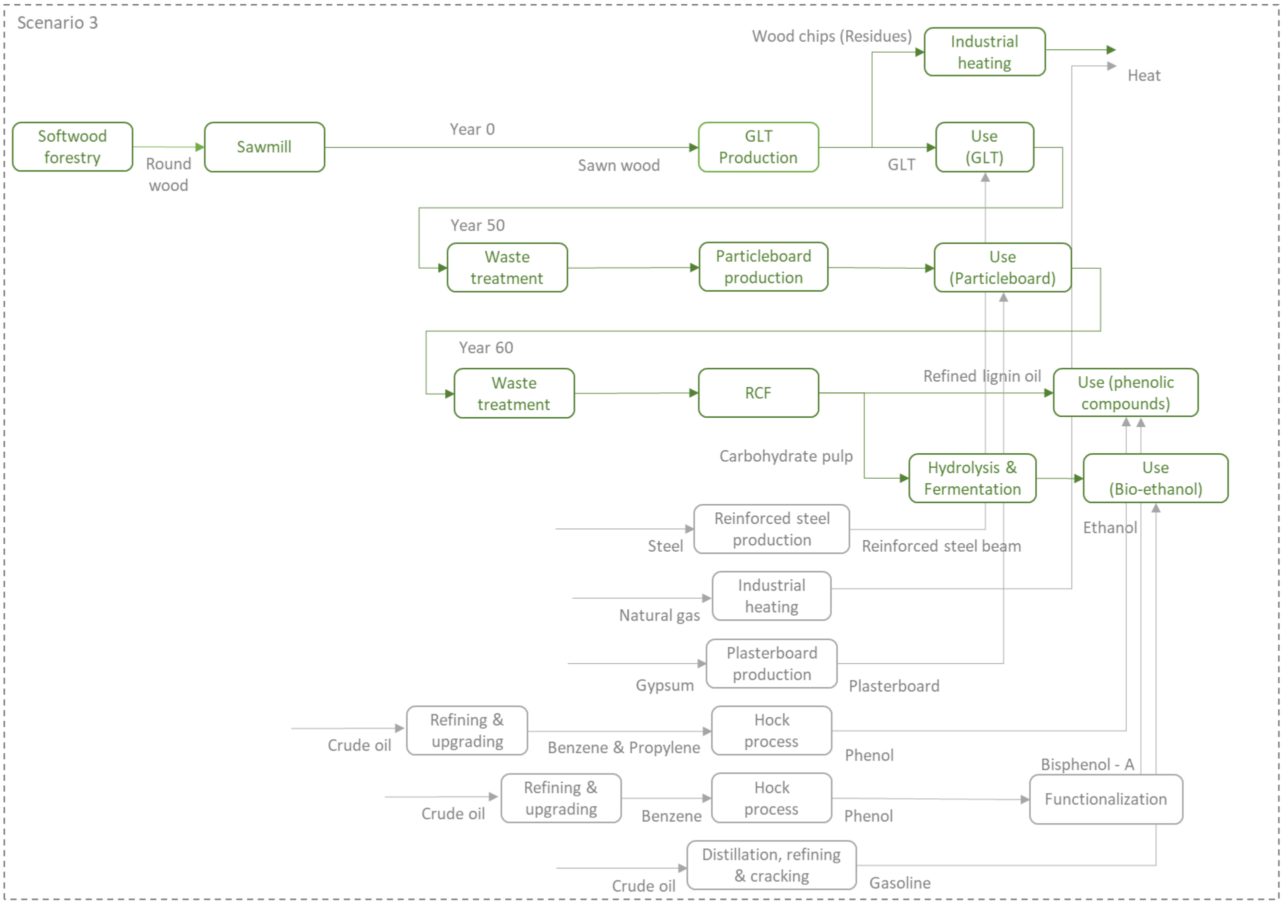
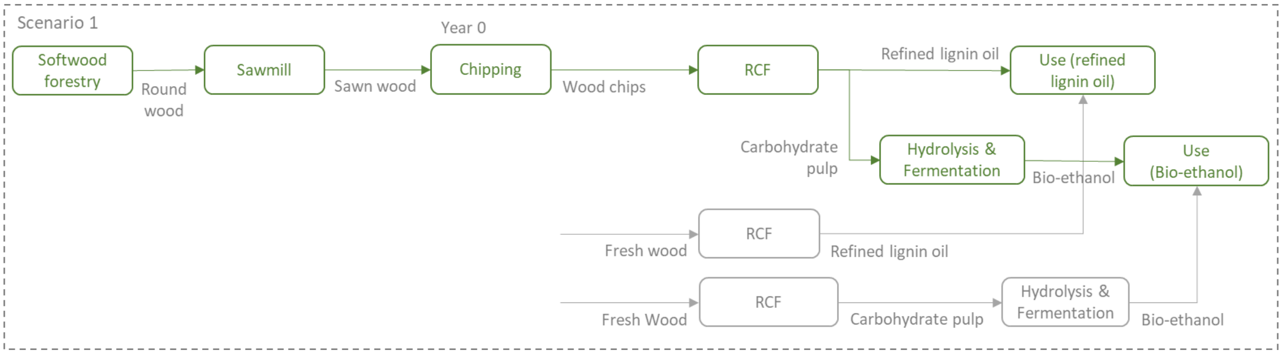


Figure D.1: Detailed system boundary for the three cascading scenarios

The boxes represent process and arrows represent flows. The grey arrows represent the non-wood products being substituted



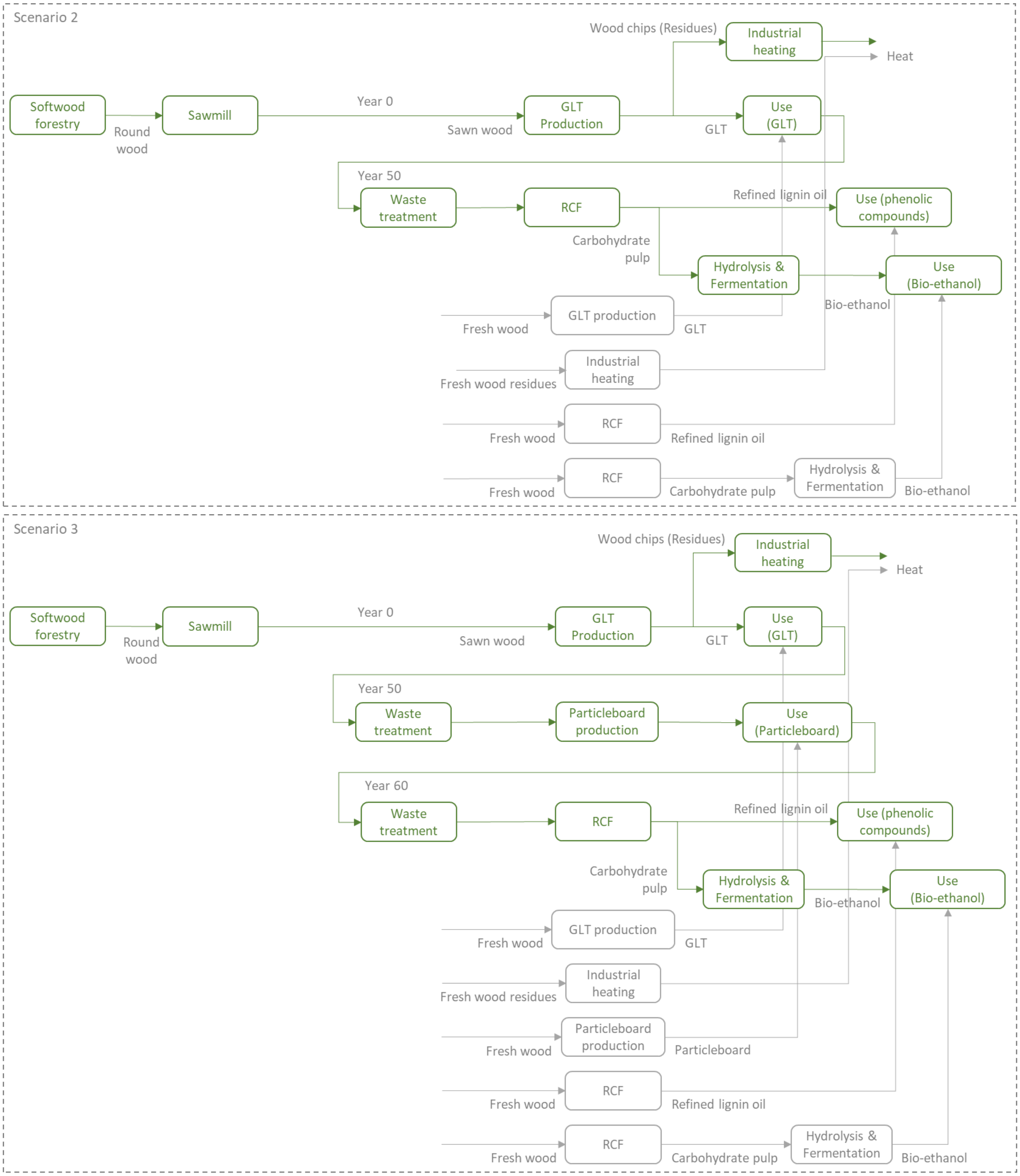


Figure D.2: Detailed system boundary for the three cascading scenarios, when examining the net benefit of use of wood to provide the same material functions with and without cascading

The boxes represent process and arrows represent flows. The grey arrows represent the products from virgin wood being substituted because of cascaded use of wood.

D.2. Assumptions

Table D.1: List of the assumptions considered for modelling the life cycle inventory

Parameter	Values	Reference
Life time of GLT	50 years	Petersen and Solberg (2002), Sandin et al. (2014)
Life time of particleboard	10 years	Faraca et al. (2019b)
Life time of phenol-based products	10 years	Mutha et al. (2006)
Consequently, service life of wood in different wood cascade systems	Scenario 1 – 10 years Scenario 2 – 60 years Scenario 3 – 70 years	
Density of sawn wood	1 m^3 = 450 kg (dry mass)	
Density of glued laminated timber	1 m^3 = 393 kg (including resin)	
Density of particleboard	1 m^3 = 500 kg	Sathre and Gustavsson (2006)
Rotation period	60 years	Biermayer (2020), Nabuurs et al. (2014)

D.3. Life cycle inventory (LCI)

Table D.2: Inventory data for glued laminated timber manufacturing from sawn wood
This is based on the data provided by Risse et al. (2019), which is based on based on literature (Rüter and Diederichs, 2012) and their own experiments

Input flows	**Quantity**
Sawn wood (m^3)	1
Diesel (MJ)	32.1
Electricity (MJ)	319
Heat (MJ)	1072
Lubricating oil (kg)	0.069
Urea Formaldehyde resin (kg)	10.1
Wooden board factory (pieces)	3.33 e^{-8}
Tap water (kg)	0.024
Water (m^3)	0.0346
Output flows	**Quantity**
Glued laminated timber (m^3)	1
Waste wood (m^3)	0.149
Formaldehyde (emissions to air; kg)	0.0115
Waste polyurethane (kg)	0.82
Waste water (m^3)	0.035

Table D.3: Inventory data for particleboard production from fresh wood
This is based on the data provided by Kim and Song (2014).

Input flows	**Quantity**
Virgin wood (kg)	138

Residual fuel oil (litre)	4.05
Water (kg)	47.4
Electricity (kWh)	26.8
Urea Formaldehyde resin (kg)	18.63
Output flows	**Quantity**
Particleboard (kg)	109
Waste wood (kg)	9.96
Waste water	0.489
Waste resin (kg)	0.475
Sludge (kg)	0.184
Loss (kg)	83.2

Table D.4: Inventory data for particleboard production from waste wood
This is based on the data provided by Kim and Song (2014).

Input flows	**Quantity**
Waste wood (kg)	120
Virgin wood (kg)	9.96
Residual fuel oil (litre)	2.49
Water (kg)	47.4
Electricity (kWh)	26.8
Urea Formaldehyde resin (kg)	18.63
Output flows	**Quantity**
Particleboard (kg)	109
Waste wood (kg)	9.96
Waste water	0.489
Waste resin (kg)	0.475
Sludge (kg)	0.184
Loss (kg)	83.2

Table D.5: Inventory data for the reductive catalytic fraction process for the production of refined lignin oil and carbohydrate pulp from different feedstocks

Input flows	**Scenario 1 (Fresh wood to RCF)**	**Scenario 2 (Waste wood A to RCF)**	**Scenario 3 (Waste wood B to RCF)**
Wood chips (dry mass in kg)	15862	15862	15862
Methanol (kg)	2299	2299	2299
H_2 (kg)	101.7	72.86	69.28
Ethyl Acetate (kg)	236.9	327.8	563.6
Water (kg)	80614	80526	83099
Nickel catalysts (kg)	0.1	0.1	0.1
Natural gas for steam production (kg)	1648	1626	1528
Electricity (kWh)	1470	1459	1482

Output flows				
Carbohydrate pulp	Sugars (kg)	13586	13874	13198
Refined lignin oil	Monomer (kg)	645	623	656
	Oligomer (kg)	1377	1205	1471
CO_2 (kg) – Biogenic		342	342	344
CO_2 (kg) – Non-biogenic		7083	6761	6528

Table D.6: Inventory data for the production of 1MJ bio-ethanol from carbohydrate pulp

This data is from Sebastião et al. (2016), which is adapted based on sugar content in carbohydrate pulp from RCF.

Neutralisation and hydrolysis process	
Input flows	**Quantity**
Carbohydrate pulp (kg)	0.175 (in scenario 1) 0.161 (in scenario 2) 0.127 (in scenario 3)
Water (kg)	0,7949
Enzyme	0,00446
Belt conveyors (kWh)	0,000437
Hydrolysis tanks agitation (kWh)	0.0126
Hydrolysis tanks heating (MJ)	0.872
Concentration process	
Input flows	
Evaporator heating (MJ)	0,427
Output flows	
Waste water (m^3)	0,000176
Fermentation process	
Input flows	
Copper sulphate (kg)	$7.49 * 10^{-6}$
Urea (kg)	$5.74 * 10^{-4}$
Magnesium sulphate (kg)	$4.63 * 10^{-4}$
CSL (kg)	$1.11 * 10^{-2}$
Yeast (kg)	$3.60 * 10^{-4}$
Fermenters agitation (kWh)	$3.35 * 10^{-3}$
Hydration tank agitation (kWh)	$7.99 * 10^{-8}$
Downstream processing	
Input flows	
Distillation columns heating (MJ)	0,623
Output flows	
Waste water (m^3)	$7.42 * 10^{-4}$
Solid to landfill (kg)	$1.02 * 10^{-3}$

Table D.7: Overview of other utilised datasets from the database Ecoinvent

Process/product	**Dataset**	**Location**	**Remarks**
Process relevant for all scenarios			

Sawn wood production	market for sawnwood, softwood, raw, dried (u=10%) ecoinvent 3.3	RER (Europe)	
RCF input - methanol	market for methanol ecoinvent 3.3	GLO (Global)	
RCF input - ethyl acetate	market for ethyl acetate ecoinvent 3.3	GLO (Global)	
RCF input - nickel	market for nickel, 99.5% ecoinvent 3.3	GLO (Global)	
RCF input - natural gas	market group for natural gas, high pressure ecoinvent 3.3	Europe without Switzerland	
RCF input - hydrogen	Hydrogen (steam reforming from natural gas) PlasticsEurope	RER (Europe)	From thinkStep db
RCF input – water	market for water, deionised, from tap water, at user ecoinvent 3.3	Europe without Switzerland	
RCF input – electricity	market group for electricity, medium voltage ecoinvent 3.3	RER (Europe)	
Bioethanol production input - urea	RER: urea production, as N ecoinvent 3.3	RER (Europe)	
Bioethanol production input – heat	market group for heat, district or industrial, natural gas ecoinvent 3.3	RER (Europe)	
Bioethanol production input - electricity	market group for electricity, medium voltage ecoinvent 3.3	RER (Europe)	
Bioethanol production input - yeast	market for fodder yeast ecoinvent 3.3	GLO (Global)	
Bioethanol production input – tap water	market group for tap water ecoinvent 3.3	RER (Europe)	
Bioethanol production input - copper sulfate	market for copper sulfate ecoinvent 3.3	GLO (Global)	
Bioethanol production input - magnesium sulfate	magnesium sulfate production ecoinvent 3.3	RER (Europe)	
Bioethanol production input - Enzyme		RER (Europe)	The process for all input of enzyme production were not available in ecoinvent db, so the GWP of enzyme production documented in Sebastião et al. (2016) is considered as is
Bioethanol production input – waste water treatment	market for wastewater, average ecoinvent 3.3	Europe without Switzerland	
Bioethanol production input – solid to landfill	treatment of sludge from pulp and paper production, sanitary landfill ecoinvent 3.3	Europe without Switzerland	
Phenol production	Phenol [Plastics Europe]	RER (Europe)	Product substituted by monomer part of refined lignin oil
Bisphenol A production	bisphenol A production, powder ecoinvent 3.3	RER (Europe)	Product substituted by oligomer part of refined lignin oil

Fossil-based petrol (gasoline) production	market for petrol, unleaded ecoinvent 3.3	RER (Europe)	Product substituted by Bio-ethanol
Processes applicable in scenario 1			
Sawn wood chipping process (to produce wood chips for RCF)	wood chips production, softwood, at sawmill	RER (Europe)	
Processes applicable in scenario 2 and 3			
GLT Production input-urea formaldehyde resin	urea formaldehyde resin production ecoinvent 3.3	RER (Europe)	
GLT Production input - diesel, (burned in building machine)	market for diesel, burned in building machine ecoinvent 3.3	GLO (Global)	
GLT Production input - lubricating oil	lubricating oil production ecoinvent 3.3	RER (Europe)	
GLT production input – tap water	market group for tap water ecoinvent 3.3	RER (Europe)	
GLT production input – tap water	water production and supply, decarbonised ecoinvent 3.3	RER (Europe)	
GLT production input – heat	market group for heat, central or small-scale, natural gas ecoinvent 3.3	RER (Europe)	
GLT production input – electricity	market group for electricity, medium voltage ecoinvent 3.3	RER (Europe)	
GLT production input - Wooden board factory	wooden board factory construction, organic bonded boards ecoinvent 3.3	RER (Europe)	
GLT production treatment of waste polyurethane	Europe without Switzerland: market for waste polyurethane ecoinvent 3.3	Europe without Switzerland	
GLT production treatment of waste water	market for wastewater, average ecoinvent 3.3	Europe without Switzerland	
GLT production residue treatment (before incineration)	treatment of waste wood, post-consumer, sorting and shredding	CH (updated to RER)	Since the material is already of small dimensions and a large share is shavings and sawdust, the inventory values are reduced by 50%.
Industrial and district heating from residual wood chips	heat production, wood chips from industry, at furnace 5000kW	CH (updated to RER)	heat production from incinerating residues from GLT production
Industrial and district heating from residual wood chips	market group for heat, district or industrial, natural gas	RER	Heat production by incinerating residues substitutes heat production from natural gas
Building steel production	reinforcing steel production	RER (Europe)	
Post-consumer GLT treatment	treatment of waste wood, post-consumer, sorting and shredding	CH (updated to RER)	The upstream process chosen specific to RER
Processes applicable in scenario 3			

Gypsum fiberboard production	market for gypsum plasterboard ecoinvent 3.3	GLO (Global)	
Particleboard production input – electricity	market group for electricity, medium voltage ecoinvent 3.3	RER (Europe)	
Particleboard Production input- urea formaldehyde resin	urea formaldehyde resin production ecoinvent 3.3	RER (Europe)	
Particleboard production input – tap water	market group for tap water ecoinvent 3.3	RER (Europe)	
Particleboard production treatment of waste water	market for wastewater, average ecoinvent 3.3	Europe without Switzerland	
GLT production residue treatment (before incineration)	treatment of waste wood, post-consumer, sorting and shredding	CH (updated to RER)	Since the material is already of small dimensions and a large share is shavings and sawdust, the inventory values are reduced by 50%.
Industrial and district heating from residuals	heat production, wood chips from industry, at furnace 5000kW	CH (updated to RER)	heat production from incinerating residues of particleboard production
Industrial and district heating from residual wood chips	market group for heat, district or industrial, natural gas	RER	Heat production by incinerating residues substitutes heat production from natural gas
Post-consumer particleboard treatment	treatment of waste wood, post-consumer, sorting and shredding	CH (updated to RER)	The upstream process chosen specific to RER

D.4. Substitution rates

Table D.8: Substitution rates considered in the study

Wood product	Amount	Substitution product	Amount	Reference
Monomer	1 kg	Phenol	1 kg	
Oligomer	1 kg	Bisphenol – A	1 kg	
Bio-ethanol (produced from carbohydrate pulp)	1 kg	Gasoline	0.6 kg	This based on the low heating value of the fuels. The heating value of bio-ethanol is 27 MJ/kg and that of Gasoline is 45 MJ/kg (Chiaramonti, 2007; Pacheco and Silva, 2019)
Glue laminated timber	1 kg	Building steel beams	0.66 kg	Cardellini (2018)
Particleboard (from recovered wood)	1m^3 (= 500 kg)	Gypsum plaster board	1m^3 (= 750 kg)	Sathre and Gustavsson (2006)

Industrial and district heating from residual wood chips	1 MJ	Industrial and district heating from natural gas	1 MJ	

D.5. Description of RCF process

The RCF technology is based on the fractionation of the lignocellulosic biomass. RCF is carried out at elevated temperatures of 180-250 °C using alcohol (e.g. methanol) or ether as a solvent, possibly with water as a co-solvent to extract the lignin from the lignocellulose matrix (Van Den Bosch et al., 2015; Van Den Bossche et al., 2021). This step is followed by lignin depolymerisation via solvolysis and catalytic hydrogenolysis to produce reactive lignin fragments. These lignin fragments are prone to subsequent re-polymerisation. So, they are stabilised by hydrogenation by adding a reductive catalyst and a hydrogen source in the form of pressurised hydrogen gas or hydrogen donors to the reaction mixture, resulting in a handful of soluble and stable phenolic products (Van Den Bossche et al., 2021).

The carbohydrate fraction of the biomass is extracted as a by-product, cellulose pulp. In this process, the delignification of woody biomass can be achieved without significant carbohydrate degradation (Liao et al., 2020). Conversion of carbohydrate pulp to bioethanol is chosen as a product for demonstration in this study, but other applications such as (news)paper, cardboard and other chemicals are also possible (Liao et al., 2020).

The RCF is carried out in stirred batch reactors where the solvolytic lignin extraction, lignin depolymerisation and reductive stabilisation occur simultaneously in one vessel. The fractionation process occurs under reductive conditions in the presence of a catalyst. Hence, this technique is called 'Reductive Catalytic Fractionation'. This strategy is known as lignin-first because lignin valorisation is prioritised. While in other pulping techniques (e.g., Kraft pulping), the recovery of pulp prevails and lignin is recovered as a degraded material.

In summary, the RCF reaction requires the lignocellulosic feedstock, a heterogeneous redox catalyst (Nickel), alcohol as solvent (methanol) and co-solvent (water and ethyl acetate) to produce refined lignin oil and carbohydrate pulp. The secondary inputs for the process are pressurised hydrogen and energy (thermal and electrical). The detailed input and output (mass and energy) balance for the RCF reaction is collected from laboratory experiments and simulation of process design in Aspen HYSYS (provided in Annexe D.5). The LCI is modelled based on this data. The laboratory experiments include the RCF process with fresh/virgin softwood as the lignocellulosic feedstock in scenario 1 and recovered (post-consumer) wood for scenarios 2 and 3. The mass balance obtained from these experiments was upscaled to an industrial scale by the process simulation, from which a net mass and energy balance of the RCF process is obtained. The recovered wood or post-consumer wood includes several waste wood streams, mainly packaging wood (e.g. pallets), CDW, commercial and industrial wood and municipal solid waste. This wood is characterised in four different grades (Faraca et al., 2019a), as per the EU Waste Framework Directive:

- **Grade I** (or waste wood A): clean, recyclable wood waste from packaging and off-cuts containing minor amounts of physical (e.g. nails) and organic (e.g. paint, glue) contaminants. It is generally recycled to lower grade material applications (e.g. panel boards, animal bedding)
- **Grade II** (or waste wood B): clean wood from CDW and household furniture waste. It contains increased amounts of non-wood material, such as paints, coatings, glues, and glass, and is recycled towards materials, mainly wood-panel (e.g. particleboards).
- **Grade III** (or waste wood B): wood waste with considerable contamination. It comprises fencing material and flat-pack furniture made from wood panels (such as particleboard and oriented strand board) and is used mainly for energy recovery.
- **Grade IV**: Hazardous wood waste comprising wood from fences, railway sleepers, transmission poles and cooling towers, which has to be disposed of at special facilities.

In this study, the feedstock for RCF in scenario 2 is less-contaminated high-grade waste. So, the laboratory experiments of RCF for scenario 2 were performed on grade II waste that contains CDW. The feedstock for RCF in scenario 3 is highly-contaminated (non-toxic) low-grade waste. So, grade III waste, consisting of particle or fibre-based wood waste, was collected from the waste treatment facility as a feedstock for the RCF process for scenario 3.

D.6. Variability in the data

Table D.9: The values for the input parameter from different sources

Wood product	Values considered in the study	Other values in the literature		Remarks
Substitution rate of steel beam by GLT	1m^3 (259.8 kg) steel beam is equivalent to 1m^3 (393 kg) GLT Substitution rate = Steel use in steel beam (in kg) / Wood use in GLT (in kg) = 0.66	Cardellini (2018)	1.27	The most conservative value has been chosen. The substitution benefit will increase with increase in this substitution rate
		Höglmeier et al. (2015)	0.94 (1 m^3 GLT is equivalent to 369.5 kg steel beam)	
		Petersen and Solberg (2002)	1.09 (0.14 m^3 GLT substitutes 60 kg steel)	
		The Engineered Wood Association (2007)	Minimum 0.66 Maximum 1.66	
		Sandin et al. (2014)	0.99 (1280 kg GLT is equivalent to 1270 kg steel beam)	
Substitution rate of gypsum plasterboard by particleboard	1 m^3 (500 kg) particleboard replaces 1m^3 (750 kg) gypsum plasterboard in a competing structure Substitution rate = mass of gypsum plasterboard/ mass of equivalent particleboard = 1.5	Höglmeier et al. (2015)	1.87 (1 m^3 particleboard is equivalent to 933 kg gypsum plasterboard)	
		Sathre and Gustavsson (2006)	1.5 (1 m^3 ,i.e. 500kg, particleboard is equivalent to 1 m^3 ,i.e. 750kg, gypsum plasterboard)	
		Suter (2016)	3.13 (1 m^3 particleboard is equivalent to 1567 kg gypsum plasterboard)	
Substitution rate of gasoline by bio-ethanol	The heating value of bio-ethanol is 27 MJ/kg and that of Gasoline is 45 MJ/kg Substitution rate (mass of gasoline / mass of bio-ethanol	Ngee Ann (2011)	0.639	The heating value of bio-ethanol is 26.4 MJ/kg and that of Gasoline is 41.3 MJ/kg
		Nwufo et al. (2013)	0.671	The heating value of bio-ethanol is 29.78 MJ/kg and

	with the same heating value) = 0.6			that of Gasoline is 44.4 MJ/kg
		Chiaramonti (2007)	0.616	The heating value of bio-ethanol is 26.9 MJ/kg and that of Gasoline is 43.7 MJ/kg
		European Commission (2009)	0.628	The heating value of bio-ethanol is 27 MJ/kg and that of Gasoline is 43 MJ/kg
Rotation period	60 years	Kaipainen et al. (2004)	Finland – Pine & Spruce 90 years	
			Germany – Pine 120 years Spruce 100 years	
			Spain Pine 80 - 100 -years	
		Nabuurs et al. (2014)	Softwood forest 40-80 years	

D.7. Life cycle inventory analysis results: substitution effects

Table D.10: GWP of the three cascading scenarios when wood substitutes non-wood products.

All the GWP values are in unit kg CO2 equivalent and are rounded to nearest integer. The process emissions are in colour red and embedded carbon emissions are in green.

Stages	Process	Year of emission	Avoided impact [Yes/No]	GWP (Non-biogenic C)	CO_2 bio quantity	Characterisation Factor	GWP (Biogenic C)
Stage 1 : Bio-refinery	Sawn wood production	0		98			
	Sawn wood chipping	0		6			
	RCF	0		345	10	0.25	2
	Carbohydrate pulp to bio-ethanol conversion	0		148	82	0.25	21
	Avoided impact of gasoline production	0	Yes	-39			
	Emission of embedded carbon (at end of life of gasoline)	0	Yes	-115			
	Emission of embedded carbon (at end of life of bioethanol)	0			581	0.25	145

	Avoided impact of phenol production	0	Yes	-44			
	Emission of embedded carbon (at end of life of phenol products)	10	Yes	-51			
	Emission of embedded carbon (at end of life of monomer products)	10			46	0.17	8
	Avoided impact of bisphenol A production	0	Yes	-215			
	Emission of embedded carbon (at end of life of bisphenol A products)	10	Yes	-113			
	Emission of embedded carbon (at end of life of oligomer products)	10			182	0.17	17

Stages	Process	Year of emission	Avoided impact [Yes/No]	GWP (Non-biogenic C)	CO_2 bio quantity	Characterisation Factor	GWP (Biogenic C)
Stage 1 : GLT production	Sawn wood production	0		98			
	GLT Production	0		159			
	Heating using residues	0		4	122	0.25	30
	Avoided impact of heat production (from natural gas)	0	Yes	-32			
	Avoided impact of reinforcing steel production	0	Yes	-575			
Stage 2 : Bio-refinery	Post-consumer GLT treatment	50		4			
	RCF	50		283	8	-0.16	-1
	Carbohydrate pulp to bio-ethanol conversion	50		140	78	-0.16	-12
	Avoided impact of gasoline production	0	Yes	-37			
	Emission of embedded carbon (at end of life of gasoline)	0	Yes	-147			
	Emission of embedded carbon (at end of life of bioethanol)	50			499	-0.16	-80
	Avoided impact of phenol production	0	Yes	-36			

	Emission of embedded carbon (at end of life of phenol products)	10	Yes	-42			
	Emission of embedded carbon (at end of life of phenol/monomer products)	60			37	-0.26	-10
	Avoided impact of bisphenol A production	0	Yes	-160			
	Emission of embedded carbon (at end of life of bisphenol A products)	10	Yes	-84			
	Emission of embedded carbon (at end of life of oligomer products)	60			72	-0.26	-19

Stages	Process	Year of emission	Avoided impact [Yes/No]	GWP (Non-biogenic C)	CO_2 bio quantity	Characterisation Factor	GWP (Biogenic C)
Stage 1 : GLT production	Sawn wood production	0		98			
	GLT Production	0		159			
	Heating using residues	0		4	122	0.25	30
	Avoided impact of heat production	0	Yes	-32			
	Avoided impact of reinforcing steel production	0	Yes	-575			
Stage 2 : Particleboard production	Post consumer GLT treatment	50		4			
	Particleboard production	50		79	161	-0.16	-26
	Avoided impact of gypsum plasterboard production	50	Yes	-206			
Stage 2 : Bio-refinery	Post-consumer GLT treatment	60		3			
	RCF	60		223	6	-0.26	-2
	Carbohydrate pulp to bio-ethanol conversion	60		130	72	-0.26	-19
	Avoided impact of gasoline production	0	Yes	-34			
	Emission of embedded carbon (at end of life of gasoline)	0	Yes	-136			
	Emission of embedded carbon (at end of life of bioethanol)	60			357	-0.26	-93

	Avoided impact of phenol production	0	Yes	-29			
	Emission of embedded carbon (at end of life of phenol products)	10	Yes	-34			
	Emission of embedded carbon (at end of life of monomer products)	70			30	-0.36	-11
	Avoided impact of bisphenol A production	0	Yes	-150			
	Emission of embedded carbon (at end of life of bisphenol A products)	10	Yes	-79			
	Emission of embedded carbon (at end of life of oligomer products)	70			68	-0.36	-24

D.8. Life cycle inventory analysis results: scenario analysis

Table D.11: GWP of the three cascading scenarios when wood use in cascade substitutes virgin wood to provide the same material functions (all values rounded to nearest integer)

Stages	Process	Year of emission	Avoided impact [Yes/No]	GWP (Non-biogenic C)	CO_2 bio quantity	Characterisation Factor	GWP (Biogenic C)
Stage 1 : GLT production	Sawn wood production	0		**98**			
	GLT Production	0		**159**			
	Heating using residues	0			**122**	0.25	**30**
	GLT production from fresh wood	0		**-257**			
	Biogenic carbon emission (GLT from fresh wood - during production)	0	Yes		**-122**	0.25	**-30**
	Biogenic carbon emission (GLT from fresh wood - post consumer use)	50	Yes		**-694**	-0.16	**111**
Stage 2 : RCF	Post-consumer GLT treatment	50		**4**			
	RCF	50		**283**	**8**	-0.16	**-1**
	Carbohydrate pulp to bio-ethanol conversion	50		**140**	**78**	-0.16	**-12**

	RCF of fresh wood to produce carbohydrate pulp (emissions during the process)	0	Yes	**-509**			
	Emission of embedded carbon (at end of life of bioethanol from fresh wood)	0	Yes		**-617**	0.25	**-154**
	Emission of embedded carbon (at end of life of bioethanol from waste wood)	50			**499**	-0.16	**-80**
	RCF of fresh wood to produce monomer (emissions during the process)	0	Yes	**-18**	**-0.32**	0.25	**0**
	Emission of embedded carbon (of monomer products from fresh wood)	10	Yes		**-27**	0.17	**-5**
	Biogenic carbon emission (of monomers products from waste wood)	60			**37**	-0.26	**-10**
	RCF of fresh wood to produce oligomer (emissions during the process)	0	Yes	**-26**	**-0.64**	0.25	**0**
	Biogenic carbon emission (of monomers from fresh wood)	10	Yes		**-53**	0.17	**-9**
	Biogenic carbon emission (of oligomer from waste wood)	60			**72**	-0.26	**-19**

Stages	Process	Year of emission	Avoided impact [Yes/No]	GWP (Non-biogenic C)	CO_2 bio quantity	Characterisation Factor	GWP (Biogenic C)
Stage 1 : GLT production	Sawn wood production	0		**98**			
	GLT Production	0		**159**			
	Heating using residues	0			**122**	0.25	**30**
	GLT production from fresh wood	0		**-257**			
	Biogenic carbon emission (GLT from fresh wood - during production)	0	Yes		**-122**	0.25	**-30**

	Biogenic carbon emission (GLT from fresh wood - post consumer use)	50	Yes		**-694**	-0.16	**111**
Stage 2 : Particleboard production	Post-consumer GLT treatment	50		**4**			
	Particleboard (from recovered wood)	50		**79**	**161**	-0.16	**-26**
	Biogenic carbon emission (particleboard from fresh wood - during production)	0	Yes		**-161**	0.25	**-40**
	Biogenic carbon emission (particleboard from fresh wood - post consumer use)	10	Yes	**-143**	**-600**	0.17	**-102**
Stage 3 : RCF	Treatment of post-consumer particleboard	60		**3**			
	RCF	60		**223**	**6**	-0.26	**-2**
	Carbohydrate pulp to bio-ethanol conversion	60		**130**	**72**	-0.26	**-19**
	RCF of fresh wood to produce carbohydrate pulp (emissions during the process)	0	Yes	**-472**			
	Emission of embedded carbon (at end of life of bioethanol from fresh wood)	0	Yes		**-621**	0.25	**-155**
	Emission of embedded carbon (at end of life of bioethanol from waste wood)	60			**357**	-0.26	**-93**
	RCF of fresh wood to produce monomer (emissions during the process)	0	Yes	**-12**	**-0.26**	0.25	**0**
	Biogenic carbon emission (of monomers from fresh wood)	10	Yes		**-22**	0.17	**-4**
	Biogenic carbon emission (of monomers from waste wood)	70			**30**	-0.36	**-11**
	RCF of fresh wood to produce oligomer (emissions during the process)	0	Yes	**-28**	**-0.6**	0.25	**0**

	Biogenic carbon emission (of monomers from fresh wood)	10	Yes		**-50**	0.17	**-8**
	Biogenic carbon emission (of oligomer from waste wood)	70			**68**	-0.36	**-24**

D.9. Sensitivity analysis

Table D.12: Sensitivity ratio of the GWP with the increase in the substitution rate of each product by 10%

	Bio-ethanol substitution rate		Monomer substitution rate	
Scenario	**Method 1**	**Method 3**	**Method 1**	**Method 3**
Scenario 1	0.131	0. 808	0.147	0.499
Scenario 2	0.244	0.463	0.239	0.152
Scenario 3	0.104	0.236	0.089	0.088

	Oligomer substitution rate		GLT substitution rate	
Scenario	**Method 1**	**Method 3**	**Method 1**	**Method 3**
Scenario 1	0.737	1.743		
Scenario 2	1.054	0.473	3.822	1.123
Scenario 3	0.46	0.318	1.777	0.807

	Particleboard substitution rate	
Scenario	**Excluding biogenic carbon**	**Including biogenic carbon**
Scenario 1		
Scenario 2		
Scenario 3	0.613	0.278

Table D.13: Sensitivity ratio of the GWP with increase in the lifetime of each product by 10% (when substituting non-wood products)

Scenario	Monomer based product lifetime	Oligomer based product lifetime	GLT lifetime	Particleboard lifetime
Scenario 1	0.99	1.01		
Scenario 2	0.234	0.227	0.356	
Scenario 3	0.081	0.087	0.516	0.195

Table D.14: Sensitivity ratio of the GWP with increase in the lifetime of each product by 10% (when substituting virgin wood).

Scenario	Monomer based product lifetime	Oligomer based product lifetime	GLT lifetime	Particleboard lifetime
Scenario 1				
Scenario 2	0.005	0.021	0.003	
Scenario 3	0.003	0.006	0.008	0.011

Annex E.

E.1. Life cycle inventory

Table E.1: Life cycle inventory for the production of 1 single-use pallet, based on the data provided by Gasol et al. (2008)

Input	Amount
Sawn timber (kg)	15.7
Nails (kg)	0.27
Electricity (kWh)	0.43
Gas (kWh)	1.05

Table E.2: Life cycle inventory for the production of 1 cardboard pallet

Input	Amount
Cellulose pulp (kg)	5kg
Electricity (kWh)	0.79

Table E.3: Life cycle inventory for the production of 1 multiple-use pallet, based on the data provided by Gasol et al. (2008)

Input	Amounts required for		Total
	Production	Maintenance	
Sawn timber (kg)	25.62	8.43	34.05
Nails (kg)	0.44	0.38	0.82
Alkyd paint (litre)	0.04	0.06	0.10 litres or 0.13 kg Assuming density = 1.3 kg/litres (Jotun Protects Property, 2021)
Electricity (kWh)	0.71	1.15	1.86
Gas (kWh)	1.73	0	1.73

Table E.4: Overview of other utilised datasets from the database ecoinvent

Process/product	Dataset	Location	Remarks
Process applicable for solid wood (single-use amd multiple-use) pallet production			
Sawn wood production	market for sawnwood, softwood, raw, dried (u=20%) ecoinvent 3.3	RER (Europe)	
Nails	steel production, low-alloyed, hot rolled ecoinvent 3.3	RER (Europe)	
Heat	market group for heat, district or industrial, natural gas ecoinvent 3.3	RER (Europe)	
RCF input – electricity	market group for electricity, medium voltage ecoinvent 3.3	RER (Europe)	
Waste wood incineration – heat production	heat production, wood chips from industry, at furnace 5000kW ecoinvent 3.3	CH (Switzerland)	
Waste wood incineration – furnace	market for furnace, wood chips, with silo, 5000kW	RER (Europe)	
Waste wood incineration – electricity supply	market group for electricity, low voltage	RER (Europe)	
Waste wood incineration – Dust collector	GLO: market for dust collector, electrostatic precipitator, for industrial use ecoinvent 3.3	GLO (Global)	

Wood ash treatment	market for wood ash mixture, pure	RER (Europe)	
Avoided impact of heat production	market group for heat, district or industrial, natural gas	RER (Europe)	
Transport of the pallet	transport, freight, lorry 16-32 metric ton, EURO6	RER (Europe)	Transport distance – 150 tkm
Treatment of waste pallets	treatment of waste wood, post-consumer, sorting and shredding	CH (updated to RER)	The upstream process chosen specific to RER
Process applicable for cardboard pallet production			
corrugated board box production	corrugated board box production	RER (Europe)	
Electricity supply	market group for electricity, medium voltage	RER (Europe)	
The LCI for the production of particleboard from virgin and waste wood is the same as in Chapter 6.			

List of Publications

Peer Reviewed Articles - Published

Navare K, Arts W, Faraca G, Bossche G Van den, Sels B, Van K. Environmental impact assessment of cascading use of wood in bio-fuels and bio-chemicals. *Resour Conserv Recycl*. 2022;186(2006):106588. doi:10.1016/J.RESCONREC.2022.106588

Boekaerts B, Vandeputte M, **Navare K**, et al. Assessment of the environmental sustainability of solvent-less fatty acid ketonization to bio-based ketones for wax emulsion applications. *Green Chem*. 2021;23(18):7137-7161. doi:10.1039/D1GC02430B

Navare K, Muys B, Vrancken KC, Van Acker K. Circular economy monitoring – How to make it apt for biological cycles? *Resour Conserv Recycl*. 2021;170:105563. doi:10.1016/j.resconrec.2021.105563

Kumaniaev I, **Navare K**, Crespo Mendes N, Placet V, Van Acker K, Samec JSM. Conversion of birch bark to biofuels. *Green Chem*. 2020;22(7):2255-2263. doi:10.1039/d0gc00405g

Liao Y, Koelewijn SF, van den Bossche G, van Aelst J, van den Bosch S, Renders T, **Navare K**, Nicolaï T, van Aelst K, Maesen M, Matsushima H, Thevelein JM, Van Acker K, Lagrain B, Verboekend D, Sels BF. A sustainable wood biorefinery for low-carbon footprint chemicals production. *Science (80-)*. 2020;367(6484):1385-1390. doi:10.1126/science.aau1567

Marques A, Cunha J, De Meyer A, **Navare K.** Contribution towards a comprehensive methodology for wood-based biomass material flow analysis in a circular economy setting. *Forests*. 2020;11(1):106. doi:10.3390/f11010106

Peer Reviewed Articles – In preparation

Navare, K., Parchomenko, A., Vrancken, K. C. & Van Acker, K. Statistical entropy analysis to evaluate cascading use of wood.

Baddigam, K. R., **Navare, K.**, Witthayolankowit, K., Mathew, A. P., Van Acker, K., Samec, J. S. M. Recycling of PET by organo-catalyzed methanolysis depolymerization: Sustainability evaluated by LCA.

Book chapter

Van Den Bossche, G., Vangeel, T., Van Aelst, K., Arts, W., Trullemans, L., **Navare, K.**, Van Den Bosch, S., Van Acker, K., Sels, B.F. Reductive Catalytic Fractionation: From Waste Wood to Functional Phenolic Oligomers for Attractive, Value-Added Applications. In: *ACS Symposium Series*. Vol 1377. ; 2021:37-60. doi:10.1021/bk-2021-1377.ch003

Published reports

Vandereydt I, Breemersch K, **Navare K**. *Biomass Flows in the Flemish Economy – Circular Economy (CE) Center publication N° 8.*; 2019.

Oral and Poster Presentations at (Inter)National Conferences

Presented at the international engineering conferences - Life Cycle Sustainability Assessment for Waste Management and Resource Optimisation
https://engconf.us/conferences/civil-and-environmental-engineering/wastelca-3-life-cycle-sustainability-assessment-for-waste-management-and-resource-optimization-iii/
Date: 05th – 10th June 2022
Oral presentation titled 'Evaluating carbon balance of wood cascading – the need for accounting temporal information'

Presented at the International conference on life cycle management (LCM)
https://www.lcm2021.org/
Date: 08th September 2021
Oral presentation titled 'Statistical entropy analysis to evaluate cascading use of wood and its impact on material circularity'

Presented at the conference Entropy 2021 - The Scientific Tool of the 21st Century
https://entropy2021.sciforum.net/
Date: 6th May 2021
Oral presentation titled 'Statistical entropy analysis to evaluate cascading use of wood'

Presented at the society of environmental toxicology and chemistry (SETAC)
https://helsinki.setac.org/
Date: 28th May 2019
Poster presentation titled 'Circular economy indicators: Do they measure circularity of biological cycles?

Master thesis supervisions

Stijn Heineman with topic 'Modelling an RCF biorefinery to assess the environmental impact of bio-oil production using waste woods', who successfully defended it in June 2021.

Margot Vandeputte with topic 'A comparative assessment of the environmental sustainability of biowax versus paraffins via a Green Chemistry and Life Cycle Assessment approach', who successfully defended it in June 2019.