Life-cycle analysis in timber construction - environmental impact and decision-making

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ABSTRACT

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Keywords life cycle assessment, life cycle thinking, timber, carbon footprint, circular economy, construction and demolition waste, decision-making, risk-informed approach

The construction sector is recognized as a major player in climate change worldwide, requiring a shift towards renewable energy sources and sustainable material use. Timber, as a natural and renewable material, has been increasingly advocated as a replacement for carbon-intensive construction materials such as steel and concrete. The life cycle approaches such as life cycle assessment (LCA) are adopted, to address relevant benefits and obstacles from sustainability perspective. The main objective of this thesis is investigating the environmental performance of timber construction projects from life cycle perspective, to discuss relevant potential and challenges in climate change abatement. The research approach involves (i) an overview of existing LCA implementation on timber construction projects to find the research gap, and (ii) investigation on the selected overarching topics, including both upfront and post-use schemes of timber use in construction.

The overview reveals large variation in the existing literature of LCA, as well as discovers common features. With respect to the large variation found in the overview, the research investigates the potential of using environmental product declarations (EPDs) to reduce the variability of LCA. However, the results show the obvious variation and inconsistency in EPDs for the same timber product. Similar finding is also observed for generic inventory datasets. Nonetheless, applying LCA to assist decision-making during the tendering process, with using EPDs, is explored. The results indicate that setting limits in the bidding document can effectively reduce the variability of LCA, meanwhile improve efficiency and comparability. Thus, consideration of environmental impact at design stage, as a decision rule to optimize design for sustainable construction is explored. The environmental impact is focused on climate change, depicted by CO_2-eq. obtained from LCA results. The risk-informed optimization approach is utilized, which is cost-based. This approach is broadened covering environmental aspect, apart from structural safety and cost. A cost function reflects the above-mentioned aspects is developed.

The influence of different end-of-life (post-use scheme) scenarios on the environmental impact of timber, is studied. The focus is wood cascading, addressing the relevant benefits and challenges in prolonging the life of timber and combating climate change. Three aspects are enclosed: technology, environment, and economy. The investigation reveals that policy is anticipated to be the driving force for the reuse of timber, in the Finnish context. Furthermore, it also indicates that, the equilibrium between reuse and energy recovery of timber should be accounted, as timber serves dual roles: material use for carbon storage and incineration for renewable energy, with each choice involving a trade-off.

Preface

This dissertation is the culmination of years of dedicated research. My passion about pursuing doctoral research originated from a Nordic project, where Prof. Lauri Salokangas was the coordinator and my initial supervisor. Lauri, thanks for the inspiration and for providing the opportunity to pursue my doctoral studies. Throughout the research process, I have gained invaluable insights and faced challenges that pushed my boundaries. This journey embodies not only my academic pursuit but also a voyage of self-discovery and growth.

I warmly thank my supervisor, Prof. Gerhard Fink, for constant support and supervision throughout the years. With countless discussions and debates, I have profoundly learned about scientific rigor and clarity, which I will uphold in the future research. Aslo, I sincerely acknowledge preliminary examiners of my dissertation, Prof. Chiara Piccardo and Prof. Alexander Hollberg, for their time and constructive comments, which have obviously enhanced the quality of this dissertation.

I would like to express my gratitude to co-authors: Prof. Mark Hughes, Prof. Minna Halme, Dr. Ramon Hingorani, and Prof. Jochen Köhler. Special thanks also to my group members, colleagues, and friends for professional discussions and joyful casual conversations.

Appreciation to Emma, Camilla, and Jenni: our priceless “S” group has been my energy station and source of laughter. I am truly grateful for the lovely friendship we have shared over the past years. Now, it can be named as “Dr. S” group. A special thanks to Emma for the attentive listening, constant support, and encouragement, especially during tough times.

I would like to express my gratitude to my dear friends Han, Yang and Yauri, for the beautiful friendship and invaluable communications. Yang, thanks for listening, always understanding and encouraging me whenever I am under stress. Yauri, I could not be more grateful for you being there for me, especially during the late stage of finalizing this dissertation.

Thanks to my E-family, I am profoundly grateful for this lovely bond and the pleasant moments we shared. Additionally, I would like to thank those who have accompanied me throughout this challenging journey.

More importantly, I extend heartfelt and profound appreciation to my beloved family, whose non-stop love, unconditional trust, and relentless supports have been my greatest source of strength. I appreciate the care and wisdom my mother has offered along the way. Lastly, I would like to thank myself for the passion and resilience in successfully completing the doctoral studies. Reflecting on this journey, I realize it is a road less traveled, and I am so proud of myself for having walked it.

Espoo, 26.7.2025

Yishu Niu

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Niu, Yishu; Fink, Gerhard. 2019. *Life Cycle Assessment on modern timber bridges*, Wood Material Science & Engineering, 212-225, doi.org/10.1080/17480272.2018.1501421 .

II Niu, Yishu; Rasi, Kaarle; Hughes, Mark; Halme, Minna; Fink, Gerhard. 2021. *Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland*, Resources, Conservation & Recycling, 105555, doi.org/10.1016/j.resconrec.2021.105555 .

III Niu, Yishu; Fink, Gerhard. 2024. *Applying LCA in early stages of timber construction projects - Potential and challenges to support decision-making*, Submitted to Developments in the Built Environment, April 2024.

IV Niu, Yishu; Hingorani, Ramon; Fink, Gerhard; Köhler, Jochen. 2022. *Design concept for the sustainable use of timber in structures*, In 13th International Conference on Structural Safety & Reliability (ICOSSAR), proceedings .

Author’s contributions

Publication I: “Life Cycle Assessment on modern timber bridges”

Yishu Niu conducted the literature review, analyzed and summarized results, as well as wrote the manuscript. Gerhard Fink provided feedback for the manuscripts.

Publication II: “Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland”

Yishu Niu conducted the literature review, investigation and formal analysis, as well as wrote the manuscripts. Kaarle Rasi conducted the interview and proposed the conceptual framework. Mark Hughes, Minna Halme, and Gerhard Fink provided feedback for the manuscripts. All authors together were responsible for the conceptualization.

Publication III: “Applying LCA in early stages of timber construction projects - Potential and challenges to support decision-making”

Yishu Niu conducted the investigation and formal analysis, as well as wrote the manuscripts. Gerhard Fink contributed to the planning and supported the simulation, as well as provided feedback for the manuscripts. Both authors were responsible for the conceptualization.

Publication IV: “Design concept for the sustainable use of timber in structures”

Yishu Niu conducted the literature review and the analysis, as well as wrote the manuscripts, where Ramon Hingorani wrote the structural design related part, and commented on the enclosed equations. Ramon Hingorani, Gerhard Fink, and Jochen Köhler provided feedback for the manuscripts. All authors together were responsible for the conceptualization.

Abbreviations

C&D Construction & demolition

CDF Cumulative distribution function

CE Circular economy

CO_2-eq. CO_2-equivalent

COV Coefficient of variance

EoL End-of-life

EPD Environmental product declaration

FU Functional unit

GHG Greenhouse gas

GLT Glued laminated timber

GWP Global warming potential

LCA Life cycle assessment

LCC Life cycle cost(ing)

LCI Life cycle inventory

LCIA Life cycle impact assessment

LCM Life cycle management

LCSA Life cycle sustainability assessment

LCT Life cycle thinking

LVL Laminated veneer lumber

MC Monte Carlo

NZEB	Net-zero energy building
PCR	Product category rules
S-LCA	Social life cycle assessment

1. Introduction

1.1 Motivation

Rapid climate change has posed a significant challenge to humans in recent decades, which has urged the reconsideration of current economic activities in order to pursue a more sustainable future. The construction sector has been considered to be a large contributor to the global environmental burden, not only in terms of the climate change, but also through the substantial consumption of materials and energy. For example, in Europe, 36% of CO_2 emissions and 40% of energy consumption came from the construction sector (built environment), by the year 2018 [1]. Globally, it contributes the 40% of annual CO_2 emissions, and 34% of total final energy consumption in 2021 [2].

In facilitating the transformation towards a sustainable future, life cycle thinking (LCT) serves as a fundamental concept. The European Union (EU) has released initiatives such as regulations, actions, and protocols based on LCT. These initiatives cover several aspects, including e.g., circular economy (CE), waste hierarchy and management, and taxonomy for sustainable activities [3–7]. In 2020, the European Commission published a classification system of economic activities that are viewed as environmentally sustainable, called the EU Taxonomy [7]. On the national level, there are also initiatives and guidelines published for directing such sustainability and climate change considerations in practice. In Finland, the Ministry of the Environment published guidelines of carbon footprint calculation for buildings in 2019 [8] and a reformed Waste Act, together with launching a platform for the waste materials market [9].

The life cycle approach is a comprehensive framework that can be used to address climate change and pursue sustainability within the construction sector. Within the framework, several aspects such as environmental impact and circular economy are covered.

From the perspective of sustainability and LCT, as well as informed by the Author's structural engineering background, construction projects may be improved in two general directions. First, the usage life of the material could be prolonged, e.g., materials originating from decommissioned building could be reused (as its original form with the same function) in other buildings, or reprocessed for recycling into alternative applications and products. Second, the material & energy consumption (associated with environmental impact and economic cost) could be reduced at the outset. For instance, the building design can be oriented towards lowering environmental impact at early stages.

There are various techniques of LCT (often referred to as life cycle approaches), which involve e.g., the consideration of impacts caused through the product's[1] entire lifespan, as well as identifying ways to minimize those impacts. These life cycle approaches aim at assisting in decision-making for different purposes such as product development and procurement optimization [10]. One of the common approaches dealing with the aspect of environmental impact is life cycle assessment (LCA). However, the research on LCA of timber structures remained relatively underdeveloped, which was also stated in research studies [11–15]. Another approach that has gained increasing attention is CE, which promotes sustainable resource use and waste reduction, and can be effectively optimized through LCA. Both LCA and CE are supported by LCT, which also signifies a series of tools to enhance and evaluate CE strategies [16]. The CE in the timber construction sector also faces challenges, such as limited research, technological barriers, and CE modeling (see e.g., [17, 18]). Details about these life cycle approaches are presented in Section 2.1.

During the past several years, the adoption of LCA is on the rise across various domains, e.g., in agriculture and construction sectors; among manufacturers, investors, and policy makers; on both the product level and project level. Regarding the efforts and attempts in the construction sector to pursue a low-carbon built environment, green construction material application has been advocated. For example, promotion (from both government and industry) of renewable materials such as timber in construction has been ongoing, globally. As a natural and renewable material, timber is seen to be an alternative to conventional carbon-emission-intensive materials like concrete or steel. It is regarded as contributing to the abatement of climate change and the alleviation of substantial non-renewable material & energy consumption, in the construction sector. This benefit is supported by the efficient application of wood and its sourcing from sustainably managed forests. Research studies have shown that using wood products can reduce energy consumption and CO_2 emissions by up to 50%, compared to conventional building materials [15, 19, 20]. Meanwhile, organizational reports [21–23] highlighted the importance of using wood products in promoting sustainable development and mitigating climate change. Timber could store carbon when it is applied in buildings, while new trees absorb and sequester carbon dioxide when growing, and such growing trees are considered as a carbon sink. In addition, substantial timber resources and relatively massive timber industries in Finland (where the research has been conducted), make such promotion viable and favorable. However, how the benefits and potential challenges of timber can be reflected and illustrated in construction projects, in terms of LCT, along with the complexity of buildings (as a

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[1] Product here represents both construction product (incl. product portfolio) and construction project.

product system), is still under limited studies. It should be noted that, the focus of this thesis is restricted to the product system, i.e., construction projects. Consequently, other aspects enclosed in the material flow and value chains such as environmental impacts/benefits associated with the resource harvesting, forest management practices and supply chain operations, are beyond the scope of this thesis.

Currently, the decision-making process in construction projects typically emphasizes economic costs and is characterized by a short-term perspective. LCT (particularly LCA) may be considered in the planning of certain construction projects, however, it often serves only as a supplementary document rather than a decisive factor or part of decision-making criteria. The relevant difficulties include, for example: (1) LCA is typically conducted after the design process of a construction project and in isolation from other aspects like economic cost analysis. (2) The interpretation of the quantitative results of LCA usually varies widely, often overlooking critical factors such as variability in data inputs, different assumptions, and the overall quality of the underlying data. This can lead to differing conclusions. Despite these challenges, the use of LCT and LCA has the potential to facilitate more sustainable and informed decision-making. Ideally, LCT should be integrated throughout the entire lifespan of construction projects to promote sustainability, starting from the initial phase for achieving maximum effect (e.g., [24, 25]). As an example, using LCA in the early stages of a construction project can assist in identifying the most appropriate design alternative, according to the environmental performance within the life cycle. However, in practice it is rarely realized, despite the considerable potential. LCT can also be applied to existing structures that are to be demolished or refurbished, aiming to optimize material lifespan. It is important to note that individual materials may ultimately have different end-of-life (EoL) scenarios. Currently, EoL treatment of construction & demolition (C&D) waste timber often involves direct incineration for energy recovery, which overlooks cascading options and fails to maximize the material value (e.g., [11, 26]). Nevertheless, the necessity for such cascading aligns with the EU's strategy, such as the working document and action plan for the circular economy [3, 27].

1.2 Objectives and scope

The goal of this thesis is to investigate LCA applications on timber structures, identify dominant factors of environmental impact, address challenges, as well as propose potential improvements and applications. Besides the LCA, supportive tools such as CE and risk-informed approach are incorporated into the analysis. The scope is limited to timber construction projects, with a particular emphasis on the timber elements with non-hazardous treatment (which can be found in timber bridges), although the review of LCA application on such timber bridges is covered in the related publication. This exclusion is based on the understanding that timber subjected to hazardous treatment is prohibited in timber buildings, which presently constitute the dominant segment of timber construction. Furthermore, although such treatment is still permitted in certain European countries [11], it will be prohibited in the near future.

Individual research questions (RQs) are outlined below, followed by a concise overview of the research process.

RQ1: What is the status quo of analyzing the environmental impact of timber construction projects with LCT, and what are the critical issues and possible improvements?
LCA is the most common tool for assessing environmental impact with life cycle thinking, however, research on LCA of timber construction projects has not been collectively or widely studied. The focus here is to explore the status-quo, incl. critical issues, common conclusions, and potential improvement.

RQ2: How could life cycle approaches provide added value to the role of cascading timber, concerning abating climate change and prolonging the life of timber in the construction sector?
Current EoL practice of C&D waste timber does not maximize the material value, from the value chain's perspective, as it is typically subjected to direct incineration. Cascading can mitigate environmental burdens and facilitate pursuing the CE. Thus, in this thesis, LCA and CE strategy are adopted for the investigation. It is examined whether the EoL reform (e.g., by reusing timber) can add value to climate change mitigation and CE.

RQ3: What are the potential and challenges of using LCA to assist the decision-making in the tendering process of timber construction projects?
LCA is often considered as an individual evaluation. Using it in the decision-making process of construction projects may effectively influence the final environmental performance such as total CO_2-equivalent (hereafter, abbreviated as CO_2-eq.). Therefore, in this thesis, a study investigated the potential (benefits and challenges) of using LCA to assist decision-making during the tendering process of construction projects.

RQ4: How could environmental impact be considered in extending or re-configuring the concept of risk-informed optimization for structures?
Current environmental impact consideration in construction projects (with the help of LCA), usually occurs after the design stage. However, to enhance the efficacy of using LCA in achieving sustainability, it is beneficial to consider environmental impact already from the initial design phase. Thus, one part of the thesis dealt with developing a design concept, where the risk-informed optimization approach is expanded by adding the environmental impact. The objective is to mitigate climate change through optimizing structures, without compromising structural safety and durability.

The research presented in this thesis follows a structured process, as outlined in this paragraph. Initially, the status quo of LCA application on timber construction projects and its consideration of the EoL scenarios for timber was reviewed. This review aimed to provide an overview of the current state of knowledge, as well as identify common characteristics and potential research themes (relevant to RQ1 and partly RQ2). The insights derived from this review subsequently informed the research topics explored in this thesis. These topics can be categorized into two groups: late stage (relevant to RQ2) and early stage (relevant to RQ3 and RQ4). Here the "late stage" represents the stage starting from the EoL stage, e.g., EoL stage and subsequent reuse, recycling, etc. Thus the investigation focused on the EoL scenarios of timber, with an emphasis on prolonging the life of timber materials through cascading. The "early stage" represents the stage before the permission for construction, e.g., early planning and procurement. The corresponding investigation centered on applying LCA to timber projects to fulfill two primary roles: assisting the decision-making during the tendering process, and incorporating LCA into the risk-informed optimization approach.

1.3 Research contribution

Status quo of environmental life cycle assessment on timber construction (with focus on the material and bridges) (Publication I & II)

Apart from the small amount of timber application in the construction sector globally, the LCA implementation on timber structures is rather limited but versatile. The status quo of construction timber materials (incl. the end-of-life stage) was explored. The study revealed the substantial proportion of wood waste in the construction sector in the Finnish context, the common EoL scenario of wood waste, and the potential of other EoL scenarios of wood waste with considering waste hierarchy regulated by the European Committee. The study also presented general conclusion of environmental performance in different life cycle stages, potential improvements for the future research.

Prolonging the life of timber materials with life cycle thinking (Publication II)

Extending the life of existing buildings and materials is considered to be one of the sustainable solutions, for combating both climate change and resource scarcity. A holistic investigation on the technical, economic and environmental aspects regarding the extension of the usage life of C&D timber was conducted. A case study of a cascading scenario for timber is presented, where the potential of reusing timber to mitigate climate change was quantified. The study addressed relevant challenges and potentials, and also proposed a reconfigured conceptual framework to attain circularity in the use of wood/timber, which contributes to combating resource scarcity. The balance between the reuse and energy recovery of wood is also addressed.

Application of LCA for decision-making of timber projects (Publication III)

LCA is preferably applied in the early stages of projects, and is expected to be accounted in decision-making. Characteristics of applying LCA in early stages of construction projects (especially timber projects) for the decision-making during the tendering process were investigated. The investigation includes: addressing aspects regarding the variability of LCA, analyzing influential parameters and associated uncertainties of LCA for structural components, and comparing the variability of LCA through a case study where selected parameters and different scenarios were included. The study addressed potential benefits and challenges when applying LCA for timber construction projects during the tendering process. The results of the case study noted the significance of considering the variability associated with LCA calculations, and revealed the potential of reducing the uncertainty of LCA, to enhance the efficiency (i.e., reduce the possibility of making wrong choices) and comparability for decision-making.

Inclusion of environmental impact in design rules of timber projects (Publication IV)

The use of timber in structures is considered to be a solution for reducing the environmental impact and energy consumption. However, structural safety needs to be guaranteed, along with other performance goals required in the standards. To achieve optimal structural design while considering sustainability of structures, manifold requirements and constraints are subjected, including safety, functionality, economy and environmental performance among others. The study compared the global warming potential (GWP) and corresponding monetized values of two systems that are functionally equivalent from a structural perspective: timber and concrete floor systems. The study then proposed a concept for integrating LCA into existing decision rules, incorporating a cost-based, risk-informed optimization approach.

1.4 Structure of the thesis

The structure of the thesis and compilation of publications are illustrated schematically in Figure 1.1. Chapter 1 presents the overview of the thesis, including the introduction, aim and scope, research questions, structure of the research and relevant contributions. In Chapter 2, the background and state-of-the-art review on the research topics are addressed, and selected research gaps are identified. Research gaps are used to select research topics addressed in the present thesis. Specifically, LCT concept and approaches (e.g., LCA) are explored. An overview of selected approaches (LCA, CE, and risk-informed optimization) assisting the research of this thesis is also provided. In Chapter 3, the methods employed in this thesis, as well as the overview of the research process are described. These methods are: information collection, interview, questionnaire, case studies, Monte Carlo (MC) method, risk-informed optimization. Results of the research are summarized in Chapter 4. A summary of findings and all relevant aspects of the publications, is provided individually. Limitations embedded in the publications are also discussed. In the final chapter (Chapter 5), conclusions of the thesis, contributions, and recommendations for future prospects are presented.

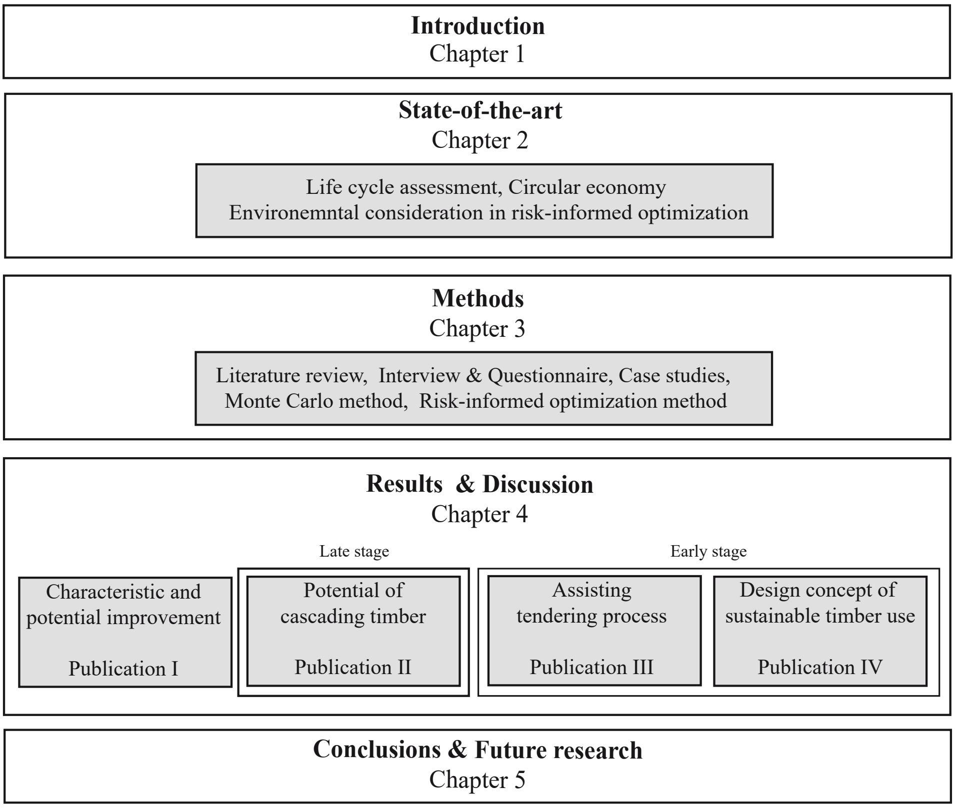

Figure 1.1. Illustration of the structure of thesis.

In the following paragraph, links between the publications are described. In Publication I, the LCA implementation in timber (use in) construction was examined, with a focus on climate change and sustainability. This initial investigation was crucial as it identified the existing gap in the literature. Findings from this investigation, such as typical characteristics and potentials, were used to shape the overarching research topics for Publication II - Publication IV. Consequently, the research was conducted in two directions: early stage and late stage (as defined in Section 1.2).

- In the late stage, LCT was applied to investigate its added value in prolonging the life of timber. A review of existing research and relevant policy and action regarding timber cascading was conducted, together with interviews for obtaining industrial insights and an LCA case study on the EoL scenario of timber (see Publication II).

- In the early stage, LCA was explored for use in assisting decision-making and optimization (see Publication III and Publication IV). Due to the large variation among LCA studies found in Publication I, uncertainty was investigated. Therefore, implementing LCA as part of decision-making criteria in tendering was explored, through a questionnaire and a case study (see Publication III). In addition, the ideal situation of using LCA is to consider it from cradle, even earlier than the tendering process. Thus, integrating LCA into the decision rules applied in risk-informed optimization for structural design at early stages, was investigated. A design concept based on risk-informed calibration was then proposed, to achieve an optimal design solution (see Publication IV).

2. State-of-the-art

This chapter introduces the state-of-the-art in various research topics pertinent to this thesis. It provides an overview of fundamental concepts, terminology, and methodologies. Research gaps are subsequently summarized at the end.

2.1 Life cycle thinking and approaches

LCT acts as umbrella concept for approaches addressed in various aspects of sustainability. The overview of LCT, relevant approaches, and sustainability is illustrated in Figure 2.1. The main objective of LCT is to reduce the resources consumption and emissions to the environment, while also improving socio-economic performance throughout the entire lifespan, thereby avoiding burden shifting [10, 28]. LCT is a concept (qualitative approach), which originally focuses on the production system to consider environmental, economic, and social impact over its entire life cycle (cradle-to-grave) [28, 29]. These three aspects are also recognized as the fundamental pillars of sustainability, which can be pursued by applying LCT [30].

To make the LCT operational, life cycle management (LCM) has been introduced. It is considered as business or management approach that combines various tools, techniques, and methodologies associated with LCT, thus facilitates its practical application [31]. Research concerning the application of LCM in the construction sector has been on-going over the past decades, e.g., [32–36]. It is important to acknowledge that the definition and interpretation of LCM might vary slightly across different disciplines.

Various life cycle approaches have been developed [31], and from the author's perspective as a structural engineer, they can be divided into two aspects: analytical (e.g., tools, techniques) and managerial (e.g., policy, regulation, certification, programme). For the analytical aspect, the purpose is to quantitatively assess the potential effects or impacts of an object throughout its lifetime. Common tools for quantitative assessment are: LCA, life cycle cost (LCC), social life cycle assessment (S-LCA), risk assessment, and input-output analysis. For the managerial aspect, the target is to guide and manage the shift towards sustainability. Measures may include, for exam-

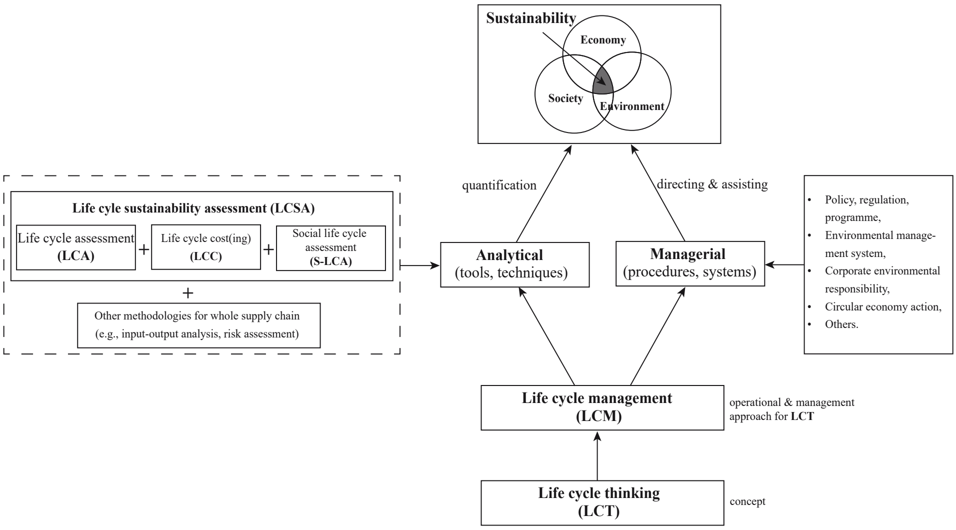

Figure 2.1. Overview of life cycle approaches and sustainability (the author's own perception regarding the research topic of this thesis, based on [28, 31, 37]).

ple, regulation, governmental policy programs and corporate programs, sustainable procurement, and integrated waste management systems [10].

With the increasing sustainability demand and advocacy, there has been a growing interest in using life cycle approaches to assess the sustainability of products and processes, has been stimulated. A more comprehensive approach has emerged to include not only environmental impact but also social and economic dimensions of sustainability. This approach provides a full evaluation of life cycle sustainability assessment (LCSA), composed by the analysis of LCA, LCC, and S-LCA [31, 37]. However, it has been observed that in practical applications, these three analyses are often performed individually and reported separately [38, 39]. Another important aspect is, given the critical imperative to tackle climate change and the excessive emphasis on this matter, LCA might become the only focus. This means that other critical sustainability factors such as cost and social impacts are overlooked. Additionally, LCA may be mistakenly equated with sustainability analysis (i.e., LCSA) [37, 40].

Life cycle approaches are applicable across all sectors, such as food, textile, energy, and construction. The LCA implementation in the construction sector occurred relatively late compared to other sectors, but has been increasing rapidly. This is mainly due to the urgent need of reducing the carbon footprint and operational energy consumption from the built environment. In addition, life cycle approaches can be applied at different life cycle stages with various scenarios, such as an existing building that needs renovation and a new building that is being designed and later constructed. More details are provided in the following sections.

2.2 Life cycle assessment (LCA)

2.2.1 LCA methodology

In this thesis, the primary methodological tool employed is LCA, which denotes life cycle environmental impact assessment, as mentioned in Section 1.2. The concept of LCA originated in the industry over 50 years ago. In 1969, Coca-Cola company conducted a confidential study on environmental issues of its products. Through an environmental comparison of different container alternatives, the company realized a significant reduction in energy consumption throughout the product's lifetime [41]. This could be considered as the overture of (environmental) LCA. Following a period of quiet in the 1970s, there was a rise in method development and international collaboration in the scientific and research community during the 1980s and 1990s [42]. Until 1990, the term LCA was created during the first international workshop supported by the Society of Environmental Toxicology and Chemistry (SETAC). The International Organization for Standardization (ISO) also involved, in 1997, it published ISO 14040 standard [43] for LCA, providing LCA principles and framework [42]. Following this, a series of ISO standards have been released elaborating the LCA methodology. For example, ISO 14040 [43] got updated in 2006, along with a new standard providing the requirements and guidelines for LCA - ISO 14044:2006 [44], as well as standard for environmental declaration ISO 14025 [45]. Since then, as part of life cycle analysis, LCA study in various industrial sectors and products has been conducted increasingly and extensively. Meanwhile, relevant ISO standards have been developing and updating, some regional standards (such as EN standards) tailored for the LCA of construction works [46–48] have also been published.

In the ISO 14040:2006 [43], the LCA is defined as *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"*. The "potential environmental impacts" here are related to the functional unit (FU) of a product system, and the functional unit should be clearly defined prior to the assessment. The life cycle represents consecutive and interlinked stages (i.e., cradle-to-grave), starting from raw material acquisition, through production and use, to the end-of-life treatment for reusing, recycling, recovery and final disposal [43, 49, 50]. The assessment framework of LCA is also defined in ISO 14040:2006 [43], see Figure 2.2. As a general framework, it is also applied in other analytical life cycle approaches, such as LCC and S-LCA, but they are not the focus of this thesis. In Figure 2.2, it can be seen that, four phases are involved: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. Before delivering the results, completeness, consistency, and sensitivity check need to be conducted. The results could be directly applied to support decision-making, as well as assist product development and refining production processes. The identified threshold or the hot-spot from this application, could in turn guide the re-modeling and recalculation of the LCA study. The entire process is iterative, as illustrated by the arrows in Figure 2.2, meaning that the assessment is continuously refined and

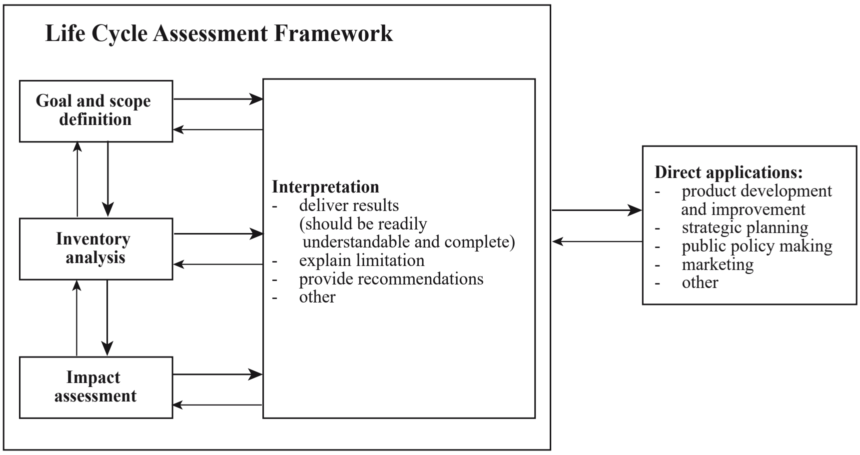

Figure 2.2. LCA steps (based on ISO 14040 [43]).

improved through feedback loops. The iteration may occur at each phase, due to factors such as available new inputs, accuracy and validity of inventory data changes, update of assessment method, and necessary revisions for optimizing the analysis. As a result, this approach may prolong the duration of the process. Nevertheless, the iterative nature of this methodology facilitates necessary modifications and updates, thereby enhancing the consistency and comprehensiveness of the LCA study. Additionally, it is imperative to highlight that, the interpretation phase plays an important role, particularly given the potential lack of LCA knowledge among decision-makers or clients.

With respect to the practical implementation, ISO 14044 [44] describes the requirements for conducting an LCA, listing guidelines for calculation rules, reporting, critical review requirements, and informative examples. However, there is embedded uncertainty in the results, and the use of LCA to support decision-making raises concern and necessitates critical review, as this process most likely affect stakeholders with other interests than the environmental impact or those external to the LCA.

2.2.2 LCA in the construction sector

Initially the LCA is applied for the product or service, which is usually specific and straightforward. The application scope is extended to complex product systems including construction projects. This is mainly due to the construction sector's significant impact on the climate change and its substantial consumption of raw materials and energy. Concurrently, LCA related standards tailored for construction works have been introduced. Take EN 15978 [47] as an example, it defines life cycle stages and relevant modules for construction works (see Figure 2.3). The stages range from the production and construction, through use, to the EoL stage, even beyond the life cycle (i.e., module D).

For construction products, the Environmental Product Declaration (EPD) has been

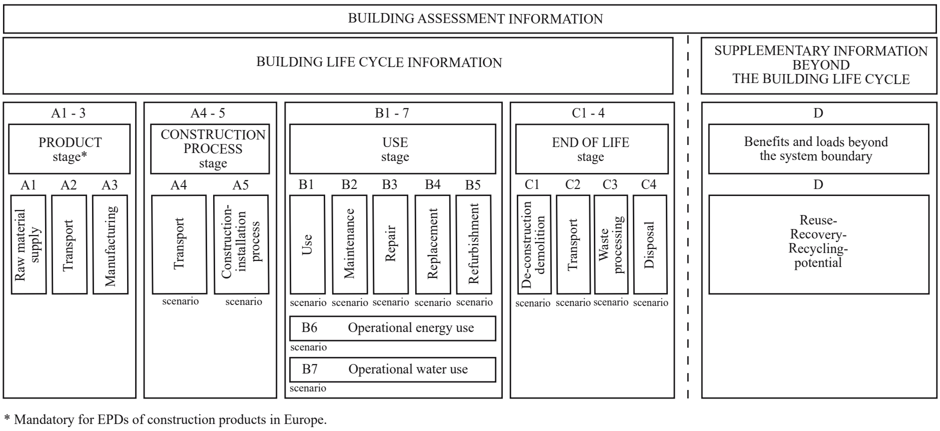

Figure 2.3. LCA modules of construction works (based on EN 15978 [47]).

introduced to establish standard and metrics for quantifying the associated environmental impact. The EPD delineates LCA in accordance with Product Category Rules (PCR). An EPD, defined by ISO 14025 [45] as a Type III declaration, is based on the LCA tool following ISO 14040 series (i.e., [43, 44]). Over the past decade, various standards have been designated for the core rules of EPD for construction products and services, including timber products. For instance, ISO 21930 [51] for the construction products and services, EN 15804 +A1 [52] and EN 15804 +A2 [53] for construction works, EN 16485 [48] specifically for round and sawn timber. The EN 15804 standards [46, 52, 53] establish general core rules for creating consistent and comparable EPDs across different construction products, primarily focusing on the environmental declaration framework. EN 16485 [48] provides specific rules and tailored guidance for wood and wood-based products, such as carbon storage and energy content of wood. It adapts and extends the general principles of EN 15804 standards [46, 52, 53], thereby ensures the EPDs of wood and wood-based products are consistent, relevant, and comparable. With respect to the biogenic carbon of wood and wood-based products, EN 16449 [54] stipulates the relevant calculation method. These standards facilitate the boundary and scope setting within this thesis, and contribute to the selection of standardized impact indicators and relevant declaration of timber construction products from manufacturers.

The application of LCA has been expanded in various aspects in the construction sector, varying from the product's EPD (e.g., ready-mix concrete, steel profile), and EoL scenarios of the material (e.g., recycling, incineration), to different project types (e.g., infrastructures, buildings). The focus of impact ranges from GWP-only to comprehensive impact indicators (e.g., defined in EN 15804 +A2 [53]). The LCI of construction works (products and services) has been developed continuously, for instance, the precision of data sources varied from globally to nationally even specific product or provider (i.e., EPD). Commonly used LCI databases are e.g., (1) commercial database - Ecoinvent [55], IDEA v2 [56]; (2) public databases - ELCD from European Commission, which has been discontinued since 2018 [57]; USLCI from USA [58]. Some databases provide only CO_2-eq. values, e.g., public database: co2data provided by SYKE [59], ICE database by Circular Ecology [60]. It should be noted that, geographical scope and version (time-dependent) of LCI databases may significantly influence the final results, i.e., metrics. Consequently, the comparability between similar LCA studies is also affected.

The LCIA method, is understood as quantifying a set of impact categories, two groups exist: midpoint (comprehensive) and endpoint (concise). The endpoint indicators are evaluated at ultimate level depending on the area of protection, and the midpoint indicators are assessed at intermediate level, i.e., between the emission and the endpoint. Taking climate change as example, emissions like CO_2 and CH_4, enhance the atmosphere's capacity to absorb infrared radiation. This is the potential environment impact after the emission, and commonly used as midpoint indicator for GWP (expressed by kg CO_2-eq.). The absorbed infrared radiation results in a series of subsequent effects such as increase of temperature, which in turn causing sea-level rise, eventually reflect damages in different areas of protection such as resource availability and human health. These are categorized as endpoint indicators, for instance, the effect of human health impact can be expressed as disability-adjusted life years (DALYs). Compared with midpoint indicators, the endpoint indicators may be harder to calculate and interpret, as they involve more subjective evaluations and uncertainty. For both groups, weighting factors (for individual indicator) may be used for obtaining a single score. The single score represents the overall environmental impact, which may ease the decision-making process, especially for decision-makers who have limited familiarity regarding LCA. However, it should be noted that, the weighting factor for individual indicator represents the contributions of the respective impact category to the overall environmental impact. Therefore, it brings subjectivity, as well as offers simplicity as it presents the result just as a single score, which facilitates the decision-making. There are various LCIA methods that are widely used: common midpoint methods include: CML, ReCiPe midpoint, ILCD 2011 midpoint+ (superseded), TRACI 2.1 (mostly used in North America), etc. Among them, climate change, indicated by GWP, always follows the IPCC policy. Commonly applied endpoint methods include ReCiPe Endpoint and USEtox 2 [61].

LCIA methods have been updated continuously, based on the changing environment (e.g., techno-spherical and social) and relevant policy (e.g., IPCC for CO_2-eq.). It should be noted that, considering the complexity and long lifespan of the construction product and project, using EPDs in building LCA may be helpful, but the LCIA method enforced for the EPD should be applied for other inventory data sources, to keep the data consistency. For instance, LCIA method for EPD complies with European standards is EN 15804 +A2 [53]. In relation to LCA implementation tools, several software for LCA have been developed, most used ones are e.g., SimaPro [62], GaBi [63], openLCA [64], Ecochain [65], and OneClick LCA [66] which is specifically designed for the construction sector. Finally, expertise of LCA practitioner, as well as the knowledge and experience about the specific studied product system (here, structures) affect the quality of the evaluation.

EPDs used in LCA

EPD shows manufacturer's commitment to measuring and striving to minimize the environmental impact of its products and services, while also contributing to its sustainability goals. The validity of EPD is usually 5 years, to ensure the data quality. Moreover, EPDs are supervised and registered by independent agencies named EPD program operations (POs), who are responsible for creating PCRs for EPDs. All EPDs must be verified by independent experts approved by the EPD POs, before getting published in the relevant EPD platform. Accordingly, comparability could be ensured when following EPD standards and rules.

EPDs help differentiating products from manufacturers, as well as stimulate manufacturers to reduce their environmental impact to be more competitive in the market. On the other hand, EPDs are critical for conducting LCA on construction works such as buildings and bridges, in terms of transparency, consistency, accuracy and reliability. Consequently, it supports stakeholders in making informed decision. Furthermore, EPDs are used and often mandated in evaluating building sustainability, for instance to obtain green building certificate such as LEED and BREEAM.

There are various standards regulating the EPDs of construction products and works. In Europe, standards designated for EPDs of construction works are published, e.g., EN 15804 [46, 52, 53] and EN 15978 [47]. Non-European countries also publish EPDs following these standards, e.g., Australia and New Zealand. The impact indicators required for EPDs comply with different EN standards can be seen in Table 2.1. Relevant rule is also available in North America (e.g., [67]). Other countries typically comply with EN and ISO standards, or have not yet initiated the EPD promotion and regulation. In recent years, EPDs of construction products have been increasing rapidly, and several platforms manage the processing and publishing of EPDs (e.g., [68–71]). Also, standards for the EPD have been developing continuously. For instance, in Europe, the latest EN 15804 +A2 [53] published in 2019 urges that previously issued EPDs be updated accordingly. This standard came into force in July 2022, however, by that time, only limited number of EPDs for timber products had been updated. It should be noted that, LCIA method, impact categories and relevant units for indicators are not identical in [52] and [53]. The EPDs comply with [52] may still be valid, but they are not compatible with the newly published EPDs that comply with [53]. In particular, for the EPDs of timber products, sub-categories of GWP, such as GWP-biogenic and GWP-luluc, are necessitates in [53] (see Table 2.1). Other indicators are even expressed by different units. Taking acidification indicator as an example, the unit was mol H^+ eq. in EPDs following [52]. However, it has been revised to kg SO_2 eq., as requested in EPDs comply with [53]. Thus, if an LCA study uses mixed EPDs adhere to different standards, the results are likely to be associated with large uncertainties. The mixed use of EPDs (comply with either [52] or [53]) should be paid attention, especially when the GWP or GWP-total is the sole indicator of interest. In addition, decision-making or comparison criteria may require other indicators than GWP. Therefore, consideration of indicators that are commonly used in the LCA of timber construction products and structures, as well as relevant variations, worth further investigation. However, this falls outside of the scope of this thesis. In addition,

Table 2.1. Core environmental impact indicators according to the standard EN 15804:2012+A2:2019 [53] and EN 15804:2012+A1:2013 [52], which is the obsolete version since late 2019. Table adapted from Publication III.

Impact category	Abbreviation for the indicator	Unit (per functional unit or per declared unit).	
		in [53]	in [52]
Depletion of abiotic resources – minerals and metals (noted as 'elements' in [52])	ADP-non-fossil*	kg Sb eq.	kg Sb eq.
Depletion of abiotic resources – fossil fuels	ADP-fossil*	MJ, net calorific value	MJ, net calorific value
Acidification	AP	kg SO_2 eq.	mol H^+ eq.
Eutrophication potential	EP	—	kg $(PO_4)^{3-}$ eq.
Eutrophication aquatic freshwater	EP-freshwater	kg P eq.	—
Eutrophication aquatic marine	EP-marine	kg N eq.	—
Eutrophication terrestrial	EP-terrestrial	mol N eq.	—
Global warming potential	GWP	—	kg CO_2 eq.
Climate change – total	GWP-total	kg CO_2 eq.	—
Climate change – fossil fuels	GWP-fossil	kg CO_2 eq.	—
Climate change – biogenic	GWP-biogenic	kg CO_2 eq.	—
Climate change – land use and land use change	GWP-luluc	kg CO_2 eq.	—
Photochemical ozone formation	POCP	kg NMVOC eq.	kg C_2H_4/ Ethene eq.
Water use	WDP	m^3 world eq. deprived	—

*Abbreviations may be different in EPDs.

EPDs may claim the environmental impact for specific product or product portfolio, and the enclosed functional unit or declared unit can be different. For instance, the declared unit from different manufacturers can be 1 m^3 of laminated veneer lumber (LVL) or 1 m^2 of LVL panel. Therefore, these differences should be cautiously treated when choosing or comparing EPDs, furthermore, mixed usage of them in building LCAs should be avoided.

In Europe, to facilitate the LCA (and EPD) on construction works, which is more complex compared to the regular product system, EN standards (e.g., [46, 47]) defined the relevant life cycle modules associated with descriptions. In Figure 2.3, the life cycle modules defined for construction works are presented. For the LCA on the product level (i.e., EPD), module A1-A3 are compulsory. For the LCA on the project level (e.g., building LCA), whole life cycle is recommended, yet it is always project-specific, where the inclusion of modules may be determined by the LCA practitioner or stakeholder.

For example, if the EoL scenario is the focused aspect of an existing building structure, module C1-C4 and D (see Figure 2.3) may be the only stages needed for the LCA study.

LCA in design comparison
The LCA implementation in construction projects, has been ongoing with varying focus. The focus may vary significantly based on factors such as project's scope, goal, objects being studied, and project stages. For instance, these studies include the assessment on different structural systems and design alternatives of one project: comparison between different beam-floor systems [72–74] and bridge design alternatives [11, 75]. However, there is insufficient research focusing on projects that are yet to be constructed (i.e., in the design phase). Nonetheless, the significance of conducting early-stage LCA and relevant benefits have been recognized. For instance, Steele and Cole [76] compared three bridge design alternatives with LCA calculation. Azzouz et al. [77] conducted LCA of energy conservation method for a planned case office building, which compared the LCA solutions for reducing both embodied and operational energy in the lifespan, and addressed the significance of using LCA for early-stage design. Grath et al. [78] applied cradle-to-grave LCA on comparing the environmental impact of two houses: retrofit and new-build. There is also various research on the early-stage LCA application and relevant development, from the perspectives of architects and engineers. For instance, Bueno et al. [79] discussed the integration of LCA with building information modeling (BIM) to enhance the sustainability from the early design stages. Hollberg et al. [80] developed an LCA tool primarily for architects working in early planning stages, focusing on carbon emissions. Fang et al. [81] focused on strategies to reduce the embodied carbon of buildings during the early design stages, as well as emphasized that structural systems contribute a substantial portion of the embodied carbon emissions. Furthermore, there exists potential for improving the use of LCA in design comparisons during the early stages of projects. For instance, the simplifications necessary for early-stage LCA and their effects on results accuracy require further study. Also, effective methods for reducing carbon emissions among various designers, including architects, structural engineers, and civil engineers, need more investigation.

Timber in construction
Timber is regarded as a renewable material, which helps transitioning towards sustainability with reduced CO_2-eq. Use of timber in the construction sector has been increasing in the past few decades [82], as well as the relevant LCA studies. These studies include research and organizational reports, which can be found regarding various objectives, such as timber buildings and bridges [11, 83–87], timber cascading [17, 88], and application of LCA at design stage [89, 90]. The definition of timber cascading was not uniformed, however, ISO 59004 [91] clarified the term in 2024, where the definition for cascading of bio-based material is provided: *"When adopting for biobased material, cascading implies repeated use of renewable resources at decreasing quality, with final treatments such as composting, energy recovery or biodegradation, and safe return of the material to the environment."*. Nonetheless, one

concern about reaching sustainability goals of both carbon reduction and renewable energy target, is how should timber be considered for the EoL scenario: (a) material recovery vs. (b) energy recovery. Material recovery stands for reuse and recycling (here, cascading), while energy recovery means incineration (for electricity and heat). Relevant definition can be found in the EU directive [4] published in 2008, and CE related standard ISO 59004 [91] published in 2024. In ISO 59004 [91], reuse refers to *"use a product or its component parts after their initial use, for the same purpose for which they were originally designed"*, while recycling refers to *"activities to obtain recovered resources or use in a process or a product, excluding energy recovery"* and does not include reuse. The issue consequently pertains to the balance between these two EoL scenarios (a) and (b), which is also reflected in the policy for reducing C&D waste and boosting renewable energy production (and/or) consumption respectively [92, 93]. European waste hierarchy stated in the article 4 of the Waste Framework Directive [4] are: prevention — reuse — recycling — recovery — disposal.

2.3 Circular economy

2.3.1 Circular economy concept

The definition of CE was not standardized, underwent evolution and refinement over time. For instance, in 2023, the European Parliament [94] stated the CE as *"The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum."*. Later in 2024, ISO 59004 [91] provides a succinct definition of the CE *"economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development"*. To facilitate this transformation towards sustainability, the EU has been promoting a sequence of actions towards CE to minimize waste and increase resource efficiency [3, 27]. The actions focused on resource intensive sectors such as construction, electronics, and textiles. There are obvious benefits gained from circular economy: reducing raw material consumption and environmental impact, creating jobs even with emerging industries, and boosting economic growth.

In general, the CE is founded on three principles that are design-driven, as stated in the Ellen MacArthur Foundation: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature [95]. This is also in line with the EU's directives about waste hierarchy [4, 96]. In short, the CE functions as a strategy approach designed to maximize the value of materials and efficiently use the material through (closed) circular material flows, thus could decrease waste, cut primary resource consumption, reduce environmental burden and prevent the loss of biodiversity [95]. ISO 59004 [91] addresses that the CE encompasses environmental, social and economic systems and their interactions, emphasizing that the social and economic systems are reliant on and embedded into the environmental system. LCT and CE are complementary concepts that support achieving this final goal. LCA is quantitative evaluation for assessing potential environmental impacts, directly applicable to LCT and CE. Conversely, fundamentals of LCT and LCA guide the CE to make decisions that benefit the entire system. However, it should be noted that there are shortcomings and challenges when using LCA to assess CE strategies, such as modeling of multiple or open recycling loops, reliability and availability of data, and transparency of assumptions [97].

2.3.2 Circular economy in the construction sector

As a central focus of EU Actions for achieving circular economy, the construction sector serves a key role in the large scale, considering that it consumes around 50% of all extracted materials, and generated over 35% of the EU's total waste [98]. Comprehensive new strategy for pursuing sustainable built environment was launched by the EU, which promotes the circularity principles through the whole life-cycle of buildings by various actions. Explicit principle for buildings design was also provided, with specific principles designed for different target stakeholders [99]. As EU member state, Finland (as well as other countries) has been taking actions aiming to amend the EU legislation to promote and facilitate the CE transition. Actions include versatile tools and measures, such as guideline for demolition of buildings, material marketplace for wastes and side-streams, green deal, and strategic programme [100].

Waste reduction and enhancement of the relevant circularity is one of the main aspects regarding CE in the construction sector. In September 2018, EU rules on C&D waste were published, where C&D waste protocol and guidelines were introduced [101]. Also, it has been stated in [6] that construction and demolition C&D waste consists of numerous materials that could be recycled. In Finland, wood takes a large share of C&D waste, e.g., over 40% of C&D waste was wood in 2016, but only an exceedingly minor fraction of C&D waste wood is recovered for material applications [102, 103]. Thus, cascading of C&D wood material has the potential to substantially contribute to the reduction of GWP[2], EU's target of cascading C&D waste, as well as CE (transformation) [4, 96].

Few relevant research has been conducted, such as strategies to increase the reuse of wood [104], and a review about mapping the CE practices to understand the applicability in climate mitigation modeling [18]. However, the construction sector has some unique characteristics associated with challenges: (1) substantial amount of material and energy involved, (2) composite elements and components combined with at least two materials, (3) long service life with specified functionality, (4) safety assurance with health consideration (e.g., time- and labor-consuming for construction waste sorting and follow-up usage scenarios such as recycling and reuse, potential health risk for the occupants and visitors of the structure), (5) resilience requirement and capability (e.g. extension of service life, refurbishment or upgrading of the structure,

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[2] For simplification, in this thesis, GWP also represents the term greenhouse gas (GHG).

retrofit of the structure and materials). Therefore, when dealing with CE in the construction sector, feasibility should be cautiously considered and investigated. The investigation should be conducted with LCT (long-term and holistic view), and cover all relevant aspects such as technical, economic, environmental, even social.

For the CE of timber in the construction sector, studies on the environmental and economic benefits of wood cascading have been undertaken, but it predominantly focuses on the product level (e.g., particleboard) rather than the project level (e.g., timber building). The research on this topic is relatively limited, still, fewer studies specifically addressing the cascading of structural timber components (e.g., [105–107]). In addition, it appears that typically no studies have considered the macro-scale (e.g., global, national) of CE together with different actors throughout the wood value chain.

2.4 Environmental consideration in risk-informed optimization

Structures must be firstly assured with safety, which is regulated by design codes and standards. In structural designs, most common rules are based on the semi-probabilistic method where safety factors are applied, which is known as partial factor method, in order to meet the deterministic design criteria. The risk-informed decision-making method is applied in exceptional design situation, aiming at maximizing the expected utility of decision makers. For structures designed in accordance with the present Eurocodes, the level of risks (simplified as the probability of structural failure) is generally low. However, earlier studies stated that such risks diverged widely, which implicates the inefficient use of resources and non-optimized design decisions [108]. In addition, as we hurtle towards 2030 with the common goal of combating climate change as a key aspect of sustainability goals by the United Nations [109], explicit consideration of sustainability related assessment such as economic cost and environmental impact in decision rules becomes the potential and mission. With safety guaranteed, the decision should be optimized with considering other impact (e.g., cost, environmental impact) induced by construction & use or operation, as well as potential failure consequences.

Several code-based optimization studies have been conducted in the past years, in order to optimize designs within the realm of partial factor method-based design rules (e.g., [110, 111]). However, neither explicit consideration of potential failure and retrofit was included, nor the consistency of the calibration (according to economic optimization principle) was ensured. Within this context, research about reliability-based calibration has been ongoing in the past decades. Several methods have been investigated, aiming to calculate probability of failure or probability under certain threshold (e.g., load-bearing capacity), an overview of these methods is presented e.g., in [112]. Among these methods, the risk-informed optimization approach, has been considered as a robust and appropriate approach for facilitating consistent decision-making related to sustainable and resilient engineering structures, thus adopted in this thesis. It explicitly accounts for particular conditions, involved with uncertainties and consequences of failures through the entire life cycle [110, 111, 113]. It is realized through an economic cost-based formula, where both the direct cost (e.g., material cost, construction cost) and indirect cost (e.g., fatality caused by failure of structure, expected obsolete cost) are included. The indirect cost is calculated based on the expected probability of failure. The estimation of probability inherently involves dealing with uncertainty. Two types of uncertainty are presented at the end of this subsection. In brief, the approach facilitates structural design optimization, where balance is achieved between the benefits obtained through the implementation of a decision (i.e., the realization of the structure) and associated costs. Meanwhile, standardized guidance and recommendations for practical applications (e.g., [114]) provide support. Moreover, it is anticipated that the risk-informed optimization approach could account for environmental impacts such as CO_2-eq. and energy consumption (in MJ), in a structure's life cycle. Such environmental consequences could be assessed by LCA, where results of comprehensive impact categories are available.

The ideal situation is to include environmental impact in decision rules, where the structural safety and durability are ensured, complying with present design codes and standards. In the rare case, LCA is applied but used as post-design evaluation for achieving rather inefficient sustainability certification schemes [115]. However, at present, the development of structural decision rules, and sustainability assessment (e.g., LCA and LCSA) methodologies & tools, are usually investigated separately. In consequence of this lack of harmonization, sustainability aspects are often disregarded in structural design procedures. In addition, it is challenging for users to give clear verdict such as "sufficient sustainable" due to the manifold nature of structures sustainability, which includes safety, durability, functionality, apart from economic and environmental performance. Currently, there is no universally agreed evaluation criteria that comprehensively considers all these aspects, such as assessment methods, weighting and benchmark. Therefore, risk-informed optimization approach becomes crucial, where design rules is calibrated for sustainable design with broad scale including assessment of safety, risk, environment impact and social cost.

Uncertainty types

As mentioned above, the estimation for the probability of failure is associated with uncertainty. The uncertainty can be divided into two distinct types: aleatoric (inherent variability, irreducible) and epistemic (knowledge limits or boundary, reducible) uncertainty.

Aleatoric uncertainty: The uncertainty that refers to the randomness, where there is no possibility of reducing it [116]. Examples are: randomness of a phenomenon during the use of a structure, such as the snow load and seismic load; weather-associated energy consumption over the lifespan of the structure.

Epistemic uncertainty: The uncertainty that is caused by deficiency in knowledge, where there is possibility of reducing it on the basis of additional information or by refining models [116]. Examples are: inaccuracy of mathematical or physical model, statistical evaluation of limited experiments results; modeling discrepancy for building LCA, incomplete quantities of materials.

Distribution function

Common way to describe the variability of analysis is by using distribution functions. The distribution functions used in this thesis (e.g., in Publication III) are presented in the following paragraphs.

Normal distribution: $N\ (\mu, \sigma^2)$

This is the most used distribution function. The sum of many independent random values is normally distributed, which follows central limit theorem [117]. The parameter μ is the mean or expected value of the distribution, where σ^2 is its variance, with σ represents the standard deviation. The range is infinite, i.e., $-\infty < x < +\infty$, thus, there is always a probability of having negative values. However, this may become problematic when modeling .g., the amount of construction materials, which cannot be negative.

Uniform distribution: $U\ (a, b)$

The uniform distribution describes the case when arbitrary outcomes lie between certain bounds, which are defined by parameters, a and b, minimum and maximum values respectively. This provides an equal probability of occurrence for every possible outcome, meaning that all values between a and b, are equally likely to be observed. This type of distribution is applicable when there is no prior knowledge about potential outcomes, except the lower and upper limits.

Log-normal distribution: $logN\ (\mu, \sigma^2)$

The logarithm of a random variable is normally distributed. The parameter μ is the mean or expected value of the variable's natural logarithm, and σ is the standard deviation. This precludes negative values; thus, it is useful for practical applications in engineering field.

2.5 Summary - research gaps

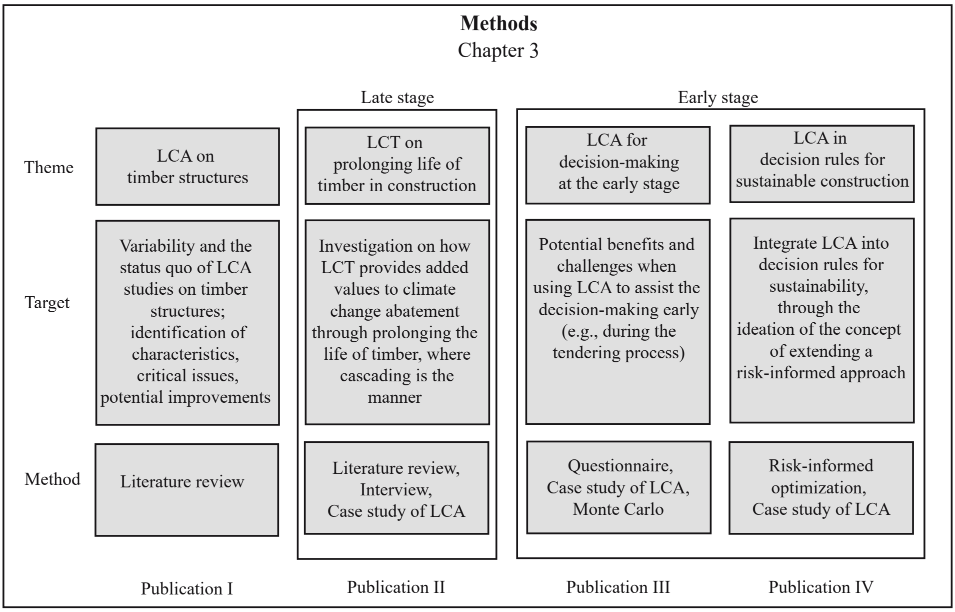
Despite the expanding literature on LCA in timber construction, notable research gaps remain. The gaps pertinent to the topics addressed in this thesis (see also RQs in Chapter 1) are outlined below.

- There is limited overview of LCA implementation in timber construction projects. Therefore, relevant characteristics worth investigation, e.g., assessment methods, variations of LCA results, comparability, and predominant life cycle stages.
- EoL scenarios of construction timber remain insufficiently examined, particularly structural timber. The typical EoL option for timber is incineration as energy recovery; however, to some extent, it contradicts the EU's waste directive and CE strategies, which prioritize reuse and recycling over energy recovery.
- There is a lack of investigation into the uncertainty and variation of the LCA results, when they are intended for decision-making at early stages. Standardized LCIA methods and development of EPDs for construction timber products

contribute to reducing the variability, however, certain consequential effects and uncertainties still remain. The uncertainty analysis is typically either oversimplified or neglected, which affects the accuracy of the results.

- Integrating LCA into the current design criteria for structures' sustainability is lacking, where the manifold nature of structures - such as safety, durability, economic cost, and environmental performance - should be considered. The risk-informed optimization approach is integral to achieving sustainable construction; however, relevant design rules should be calibrated to effectively incorporate environmental impacts.

3. Methods



Methods
Chapter 3

	Publication I	Publication II	Publication III	Publication IV
		Late stage	Early stage	
Theme	LCA on timber structures	LCT on prolonging life of timber in construction	LCA for decision-making at the early stage	LCA in decision rules for sustainable construction
Target	Variability and the status quo of LCA studies on timber structures; identification of characteristics, critical issues, potential improvements	Investigation on how LCT provides added values to climate change abatement through prolonging the life of timber, where cascading is the manner	Potential benefits and challenges when using LCA to assist the decision-making early (e.g., during the tendering process)	Integrate LCA into decision rules for sustainability, through the ideation of the concept of extending a risk-informed approach
Method	Literature review	Literature review, Interview, Case study of LCA	Questionnaire, Case study of LCA, Monte Carlo	Risk-informed optimization, Case study of LCA

Figure 3.1. Overview.

Figure 3.1 depicts an overview of the research methods used in this thesis, where the themes, targets and methods employed in the individual publications are presented. The overarching research topics originated from the literature review (see Publication I), which examined the LCA applied in timber (use in) construction, within the context of sustainability and/or combating climate change. This initial investigation was necessary, as there was no overview of how LCA had been applied in timber structures, nor of the relevant predominant characteristics. The findings derived from this initial investigation revealed a large variation among the studies examined. Accordingly, three research topics were selected for the follow-up research of this thesis. The research was conducted in two directions of construction projects: late stage (see Publication II), and early stage (see Publication III- Publication IV).

The added value of LCT in prolonging the life timber through cascading was explored in Publication II. The potential application of LCA to assist decision-making and its integration into decision rules for optimization were investigated in Publication III and Publication IV. In summary, to conduct all the above-mentioned investigations, several methods have been adopted together with case studies, as detailed in Sections 3.1 - 3.3.

3.1 Methods of data collection

3.1.1 Literature review

In order to have an overview of the current LCA applications in timber construction projects, a literature review was conducted. A thorough literature review about LCA on timber bridges was performed, covering both the methodology and implementation aspects (see Publication I). In total, 26 publications were collected for comparison. Key databases such as Google Scholar, Research Gate and university library were utilized. The inclusion criteria encompassed peer-reviewed articles published in the past two decades, focusing on studies related to modern timber bridges and structural timber, as well as LCA studies of non-timber bridges for reference. Characteristics (such as common impact categories, dominant life cycle stages, variation among studies, etc.) in terms of environmental performance, relevant weak points and potential improvements were addressed. The status quo of prolonging the life of timber through cascading was studied, along with achieving EU's CE target and conforming C&D waste hierarchy (see Publication II).

The literature review is necessary, as it offers a comprehensive contextual understanding of the research topic, identifies existing gaps and opportunities within the field, and helps avoid duplication of prior efforts. However, it exhibits potential limitations such as selection bias, varied quality of the literature, difficulties in achieving comprehensiveness, and the risk of rapid obsolescence as the chosen research field evolves quickly.

3.1.2 Interview and questionnaire

Industrial as well as academic insights about the relevant potential and challenges of wood cascading in the construction sector, to prolong the lifespan of timber and abate climate change, were explored through interviews (see Publication II). A total of 21 cross-sectional interviews were conducted in 2018, all using face-to-face interactions. The interviews adhered to the single interview approach, and were kept semi-structured to facilitate coherent and fluid conversation. The background of interviewees covered sectors relevant to the wood value chain (e.g., forestry, manufacturing, waste management), academia and policy-making. The interviews (jointly created interview questions with one of the co-authors of Publication II, who conducted the interviews in Finnish) primarily focused on the reuse of structural timber, but also considered other cascading scenarios, recognizing that they might co-exist for the same element or component.

A questionnaire (through meeting with city planning officer) was performed in 2020, to briefly understand the status quo of LCA application and its role in the decision-making process of construction projects in Finland (see Publication III). The aim was to address the current use of LCA in the procurement process, identifying obstacles and insights, as well as challenges related to the use of LCA as an assistance tool during the tendering process. The questionnaire employed a combination of open-ended and closed-ended questions, to collect qualitative and quantitative feedback.

The interview method allows for in-depth investigation of a complex topic, yields instant and qualitative responses, and offers flexibility in question formulation during the interview. Nonetheless, it exhibits certain limitations: (1) time-consuming and restricted sample size, due to lengthy scheduling and resource demands; (2) challenging and labor-intensive data analysis, since interpreting qualitative responses involves complex transcripts and nuanced responses. In contrast, the questionnaire is cost-effective from a broad population, enabling quick and standardized responses, and thereby supporting the collection of targeted insights into specific themes. However, it may involve misinterpretations and inaccurate answers, and may limit the capture of a comprehensive overview due to the lack of interactions.

3.2 Case studies of LCA

Case studies were conducted (as supportive grounds) with various purposes, the focus ranged from design/decision-making to EoL scenario (see Publication II, Publication III, and Publication IV). All case studies are LCA studies and used *openLCA* as the tool. CML and ReCiPe methods were applied, and the inventory databases were Ecoinvent, national generic database and EPDs.

To explore the environmental potential of prolonging the life cycle of construction wood material through cascading, a case study of LCA comparison for two fictitious timber halls were performed (see Publication II). The entire life cycle of the halls was encompassed, with the exception of impacts that were assumed to be equivalent for both comparative cases. Specially, the excluded impacts were those associated with the construction and use stages, in addition to transport-related impacts. In this case study, the maximum potential of cascading (e.g., reuse structural timber) was explored in a rather realistic manner, and compared with no cascading scenario (as reference) of timber, which is energy recovery - the common case in Finland.

Two other case studies were conducted concerning the LCA at early stages with different purposes: (1) to assist the decision-making during the tendering process (see Publication III), and (2) to be a factor in decision rules for sustainability (see Publication IV). The former case study was LCA on a building constructed with glued laminated timber (GLT) beams, with selected parameters (including model uncertainty), under four different scenarios. The life cycle stages encompassed were the product (A1-A3), the construction process (A4), and the EoL (C2-C4) stages (as defined in EN 15804 [46]). As the focus was the variation of results between scenarios, life cycle stages either resulting in identical environmental impact or irrelevant were excluded, such as the installation and use stages. The EoL of timber was assumed to be incineration. The purpose is to ascertain the variability difference, critical parameters, and potential for reducing the uncertainty of LCA (results) at the early planning stage. It is intended to be used for reducing the uncertainty of LCA results,and to help the alternative optimization, such as setting limits of material providers in the tender document (see Publication III). The latter case study explored the possibility of integrating LCA into design procedure with timber use. Given the commonly used wood products in construction, it is beneficial to establish more comprehensive guidelines in conjunction with existing structural design standards. These guidelines would support optimizing the value of timber while considering pertinent environmental impacts and benefits. However, present design standards do not adequately take these factors into account. The case study examined the environmental effect and pertinent CO_2 pricing of two floor systems, concrete and timber, respectively (see Publication IV). The installation and use stages were excluded, assuming they were identical for the floor systems being compared. The EoL of timber and concrete was considered consistent with current practice: timber to be incinerated and concrete to be recycled. The case study was employed for addressing the environmental impact (incl. benefits) of timber use and quantifying the GWP through monetization, with the aim of integrating it into a risk-informed optimization approach. This approach serves as a design rule which is economic cost-based.

Case studies offer in-depth analysis and contextualized insights into specific systems. This method facilitates knowledge building and provides valuable information that can guide future projects. For instance, case studies can identify key influential factors, potential pitfalls, and effective practices. However, this method exhibits limited generalizability and applicability, because findings from specific cases may not easily extend to broader populations or different contexts. Furthermore, the variability between individual case studies - such as differences in setting, participants, and context - poses challenges for synthesizing results across multiple cases, thereby limiting the overall capacity for synthesis.

3.3 Analytical methods

Besides LCA, other analytical methods are also applied in the investigation: MC and risk-informed optimization methods.

3.3.1 Monte Carlo

The MC method is used to assess uncertainties of events by considering various parameters simultaneously, with simulation being the essential aspect. An MC simulation involves random sampling from probability distributions associated with the model parameters. This process enables the estimation of mathematical quantities or the solution of analytically challenging problems. Through running simulations, it generates a range of potential outcomes, and provides insights into the uncertainty and variability associated with a specific problem. For instance, this approach can be used to assess the probability of failure of a structure or to estimate construction costs.

The MC method is selected for investigating the variation of LCA results attributable to various influencing parameters of a construction project, which are modeled as random variables. These parameters encompass quantities of materials, material providers, transport distances (see Publication III), among others. Each parameter is assumed to follow a specific (probability) distribution, and the MC method is used to simulate samples (i.e., values) accordingly. For each parameter studied, a suitable distribution was selected, which most accurately represents the actual circumstance. Subsequently, a simulation model was developed for analyzing the specific problem, such as estimating the overall GWP values of a structure by using the generated series of samples. With these samples, multiple scenarios were created, each representing a distinct combination of parameter values. In this study, for each scenario, 10^6 simulations were performed, which ensured sufficient resolution to capture the variation while avoiding excessive computational intricacy. It should be noted that, larger numbers of simulations (i.e., realizations or samples) increase the precision of the results. The result of each scenario depicts the GWP value. In other words, the MC method measures the overall variation in the LCA results. The results are presented using empirical cumulative distribution function (CDF) curves, with comparisons of variations across scenarios. Additionally, this approach could identify which parameter dominates the result.

3.3.2 Risk-informed optimization

Adapting sustainability principles into structural design codes and standards has been discussed and researched over the past years. The consistent calibration of partial factor method-based rules, as mentioned in Section 2.4, is considered an essential and imperative measure. This calibration is based on a risk-informed approach, where multiple decision rules (e.g., safety, durability, environmental impact, cost) are enclosed and to be optimized, to achieve a trade-off among economic, environmental, and societal impacts. A prevalent method for such risk-informed calibration of standardized decision rules for structural design, involves the introduction of an objective function. The function aims at minimizing the total cost C_{tot}, which is dependent on the decision parameter p (e.g., cross-section dimension), as illustrated in Equation 3.1. C_{tot} consists of both direct and indirect cost(s), which are incurred throughout the entire life cycle of the structure, from construction to deconstruction or renewal. It can be expressed as the sum of the construction cost $C_c(p)$, the expected failure cost $C_f(p)$, and the expected obsolescence cost $C_{obs}(p)$. The $C_f(p)$ includes initial (re-)construction cost and non-structural failure cost after the failure. The $C_{obs}(p)$ deals with the assumption of ongoing renewal of a structure at an annual rate, with associated construction costs, as formulated by Rackwitz [113]. To account for the environmental impact, each component of Equation 3.1 could be adapted by adding the relevant environmental consequences, e.g., in terms of socioeconomic costs/monetized values. Given the urgent need of mitigating climate change, the environmental impact analysis here focused only on the GWP category, i.e., indicated by CO_2-eq. values. Both the GWP benefits (e.g., due to biogenic carbon, energy recovery) and costs (e.g., induced by production, incineration) are accounted for.

$$C_{tot} = C_c(p) + C_f(p) + C_{obs}(p) \tag{3.1}$$

4. Results and discussion

This chapter summarizes the results of the publications enclosed in this thesis, and discusses relevant implications. The summary aims to provide key findings, and all other details can be found in the publications. Publication I examined existing literature about LCA studies in timber construction. This publication provided an overview and identified existing gaps in the literature. Findings from Publication I informed the development of the overarching research themes for Publication II - Publication IV. Publication II explored the potential of timber cascading at late stages of construction projects, from a life cycle perspective. Publication III and Publication IV investigated the use of LCA to assist decision-making and optimization at early stages of construction projects.

4.1 Publication I: Life cycle assessment on modern timber bridges

An overview of analyses of the environmental impact of timber construction projects from a life cycle perspective is conducted. The purpose is to explore how the environmental impact has been assessed, which relevant methods have been applied, and what are the critical features and potential improvements. The literature review focuses on timber bridges, as well as other bridges, such as concrete bridges, as reference. This arises because timber bridges have relatively less complicate systems than buildings, yet share similar traits. Here, less complicate system means, for instance, fewer interacted units between structural components and facilities such as electrical systems, heating, ventilation, and air conditioning (HVAC) systems. Examples of similar traits include the long lifespan of the structures, strict safety rules, the massive materials consumed, and the inspection and maintenance involved. Thus, the pertinent findings may, to some extent, provide insights into the overall environmental performance of timber construction projects. Furthermore, the findings facilitate the identification of subsequent research topics.

The literature review reveals that LCA is the predominant tool for assessing the environmental impact of product systems. Its application in construction projects has been increasing, but mostly occurs after the design stage (e.g., during the use stage, at the EoL stage). In other words, the majority of LCA studies are dealing with existing structures. The findings from the review cover different aspects, which are described in the following paragraphs: LCA settings in general, LCA applications on timber bridges, and timber-related carbon consideration in LCA.

Overall, LCA studies are case-specific; consequently, considerable variability exists between individual LCA studies. The relevant findings concerning this variability are listed below:

- The studied objects, such as the defined FU, are diverse. For instance, they can be the whole bridge deck or a 1 m^2 effective bridge surface area. The related designed service lives also differed.
- The studied system boundaries varied: full life cycle was covered, construction and use stages were covered, or only construction stage but excluding installation was covered. Despite these variations, the material production stage is typically the life cycle stage that has the most significant environmental impact, in the reviewed studies. Additionally, there is deficiency in research concerning the inclusion of EoL stage and its specific investigation within the context of LCA topics. For instance, in the reviewed literature published before 2013, only three out of ten included EoL stages. In contrast, all reviewed literature published afterwards considered EoL stage(s).
- The inventory databases and LCIA methods largely differed. For instance, the inventory was adopted based on the generic, industrial, regional or country-specific databases. Various LCIA methods were employed, leading to results with different impact categories. The most common environmental impact indicators were GWP and fossil resources consumption (i.e., indicated by MJ).
- The interpretation of results varied: either being presented as percentage or as deterministic values. Uncertainty analysis was usually ignored. Consequently, direct comparison of the values obtained from the results across these LCA studies is not feasible.

Earlier investigation on the LCA of timber bridges in Nordic countries have revealed that, (1) maintenance activities and their relevant intervals of timber bridges vary significantly, in terms of location and frequency, which may worth further study; (2) hazardous timber (e.g., creosote treated timber) may be present in existing timber bridges, and their environmental impact especially at EoL stage, is difficult to assess; (3) LCA modeling (e.g., boundary setting, assessment method determination) of timber bridges may be fixed when comparing different design alternatives, to improve efficiency by enabling parallel calculations. Timber bridges have better environmental performance compared to concrete and steel bridges in terms of GWP, even without considering the biogenic carbon stored in timber. However, more specific insights into environmental performance of timber bridges could not be obtained, as a result of limited investigations. There has been no consensus regarding the inclusion of ancillary materials, such as timber formwork, in the LCA of bridges. The proportion of other construction material (e.g., steel) than timber in bridges plays a vital role when GWP is the focus. Among the reviewed studies, no specified criteria or limits are established for bridges regarding their environmental impact.

Specific findings about timber as a material are summarized below. The consideration of biogenic carbon storage in timber as a construction material remained contentious. However, most studies generally assumed it to be carbon-neutral over its life cycle. This assumption is evident in the LCA studies reviewed prior to this study. The later published version of EN 15804 +A2 [53] standard, to some extent, provides a framework for further development and refinement, also reduces the variability regarding the consideration of biogenic carbon. Meanwhile, the details regarding biogenic carbon consideration remain under discussion. Furthermore, other issues such as consistency of impact categories exist. For instance, different LCIA methods were employed, particularly in studies conducted prior to the publication of EN 15804 [46]. This led to varied impact categories and relevant indicators, as mentioned in Section 2.2.2, and impact may be quantified differently depending on the LCIA method used. The reviewed literature also indicated that the EoL of timber was mostly assumed to be either incinerated for energy recovery or recycled as material, with a marginally greater inclination towards the former option. In addition, EPDs of construction products were limited at that time and rarely used in LCA studies, although EPDs are crucial for ensuring comparability and quality in the LCA of construction projects. More details about EPDs are discussed in Publication III.

4.2 Publication II: Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland

The viability (incl. challenges and potential) of cascading timber to abate climate change and prolong the life of timber in the construction sector is investigated, with the LCT in the Finnish context. The status quo of cascading timber, both from literature and practice, is reviewed. The significance and urgency of cascading timber are explored, with an emphasis on their role in achieving the EU's goal for CE and in reducing the large share of wood waste in Finland. An overview of the current state of cascading C&D timber in Finland was conducted initially. It was found that, Finland has a significantly lower cascading factor of wood in the EU, primarily due to the export of a large proportion of wood products. In addition, wood takes over 40% of C&D waste in Finland, and the energy recovery from waste wood is regarded as the most effective practice at the moment [102, 118]. Although Finland has already met the EU's target for renewable energy production [93], the target for GHG reduction has not yet been achieved. In principle, material recovery of wood should be given precedence over energy recovery. The viability of cascading timber (hereinafter, reusing the structural timber as the focus) is further investigated in terms of LCT, encompassing technical, economic, and environmental aspects.

From a technical perspective, the main concern regarding the reuse of structural timber relates to strength and safety guarantees. Currently, there are no grading rules and criteria for cascaded structural timber in the relevant EU standards. In theory, it can be technically achieved, but effective and standardized assessment criteria to ensure the relevant mechanical properties - and consequently, to guarantee the safety of structures - remains desirable.

In the context of CE, the business ecosystem associated with the life cycle of C&D wood is investigated. The investigation reveals that the circulation of wood has not yet been fully achieved, and its material value is clearly not maximized. On the other hand, based on the waste hierarchy and the requirements for waste reduction [4, 96], the EoL scenario of wood needs to be reorganized, such as shifting from recovery to recycling and reuse. The economic feasibility for prolonging the life cycle of C&D timber by cascading is also researched. The focus lies in reusing structural timber while considering other related cascading scenarios due to their potential coexistence. The results reveal that, the CE of construction timber is in relatively high demand, yet industrial reactions and actions are sluggish, and the driving force of reusing or recycling of solid (C&D) timber comes from policy and regulation. Accordingly, a conceptual framework to achieve the circularity of wood is developed, as shown in Figure 4.1. Two major changes are introduced: one involving the design with LCT in the early stages of the wood's life cycle (e.g., circular design, design for deconstruction), and the other involving revisions to EoL management (e.g., pre-demolition auditor, material broker). This framework provides added value to wood material and prolongs its lifespan.

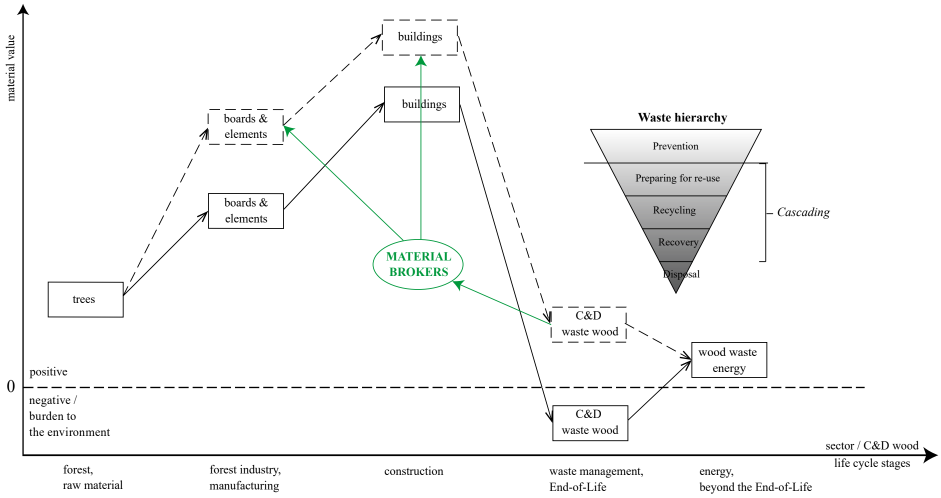


Figure 4.1. Reconfigured conceptual framework for the circularity of the wood in Finland. The existing wood products module is illustrated with solid black lines, the dashed ones represent the suggested value-added wood products module, the green ones represent the reconfigured connection in the circular ecosystem. Waste hierarchy diagram is based on [4]. Figure adapted from Publication II.

Environmental benefits and/or burden through cascading timber were examined in a case study. Two scenarios of the same product systems (i.e., timber halls) were compared: one involving cascading timber use (i.e., reuse of timber) and the other without (i.e., wood incineration for energy as the common case). Only the EoL and production stages were considered, assuming that all other life cycle stages are identical for both systems. Through this, the direct effect of cascading timber scenario could be assessed. Three LCIA methods (CML, ILCD, ReCiPe) were applied. All displayed consistent reduction in assessed environmental impact categories (except GWP, which is detailed further below) with the cascading scenario. The differences in results were also presented when using two different approaches: at the point of substitution and cut-off. Major beneficial aspects of wood cascading are addressed: (1) prolonging the lifespan of timber and extending biogenic carbon storage; (2) avoiding the extraction of virgin raw material and the associated energy consumption & carbon emissions for manufacturing new products; (3) significantly reducing environmental impacts (especially GWP when carbon neutrality is assumed), which is around 30% in this case study. However, it should be noted that, considering the biogenic carbon of wood (as negative GWP values), the GWP benefits appear to be reduced. Nonetheless, it remains beneficial, since it provides an opportunity to substitute conventional, carbon-intensive building materials such as concrete and allows trees sufficient time to grow, thereby increasing biogenic carbon absorption.

4.3 Publication III: Applying LCA in early stages of timber construction projects - Potential and challenges to support decision-making

The implementation of LCA in timber projects, to support decision making during the tendering process, is investigated. Due to the limited information available at early stages, the uncertainty of total environmental impact estimation (e.g., through LCA) is relatively high. This uncertainty decreases over the project's life; the later the LCA is conducted, the less variation in the results can be achieved, as more information becomes available. Nonetheless, there remains the potential to reduce uncertainty at early stages.

In this publication, the advantages and challenges of using LCA as part of early-stage decision-making criteria are explored. The potential benefits of applying LCA at early stages are discussed. This includes its ability to eliminate design alternatives that may cause substantial environmental impact at an early stage, as well as to identify hot-spots for reducing environmental impact. Common obstacles are also addressed, such as limited available information and inevitable estimation or assumptions. Among these, uncertainty plays an important role, leading to additional variability in the results. The design proposal with the lowest LCA results, may not actually correspond to the minimal environmental impact. This highlights the potential for making wrong choices or sub-optimal decisions. Therefore, to enhance comparability, reducing such uncertainty is crucial for effective decision-making. Typically, uncertainty consists of both embedded and epistemic characteristics. For epistemic uncertainty, some measures may be implemented to reduce it. For instance, the uncertainty induced by LCI analysis may be mitigated by using standardized EPDs or a provided generic database, which is also supported by authorities such as the Ministry of Finland [119].

Structural components of timber projects were selected as the focus. Considering prevailing net-zero energy buildings (NZEBs), operational energy and carbon (also other environmental impact indicators) may be excluded from the LCA calculation. NZEBs typically result in minimal or even negative operational carbon and energy levels [120], making embodied carbon the critical factor. This is primarily due to the significant influence of structural components, which constitute the majority of a building's mass, on the building's embodied carbon. Thus, the encompassed life cycle stages are modules A1-A4 and C2-C4 (EN 15804 +A2 [53]). Relevant parameters of structural components that may introduce uncertainty into the LCA are investigated, such as the choice of material producer, material transport, and EoL scenario. The environmental performance of these parameters was explored using either generic inventory datasets (for lorry types and EoL scenarios) or EPDs (for material production). The compared generic datasets reveal that lorry types have minor differences in terms of environmental impact, except in the AP and EP categories. Conversely, different EoL scenarios reflect significant variations across environmental impact indicators.

EPDs of the common GLT and LVL products as load-bearing structural components were studied [121–141], with a comparison of the environmental impacts associated with their production processes. The available EPDs of GLT were collected separately, either those that comply with EN 15804 +A1 [52] or those that comply with EN 15804 +A2 [53]. In contrast for LVL, all EPDs adhere to EN 15804 +A2 [53]. It should be noted that these collected EPDs were valid when the analysis was conducted, some of them may now be obsolete or no longer available. The investigation of these EPDs reveals that there is large variation in environmental impact among them (comply with [52] and [53] respectively), and the difference can be over 90%. However, the situation improves when EPDs are updated following EN 15804 +A2 [53], which stipulates specific and standardized criteria, especially the GWP category (crucial for timber products). The variation among EPDs adhering to [53] is comparatively smaller across all impact categories.

The selected parameters and their relevant influence on the LCA, when applied at early stages, were investigated through a case study of timber projects. The focus of the case study is on the embodied carbon induced by structural components (here, GLT products), associated with relevant activities such as transport and EoL management. The uncertainty of each selected parameter was considered. The aim was to quantify the variability of using LCA to assess embodied carbon, i.e., indicated by GWP. Thus, a simulation model was developed for estimating the overall GWP values, with using the MC method. Using this model, different scenarios were investigated. Providers of GLT products were assumed to be either known or unknown. For unknown providers, relevant GWP data of the product were derived from collected EPDs, which were analyzed under the assumption of a log-normal distribution. For the known provider, a fixed value (here, the mean value of this distribution to ensure the comparability) was used. Given that EPDs may not exist or may be obsolete in practice, an additional scenario using generic data was also studied. A total of four different generic datasets for GLT were employed.

The exemplary results of the study are illustrated by the empirical CDF curves (Figure 4.2). In Figure 4.2a, GWP results are compared between scenarios assuming a known provider and an unknown provider, represented by black solid lines and black dashed lines, respectively. It is evident that the variability is greater in the scenario assuming an unknown provider (coefficient of variation, COV = 0.4), compared to the scenario with a known provider (COV = 0.15). Furthermore, for comparison, the investigation was conducted with inputs having less variability, e.g., this may be the case when the study is carried out at a later stage. Relevant results are presented by the gray lines. It can be seen that the variability is slightly smaller. In Figure 4.2b, the distribution of GWP for the investigation with four selected generic datasets is illustrated individually as black solid lines. This reflects that the variability is similar to those of the scenario assuming a known provider (COV: 0.15 to 0.22), although the mean values differ largely among the generic datasets. When using generic datasets at a later stage, the variation in GWP results is slightly reduced.

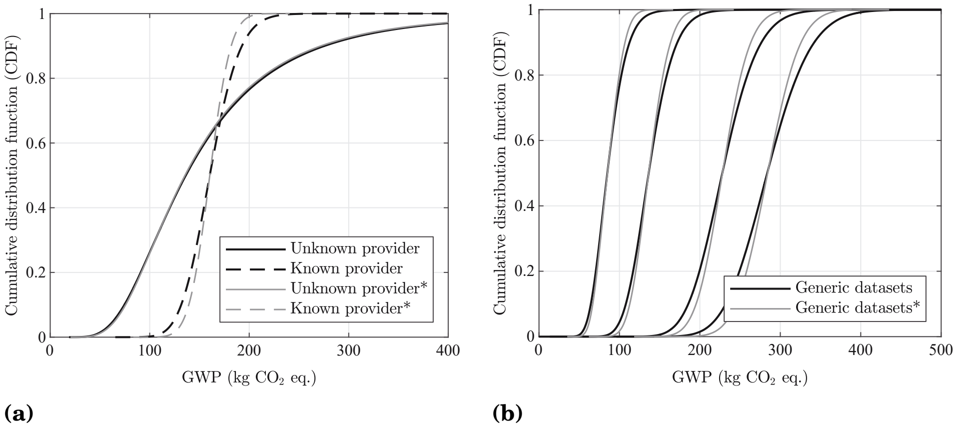


Figure 4.2. Cumulative distribution function of the GWP. (a) EPDs comply with EN 15804 +A2 [53], (b) with generic data. Grey lines marked with (*) represent the comparative study, where the inputs have less variability. Figure adapted from Publication III.

Based on the above results, the material provider is found to be a key influential factor on the GWP. This implies that setting requirements regarding material providers (such as EPDs or designated generic data) may reduce the variability of LCA. This also improves the efficiency and comparability of LCA results, which subsequently supports the decision-making during the tendering process. It should be noted that, the case study examined specific individual parameters and their influence on the uncertainty associated with LCA. The study was conducted under specific simplifications, with some influential parameters not involved. Consequently, the findings and relevant applicability are limited, and caution should be exercised when drawing general conclusions.

4.4 Publication IV: Design concept for the sustainable use of timber in structures

Considering environmental impact as part of decision rules is explored. The decision support tools for sustainable constructions adopted in this study are presented: LCA and a risk-informed optimization approach (economic-based). The former concentrates on the environmental impact of structures over their entire lifespan, while the latter aims to achieve structural performance goals (e.g., safety, durability, serviceability) through optimization. However, it is found that these two tools are often applied and developed separately. The existing risk-informed approach is selected as the basis for incorporating LCA results into decision rules in this thesis. Consequently, modifications to this approach are addressed in the case of timber structures.

LCA in construction was briefly presented, followed by a case study of LCA that assessed and compared the environmental impact (here, GWP was chosen for practical purpose) of two floor systems: timber and concrete, respectively. All life cycle stages except the use stage are covered. Common EoL scenarios are assumed for the two floor systems: timber incineration for energy recovery and concrete recycling, respectively. The results of the case study confirm the eco-friendly feature of the timber floor compared to the concrete floor, with a total GWP difference of more than threefold. Furthermore, due to timber incineration for energy recovery at the EoL stage, the timber floor has a significantly larger GWP benefit (module D) than the concrete floor, i.e., more than 25 times. The monetization of total GWP (i.e., CO_2 price) was also discussed, where two conceptually different methods [142, 143] were used. The results reveal that the CO_2 prices provided by these methods are significantly lower than the material cost of the floor system. However, the unit price of the concrete floor is currently much lower than that of the timber floor, in this case, the ratio was about 40%. Nonetheless, the CO_2 price is on an upward trend, which implies that the attention of GWP has been continuously increasing. For instance, the carbon tax in Sweden has been increased by five times in 30 years [144].

The existing risk-informed optimization approach is demonstrated through an objective function, where the optimization is simplified as the minimization of the total cost C_{tot}. This approach considers the full life-cycle of a structure, from construction to renewal after failure or obsolescence. The C_{tot} (see Equation 3.1) is summed up by the construction cost $C_c(p)$, the expected failure cost $C_f(p)$, and the expected obsolescence cost $C_{obs}(p)$. These costs are associated with economic activities (e.g., construction, demolition) and life/societal consequences (e.g., fatalities). The $C_f(p)$ includes (re-)construction costs after the failure and non-structural failure costs such as costs for demolition and compensation costs for fatalities. The $C_{obs}(p)$ accounts for the need to sustain societal functions and assumptions of ongoing renewal of a structure at an annual rate, as formulated by Rackwitz [113]. These costs are discounted to the time t_0 when the decision is made.

A new concept for considering the environmental impact within the aforementioned risk-informed optimization approach is proposed, specifically for the case of timber structures, with GWP as the focused environmental impact. On the ground of the case study, the GWP (in terms of CO_2 price) is introduced into each component of the aforementioned C_{tot}, according to the life cycle stage. All GWP values, representing both carbon emissions and carbon benefits, are enclosed in C_{tot} (see Equation 3.1). Taking the component $C_c(p)$ as an example, a significant amount of GWP associated with the production and construction stages is added, which can be expressed as $C_c^* = C_c(p) + ENV_c(p)$. The $ENV_c(p)$ represents the monetized costs of GWP embodied in structures and energy consumed during the production and construction stages. Similarly, the monetized costs of GWP related to failure and obsolescence events are added to $C_f(p)$ and $C_{obs}(p)$, respectively. Here, the monetized GWP also encompasses the benefits associated with energy recovery due to the incineration process and fossil fuel substitution. However, it should be noted that this integration of environmental impact into the risk-informed optimization approach is conceptual instead of statistical, due to (i) the ongoing debate regarding the monetization for environmental impact indicators, and (ii) the lack of uniformed monetization criteria in the literature or practice. The benefits of biogenic carbon stored in timber, in terms of GWP, might also be included in this optimization approach, but should be handled with care.

4.5 Discussion

In the broader context of building LCA, the evaluation of timber structures represents a relatively specialized field. This thesis provides insights into the status quo of LCA on timber construction, identifying benefits, challenges and research possibilities (RQ1). The reuse potential of timber was explored, highlighting the added values of cascading timber in the context of climate change combat, and addressing possible reconfiguration of the timber value chain (RQ2). However, since the focus was on the Finnish context, the relevant findings are not universally applicable and could differ in other countries or regions. In addition, in-depth investigations could be conducted to assess practical constraints and viability, such as deconstruction methods and the quality of timber waste. Relevant stakeholders may be engaged, including contractors, material dealers, manufacturers and regulatory bodies.

The use of LCA at early stages of timber projects to facilitate decision-making was investigated, highlighting both benefits and associated challenges (RQ3). As this investigation was conducted from a structural engineer's perspective, the relevant feasibility and variability of results may be further studied, involving architects, structural engineers, and building-related service designers. The conceptual integration of LCA into a risk-informed optimization approach for timber structures has been proposed (RQ4). This framework requires further academic research before practical implementation. It may be used to guide standards and regulations by incorporating the environmental impact consideration into the risk-informed optimization of design. Despite the current low CO_2 price and its minuscule impact on overall cost, there is potential for significant changes in the future. Furthermore, although this framework is currently limited to GWP, it may be expanded to encompass other environmental impact indicators.

5. Conclusions and future research

5.1 Conclusions

In this thesis, timber construction and its relevant environmental impact from a life cycle perspective were explored. Timber as a material is gaining more attention in relation to rapid climate change and the promotion of renewable materials globally. As one of the key elements of sustainability, environmental impact has captured more attention in the construction sector, where LCA is a commonly used approach. However, at the commencement of the study, there was limited research that examined LCA in timber construction projects, regarding its role in climate change mitigation and potential development or challenges. This thesis contributes to the investigation on the environmental aspect of this matter, with LCA adopted as the main methodology, partially supplemented with other LCT aspects. The overarching research topics are initiated by the overview of LCA implementation in timber construction projects, to identify characteristics, critical issues, and potential improvement. Based on the findings of the literature review and pre-studies, subsequent research topics are determined and described in the following.

The literature review on the LCA applications in timber bridges was carried out, where the key finding discovered is the large variation among studies, e.g., boundary set, assessment method, inventory data, EoL scenario, etc. Moreover, LCA is found to be applied mostly after the design stage or the construction stage, but is expected to be more beneficial when applied at the early stages. Conclusions are usually project- or case-specific, but the (material) production stage appears to be the typical stage that has the most significant environmental impact, particularly in GWP. Multiple environmental impact indicators are obtained from LCA results, but the most common one is GWP, which represents the climate change potential. The EoL stage of the construction project lacks focus in the reviewed LCA studies, and is usually neglected or assumed to be under ideal conditions. Particularly for timber used in construction projects, the EoL scenario is worth further investigation due to its dual roles: incineration for energy recovery (contributing to the renewable energy resources) and material recovery through reuse or recycling (supporting CE principles and carbon reduction). This focus is relevant in the context of EU policies aimed at reducing carbon emissions while promoting renewable energy sources. The literature review is not comprehensive. The presented results are only considered as a basis for identifying essential characteristics and research topics chosen for this thesis.

The life cycle approaches in the investigation of timber cascading provides a holistic perspective including viability in the Finnish context. The thesis addresses relevant potentials and challenges from technical, economic, and environmental aspects. Cascading timber through reusing structural components, from a technical perspective, is theoretically viable. However, barriers remain, including the prohibition of re-grading under current EU standards, uncertain strength prediction, and unclear biological damage. Hence, standardized assessment criteria and an update of the relevant standard may be desired. A conceptual framework of the current business ecosystem for the C&D wood is established, targeting for the circularity of wood and maximizing the material value, which also aligns with the waste hierarchy defined by the European Commission. Two major alterations are introduced to this business ecosystem: design with LCT at the early stages and modification of EoL management (e.g., introducing material brokers). From the literature review, it was found that for timber cascading in Finland, the CE of C&D timber is highly demanded but industrial efforts are slow-moving. To address this challenge, regulation and policy are expected to be the driving force.

In order to quantify the benefits of reusing structural timber, a case study was performed, which investigated benefits and/or burdens from the environmental perspective. The results confirm the reduction of environmental impact (all indicators) with the cascading scenario. It further shows that the selection of different LCIA methods leads to varying LCA results, primarily attributable to differences in the characterization factors employed within each method. Feasibility may be further studied, such as deconstruction methods and cost-efficiency.

Currently, LCA is rarely a primary decision-making factor in construction projects, serving instead as supplementary info. The use of LCA at the early stages of timber construction projects, to assist the decision-making in the tendering process, is anticipated, but both benefits and challenges exist. The benefits are addressed, including the ability to eliminate design alternatives that may cause greater environmental impact at an early stage. Additionally, it helps in identifying environmental hot-spots, which can subsequently guide design or construction processes. The challenges are also identified, where the key lies in the variability of LCA. Using EPDs in LCA is found to be beneficial for tackling the variability, due to their uniformity. However, EPDs may have inconsistency, e.g., adhering to the latest EN 15804 +A2 standard [53] or to the obsolete version EN 15804 +A1 [52]. The variability of LCA decreases as the project progresses, due to more available information which reduces the variability of inputs. Nevertheless, this can be affected by taking actions at the early stages, aiming to enhance the comparability of bidding documents and efficiency in decision-making. One effective measure is to restrict producers or to designate specific generic data during the tendering process.

The environmental impact can be incorporated into decision rules targeting for optimizing structures at the early stages, to support sustainable construction. A design concept for including environmental impact in the existing risk-informed optimization (cost-based) approach of timber projects is proposed, where the LCA results (here, GWP) as monetized values are added to the objective function of this approach. This modified approach can be used as one decision rule for ensuring the sustainability of structure is addressed at the early stages. However, this approach is at a conceptual rather than statistical level. It is also found that the monetized value of GWP (CO_2 price) is significantly lower than the material cost, and there are no uniform monetization criteria, rather criticism regarding the monetization of environmental impact indicators. The biogenic carbon stored in timber products or elements may be included as separate GWP value.

In conclusion, this thesis offers valuable insights into the current application of LCA in timber construction. It highlights the substantial benefits of cascading timber in reducing climate change impacts from a life cycle perspective, also re-configures a framework of the current business ecosystem of wood to achieve circular economy. By highlighting both the benefits and challenges of LCA in early-stage decision-making for timber projects, the findings emphasize the vital role of LCA in promoting sustainable construction, as well as relevant variability concerns. Furthermore, the proposal for integrating LCA into the risk-informed optimization not only enhances the efficiency of the structure but also facilitates reducing relevant environmental impacts. In addition, these findings imply a paradigm shift in stakeholders' and policy-makers' decision-making criteria, from a typical short-term-oriented and cost-focused approach to a more holistic and sustainability-oriented framework.

The findings presented in this thesis contribute to advancing sustainable practices in timber construction and encourage the utilization of LCA as an essential tool in environmental responsibility (both in the early and late stages). Despite the contributions, it should be noted that there is still a gap between this thesis' contributions and practical implementation. For instance, existing Finnish policies and regulations have not demanded the use of LCA for decision-making, but relevant possibilities and benefits are acknowledged. Similarly, cascading timber and CE strategies have gained increased recognition, and relevant actions have been actively promoted, yet this has not been reflected in Finnish regulatory frameworks.

5.2 Future research

There exist other important topics that could not be covered within the scope of the thesis. Examples for further research could be:

- Applicability of cascading timber through reusing structural components. Comprehensive systematic assessment may be performed, including the investigation on e.g., deconstruction methods, identification of characteristics of the waste timber component, quality control and evaluation, and cost-efficiency analysis.
- Environmental impact indicators, rather than just GWP, that are requested

for LCA of timber construction to assist decision-making, are worth further investigation. The appropriate weighting and variations of these indicators also require examination.

- Viability of timber cascading dependent on the built environment. The study focused on timber cascading in the Finnish context, similar research can also be conducted for other countries, even globally.
- Expansion to encompass the whole building in LCA applications. This study focused only on structural components. To gain a holistic view of the environmental performance, the entire building should be included and analyzed.

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