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Knock on (Engineered) Wood: Pathways to Increased Deployment of Cross-Laminated Timber

A Case Study of the Building Sector in Sweden

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Thesis for the fulfilment of the
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Abstract

Significant negative environmental impacts are attributed to the building sector. To complement operational building efficiency, mitigation strategies could further decrease these environmental impacts. One mitigation strategy is increased use of low-carbon and bio based building materials. The objective of this research is to support such sustainable transitions within the complex building sector of Sweden, via identification of barriers and drivers for a specific bio and low-carbon building material called cross-laminated timber (CLT). Results from literature review and questionnaire responses were used to form recommendations for increasing deployment of CLT in Sweden, via specific leverage points and instruments.

Increased deployment of CLT in Sweden is also linked with several factors unique to Sweden. For example, environmental targets of the building sector, demand for housing, timber trends, development of a bio based and circular economy, and resource efficiency. To further validate and enhance results, global examples of successful CLT manufacturing practices, sustainable innovation transitions, and CLT support instruments were also examined. Results were also analysed using multilevel perspective, technology innovation system, and innovation diffusion frameworks. These tools were used to gain an interdisciplinary, comprehensive perspective and strengthen understanding of the building sector using systems thinking.

Results showed main barriers as lack of knowledge or skills, negative perceptions, perceived costs or risks, misalignment with regulations, and technological path dependencies within the Swedish building sector. Main drivers were CLT's carbon sequestration, low embodied carbon, renewability, efficient manufacturing and construction, cost competitiveness, and prefabrication. Key actors included building project owners, contractors, architects, engineers, the national housing authority (Boverket), and municipal building companies. Recommendations included education, skill building, green procurement, stronger materials focus in certifications, environmental evaluations of materials, environmental material requirements embedded in contracts and tenders, material carbon tax, stronger focus on building lifecycle impacts, and increased political focus on building materials. Recommendations are categorised and prioritised in the conclusion for clarity.

Keywords:
Cross-laminated timber;
Low-carbon building materials;
Bio based building materials;
Swedish building sector;
Decarbonisation;

Recommended literature:

1. Renewal of forest based manufacturing towards a sustainable circular bio economy
2. The Circular Economy and Benefits for Society Jobs and Climate: Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency
3. Level(s)–A common EU framework of core sustainability indicators for office and residential buildings

Executive Summary

What does this thesis aim to do?
This thesis aims to identify and analyse barriers and drivers for low-carbon and bio based material usage in Sweden's building sector. It specifically focuses on one case study building material, cross-laminated timber (CLT), which is a type of engineered wood panel that serves as a structural material. CLT is used as a proxy to represent low-carbon and bio based building materials. This research also identifies key building sector actors which could increase the deployment of CLT in Sweden. Environmental targets, timber industry trends, and building sector developments of Sweden were also examined, then both literature review and questionnaires were used to gather data. To summarise, this research identified and analysed bottlenecks, key actors, and important contextual details to enhance understanding of CLT deployment in Sweden. It also utilised various frameworks and real-life examples, which further elevated the complexity of results. The ultimate goal of this research was to formulate prioritised recommendations for how to increase deployment of low-carbon and bio based building materials in Sweden, in this case CLT. Final categorisation and prioritisation of recommendations is aimed at guiding the intended audience.

Why is this research important?
This is important for a host of reasons. First, the building sector is responsible for significant amounts of diverse negative environmental impacts. The project based building sector is conservative and very slow in adopting new technologies and practices, thus there is a need for support mechanisms which drive sustainable transition of the sector. Representatives from Boverket suggest that identification of leverage points and recommendations for how to implement instruments to boost CLT deployment is needed. Sweden is a suitable case country for this research due to its supportive innovation environment, abundant and sustainably managed forests, industrial sophistication, ambitious environmental targets, and strong links between academia, government, and industry. The planned shifts to a bio based and circular economy in Sweden also mean that transitioning the building sector to low-carbon and bio based materials will become increasingly important. This is especially true since Swedish population and construction are both rising. While there has been significant progress in operational efficiency of buildings, the material manufacturing, material selection, construction, and end-of-life stages have been largely unresolved. These cumulative factors all point to the importance of low-carbon and bio based building materials, such as CLT. New building materials like CLT may require transition management if they are to speedily and more widely penetrate the highly inert building sector of Sweden.

Research questions
RQ1: What are the barriers and drivers for higher deployment of CLT in Sweden, and which barriers are the most important?

RQ2: How could specific instruments and actors best support increased deployment of CLT in Sweden?

Barriers and drivers
The main barriers to CLT deployment identified through literature analysis and questionnaire responses were perceptual, financial, technical, and institutional. Perceptual barriers related to lack of knowledge, inadequate skills, and a range of misconceptions regarding costs, fire safety, durability, moisture resistance, acoustics, and other factors. Financial barriers related to capital costs, unclear maintenance costs, unproven durability, and specialty labour costs. Technical barriers related mostly to questionable fire safety, limited applicability, limited panel sizes, lack of standardisations, and varying acoustic performance. Institutional barriers related mainly to

path dependencies associated with traditional building materials of concrete, masonry, and steel. Additional institutional barriers included the disregard of wood materials stemming from the wood ban of Sweden, reliance on proven and familiar materials, established standards and product options of traditional materials, and established manufacturing and construction skills associated with traditional materials.

Drivers of CLT were mainly environmental, but also related to financial savings, reduced waste, construction speed, and renewability. Current CLT deployment is driven largely by its environmental advantages, including carbon storage, renewability, low embodied carbon, non-toxic indoor environmental quality, and efficient production, transport, and construction. Although CLT has a similar or higher capital cost than traditional building materials, it is linked to delayed financial savings from its sophisticated prefabrication, efficient transport, and fast construction time. Reduced manufacturing waste and on-site construction waste were also notable drivers for CLT use. Simple and quick on-site construction was another strong driver, since less time, labour, site disturbance, and complexity is associated with on-site CLT construction compared to traditional materials.

Recommendations

The analysis of findings strongly suggests an array of mechanisms to help steer and speed up a transition to more CLT use in the Swedish building sector. These recommendations were categorised into informational, voluntary, financial, regulatory, and business model-related measures.

Informational measures included dissemination of Swedish CLT construction guides, integration of CLT into building sector education at professional and university levels, coordination with building insurance companies, communication of business opportunities to potential CLT manufacturers, and spread of environmental and financial benefits to potential CLT users. Voluntary measures included increased material focus within certifications (e.g. BREEAM, LEED, Miljöbyggnad, Svanen), addition of CLT to material databases (e.g. SundaHus and BASTA), stronger focus on building materials in politics, green procurement, and technology procurement. Financial measures included carbon taxes on materials, taxes on non-renewable materials, grants for R&D, and subsidies for manufacturers and projects using low-carbon and bio based materials. Regulatory measures included environmental requirements embedded in building project tenders and contracts, green procurement requirements (public and private), environmental analysis of materials at early design stage, required use of wood materials, and requirements related to end-of-life environmental impacts and material recovery. Business model recommendations included efficient manufacturing models, industrial symbiosis with textile and chemical industries, increased prefabrication and digitalisation, and vertical integration combining production, transport, construction, consulting and related services to form attractive packages. The manufacturing best practice examples also serve as benchmark tools for Sweden.

Conclusion

CLT represents one potential pathway for Sweden to reduce environmental impacts of its building sector. Although the recommendations made in this research focus on CLT, many could be directly used or adapted to support sectoral transition to other low-carbon and bio based materials. What is most importantly recommended is stronger focus on environmental impacts of building materials, along with consideration of full building lifecycle impacts and education of building industry actors regarding low-carbon and bio based materials. Prioritised recommendations and best practices of CLT manufacturing are viewed as highly valuable results for the Swedish audience.

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Abbreviations

BBR = Boverket building regulations

BIM = Building information modelling

EPD = Environmental product declaration

IDP = Integrated design process

GPP = Green public procurement

LKF = Lunds Kommun Fastighets AB (Lund Municipality property company)

MLP = Multi-level perspective

SABO = Sveriges Allmännyttiga Bostadsföretag (Swedish Association of Public Housing Companies)

TIS = Technology innovation system

1 Introduction

To mitigate further contributions to anthropogenic climate change, transitioning to a lower-carbon building sector is necessary (IPCC, 2014). Both adaptation and mitigation measures are needed in the forms of both incremental and transformational change (IPCC, 2014) (Giesekam, Barrett, & Taylor, 2016). Although it is responsible for less CO_2 emissions than the transport, industrial, and energy sectors according to the IPCC (2014), the building sector is highly linked to these sectors via "indirect emissions." For example, building materials and components are industrially manufactured, transported throughout production and construction, and produced using energy. Therefore, a shift to bio based and low-carbon materials, integrated building design, and efficient construction would affect not only the building sector, but all four of these sectors (Giesekam et al., 2016).

As a complex project-based industry which is notoriously resistant to change, the building sector could benefit from support which aims to increase deployment of low-carbon and bio based materials (Giesekam et al., 2016). Barriers generally common for such innovations include high costs, technical limitations, and incompatibility with existing infrastructure (Bergek et al., 2015) (Geel, 2011). With the recent rise in green building certification schemes, release of UN, EU and national environmental targets for the built environment, and growing environmental awareness among the public, some progress has been made to reduce the negative environmental impacts of the building sector. But due to lack of institutional support, existing path dependencies to incumbent building materials and practices, and poor alignment between industry actors, uptake of bio based and low-carbon materials has been slow and scattered (Bohnsack et al., 2014).

The building sector is still experiencing slow improvement and requires stronger focus on systemic efficiency, sustainable housing for the growing population, low or zero energy buildings, and reductions in full lifecycle GHG emissions of buildings (IPCC, 2014). One such pathway to address these problems is increased use of low-carbon and bio based building materials, such as CLT. To speed up the transition to low-carbon and bio based building materials, the building sector needs changes in investment patterns, guiding policy instruments, environmentally focused governmental regulations, and more informational programmes (IPCC, 2014). Giesekam et al point out the strong need for new regulatory drivers to increase the use of alternative building materials with low embodied carbon and low embodied energy (Bohnsack et al., 2014). In practical terms, some of these changes could take the form of public or private investment in manufacturing facilities for low-carbon materials, financial incentives applied to low-carbon building materials, carbon taxes on environmentally harmful materials, and building regulations which require material evaluations or green public procurement (GPP) (IPCC, 2014). Furthermore, educational programmes aimed at architects, engineers, contractors, owners, construction companies and property managers could help these key actors select low-carbon and bio based materials (IPCC, 2014).

1.1 Problem definition

The building sector is responsible for many negative environmental impacts, such as greenhouse gas emissions, acid rain agents, and significant material resource use (Khasreen et al, 2009). Rising populations, affluence levels, and rates of urbanisation are also key compounding problems which will make the building sector increasingly impactful. To meet environmental goals at international, national and municipal levels, the building sector will require significant attention and solutions that reduce its negative environmental impacts. In the EU alone, the building sector accounts for approximately ½ of material extraction, ½ of energy consumption, 1/3 of water consumption, and 1/3 of waste output (European Commission, 2017). Materials most used within the EU include aggregates, concrete, brick, and steel as shown in Figure 1-1 (Ecorys, 2014), and this quite accurately represents Sweden as well. The European Commission Communication on Resource Efficiency Opportunities in the Building Sector (2014) adds that environmental pressures arise from all life-cycle stages of buildings, including material manufacturing, transport, construction, use, renovation, and deconstruction. Many environmental issues associated with the building process stem from poor or inefficient design decisions, material choices, material manufacturing, and construction practices, showing a need for bio and low-carbon materials such as CLT (European Commission, 2014).

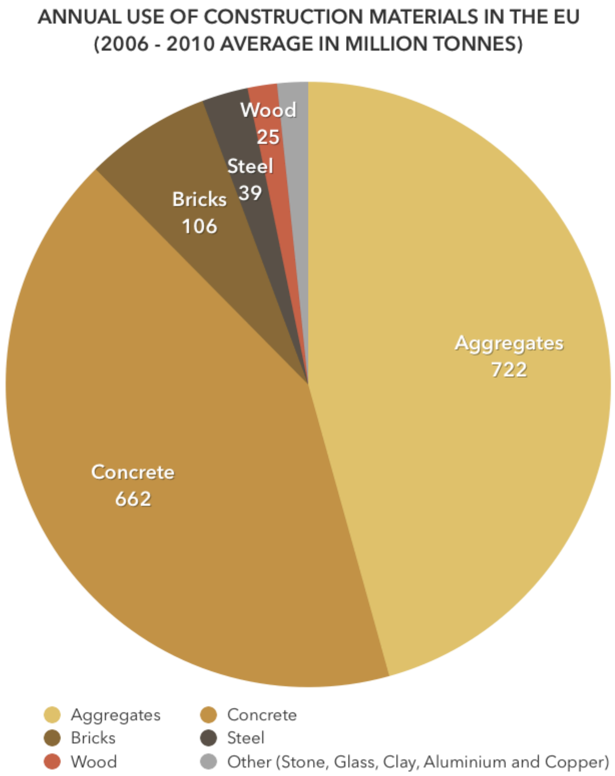

Figure 1-1. Annual use of building materials in EU

Source: Adapted from CRI calculations, 2014

As UN projections show that cities are responsible for 70% of current global GHG emissions and that 70% of the population will live in cities by 2050, it will become increasingly important to construct denser cities which are more resource and energy efficient (WWF, 2013). With buildings accounting for roughly 40% of global CO_2 emissions, and up to 80% in larger cities, this reinforces the urgency of mitigating the environmental impacts of the building sector (WWF, 2013). Previous regulations have principally focused on operational GHG emissions and energy use, thus not extending to the embodied carbon or energy involved with building material manufacturing, transport, use, and end-of-life management (Bohnsack et al., 2014). Additionally, many researchers have stressed the importance of reducing immediate or near-future GHG emissions compared to future GHG emissions, since immediate reductions are weighted as more valuable in climate change scenarios (Giesekam et al., 2016). Hence, when populations and standards of living are simultaneously rising, new construction is unavoidable and should be paired with an essential focus on mitigating embodied carbon of new buildings (Giesekam et al., 2016).

UK building industry giant Wilmott Dixon adds that the construction sector is one of the least sustainable in the world, aggravating problems of resource depletion, natural land loss, air pollution, water pollution, and landfill waste (Wilmott Dixon, 2010). Construction waste and inefficient manufacturing of building materials are key issues in need of solutions, along with the myriad negative environmental impacts associated with sand, gravel, stone and aggregate extraction for concretes (Wilmott Dixon, 2010). Additionally, increased use of sustainable materials, such as CLT, is recommended if these problems are to be solved (Wilmott Dixon, 2010). CLT is a highly relevant material in relation to many of these issues, considering its low embodied carbon, generally low environmental impacts, renewability, minimal waste, high levels of efficiency, and potential to replace or complement traditional materials.

The United Nations Environment Programme's (UNEP) Sustainable Buildings and Construction Programme and the UN Sustainable Development Goal 11 also confirm that current building sector practices are resource-inefficient, responsible for significant GHG emissions, highly energy-consuming, and produce large amounts of waste (UNEP, 2016). Additionally, the SBC programme and the UN SDG 11 have targets focusing on both building design and building materials that emphasise eco-design, optimal material use, local resource use, responsible material sourcing, and use of durable and low-maintenance materials (UNEP, 2016; UN, 2016). These targets suggest that CLT could be a suitable material in many regions, if local timber is used and source forests are sustainably managed.

European Commission Communications on building sector resource efficiency (2014) and circular economy (2015) both emphasise improving building design, construction, performance, and deconstruction (European Commission, 2017). Thus, there is a noticeable void in the building industry, which needs to be filled by materials with low environmental impact, efficient nature, renewability, and design for disassembly. The entire life-cycle requires more attention, since building material manufacturing accounts for 5-10% of EU energy consumption (European Commission, 2014) and 40% of CO_2 emissions from buildings are associated with their embodied energy (Ecorys, 2014). Additionally, the EU 2020 strategy lists buildings as capable of significantly reducing energy demands, GHG emissions, and resource consumption (Ecorys, 2014). This initiative includes a range of 2020 targets including increased material efficiency, applied life-cycle accounting, nearly net-zero new buildings, and a goal of 70% of construction and demolition waste recycled (Ecorys, 2014). Construction and deconstruction waste accounts for 33% of total waste in the EU, with concrete, asphalt, and masonry as the main components (Ecorys, 2014). Global warming potential (GWP), resource depletion, production toxicity, and embodied energy are highest for aluminium, copper, and steel (Ecorys, 2014). Furthermore, embodied energy and embodied carbon will soon become the dominant environmental factor, rather than operational efficiency of buildings (Ecorys, 2014) (Roh, Tae, Suk, & Ford, 2017). Therefore, analysis of embodied environmental impacts of building materials is increasingly important, forecasting a rise in use of low carbon, bio based, renewable, and regionally sourced materials (Giesekam et al., 2016) (Roh et al., 2017).

Specific problem

Sweden is home to a complex and highly concrete-dependent building sector (Antikainen et al., 2017). Boverket and researchers have stated that there is a clear need for identification of leverage points and measures that can be implemented to transition Sweden to bio and low-carbon building materials. Environmental and geographic factors favour a transition to wood construction and CLT could renew forests, reduce impacts of the building sector, and support a circular economy (Antikainen et al., 2017). Bio and low-carbon materials such as CLT could serve as attractive alternatives or complements to concrete, steel, and brick. Based on the severe environmental impacts of incumbent materials dominant in the Swedish building sector, low-impact and bio based building materials are an attractive pathway to reduce impacts of the sector and meet various international, state, and municipal environmental targets relevant in Sweden. Building materials which have lower levels of associated waste, such as CLT, could also serve as pathways to meet waste reduction goals. Domestic CLT manufacturing is relatively low in Sweden, and since Sweden is a net importer of CLT it is in the country's best interest to increase local production using abundant domestic timber. Leverage points and specific actions need to be identified to support increased deployment of CLT in Sweden. The complexity and wide array of actors involved in the building sector also suggest that clarification of designated roles and responsibilities could be beneficial.

1.2 Research questions and objective

RQs	Question	Answer sources
RQ1	What are the barriers and drivers for increased deployment of CLT in Sweden, and which barriers are the most important?	• Secondary data = Scientific literature, conference publications, industry reports, and governmental documents
		• Primary data = Questionnaire responses from manufacturers, architects, construction companies, municipalities, certification schemes, researchers, and additional building industry actors of Sweden
RQ2	How could specific instruments and actors increase deployment of CLT in Sweden?	• Secondary data = Framework literature; Examples of emerging sustainable innovations; Examples of CLT support in various regions
		• Primary data = Questionnaire responses from various building industry actors

Table 1-1. Research questions

Source: Own elaboration

The objective of this research is to identify the barriers, drivers, and key actors for wider deployment of a bio based and low-carbon building material, CLT, in the context of Sweden's building sector. Expert responses from various Swedish building industry actors served as the primary source for this information, with literature review providing secondary data.

Ultimately, recommendations for how to increase deployment of CLT in Sweden are provided based on questionnaire responses, contextual factors of Sweden, examples of other emerging technologies, examples of CLT support mechanisms, and applicable frameworks focused on transition management and technology diffusion. Enhancing the understanding of CLT in the context of Sweden's various environmental targets, bio economy plans, and aim to become a circular economy is also an embedded objective of this research. These objectives will be achieved through multiple steps outlined in Table 1-2.

Step 1	Establish understanding of Swedish building sector, specifically in connection to environmental targets	*Main objective:* Increase deployment of CLT in Sweden *Embedded objective*: Enhance understanding of synergies between CLT, bio economy, and circular economy within Sweden
Step 2	Summarise essential information regarding Swedish timber industry	
Step 3	Provide reviews of incumbent structural building materials, including concrete, steel, and masonry	
Step 4	Establish foundational understanding of environmental and technical characteristics of CLT	
Step 5	Examine why CLT is not more widely deployed in Sweden, despite its environmental advantages	
Step 6	Recommend methods to increase deployment of CLT in Sweden, based on Swedish context, other emerging technologies, CLT support examples, CLT manufacturing best practices, and selected theoretical frameworks	

Table 1-2. Research steps to reach objectives

Source: Own elaboration

1.3 Scope of research

1.3.1 General – Building sector

The general focus of this research is the building sector, and exploring how low-carbon and bio based building materials can help to reduce its negative environmental impacts. Additionally, it aims to highlight challenges low-carbon materials face when trying to penetrate the building industry and potential solutions to those challenges. Since the building sector is globally responsible for roughly 50% of CO_2 emissions, 50% of material resource use, 40-50% of greenhouse gas emissions, and 40-50% of acid rain agents, it is a sector that warrants this focus (Khasreen et al, 2009). Engineered and value-added timber building materials, such as CLT and glue-laminated timber, are a potential pathway to help mitigate negative environmental impacts of the building industry. Despite being a highly developed, industrially advanced, environmentally ambitious, and timber-rich country, Sweden has only experienced low levels of CLT deployment in its building sector.

1.3.2 Specific – Sweden and CLT

Since Sweden is increasing its CLT production and is meeting capacity limitations for concrete production, this creates an interesting context to explore the barriers and drivers for wider deployment of CLT. Fascinatingly, the CLT produced within Sweden does not meet the domestic demands, resulting in large amounts of CLT being imported from other countries such as Austria and Germany (Oscarsson, 2016). Considering significant transport costs of 15-20% for imported CLT and a net export of domestic wood products from Sweden, the opportunities for increased domestic CLT manufacturing and use could be very appealing (Oscarsson, 2016). Promotion of CLT and other wood materials in construction was even called the quickest route to reach a bio economy in Sweden (Antikainen et al., 2017).

Sweden is a relatively small country, but its population and levels of new construction are both expected to increase significantly within the coming years. The *Construction in Sweden – Key Trends and Opportunities to 2020* report (2016) states that the growth rate in the Swedish construction industry is forecasted to continue at 12.1% until 2020, driven by investment, continued economic recovery, and the Swedish National Reform Program of 2016 (Reportlinker, 2016). Additionally, the report mentions that residential construction permits increased by 17.4% in 2014, while Sweden is still trying to address housing shortages via government plans to finance construction of 250,000 homes by 2020 (2016). As CLT is highly applicable to the multilevel housing segment, it is considered a valuable new resource for Sweden's predicted rapid construction growth.

1.3.3 Case study material – Cross-laminated timber

Cross-laminated timber (CLT) is an established structural building material that has been produced and used widely in alpine Europe (Harris, 2015). It has numerous environmental advantages, meets technical requirements for a range of building types and applications, and is gaining recognition within global building codes and regulations (Laguarda Mallo & Espinoza, 2015) (Evans, 2013). CLT is the chosen focus material of this research due to a variety of environmental factors. Environmental benefits are further described in section 3.3.

First, it is made from renewable and CO_2 sequestering material – wood – which stores roughly 1 tonne of carbon/m^3 (Dodoo, Gustavsson, & Sathre, 2014) (WoodWorks, 2014). For example, the Dalston Lane building in London is considered carbon negative by experts, storing roughly 2,400 tonnes of carbon which is much more than a concrete equivalent (Horx-Strathern, Varga, & Guntschnig, 2017). Furthermore, CLT is also associated with much lower CO_2 emissions, with CLT shown to have roughly 17% the CO_2 emissions of either concrete or steel equivalents (Horx-Strathern et al., 2017). Secondly, it can reduce production and construction waste, energy consumption in both manufacturing and use phases, and construction time due to its prefabrication (Jones, Stegemann, Sykes, & Winslow, 2016) (Eastin & Sasatani, 2016). As CLT is delivered ready for installation and is light weight, its associated transport emissions, on-site emissions, and site disturbances are very low (Horx-Strathern et al., 2017). Third, it holds new end-of-life opportunities and modular design possibilities which can help Sweden become a more circular economy, since it could be re-used or recycled upon deconstruction (Harris, 2015) (Laguarda Mallo & Espinoza, 2015). CLT is manufactured very efficiently, making use of digital tools to avoid waste and explore heightening prefabrication designs. Fourth, CLT is relevant for Sweden due to the abundant and well-managed timber resources of the region. As the amount of forest in Sweden is steadily increasing, it is a clear opportunity to both store carbon in building materials long-term and continue using forests to absorb CO_2.

Additionally, CLT utilises "side-boards" of varying strength (see Fig. 1-2), damaged wood, low-quality wood, and small-diameter and fast-growth species otherwise wasted or used as low value products (Evans, 2013). Some companies are already using wood by-products from CLT production for biofuel or heat and energy production, thus decreasing dependence on non-renewable fuels (Evans, 2013). It also holds potential for more decentralised and bio based industry, since the production process is efficient, requires few ingredients, and is simpler compared to the manufacturing of concrete, steel, and brick (Evans, 2013). Its growing range of applications also make it a more versatile material than standard timber (Evans, 2013).

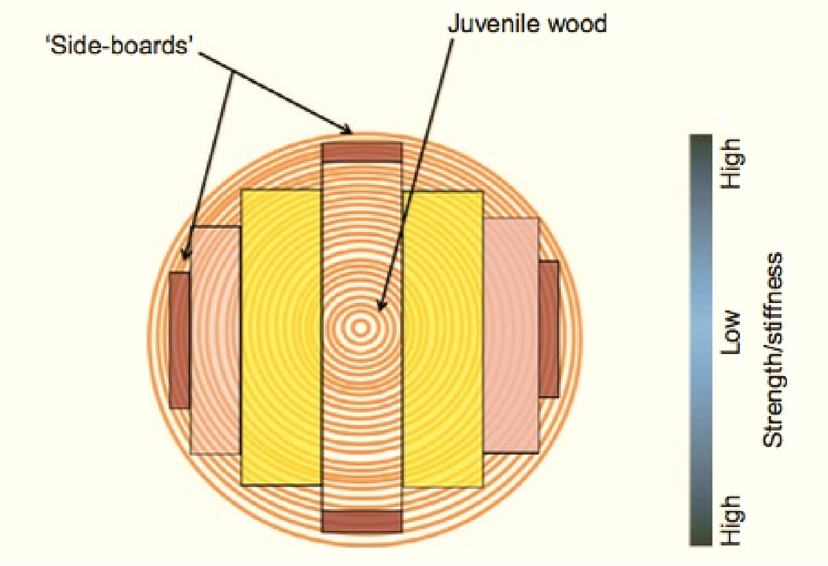

Figure 1-2. "Side-boards" diagram

Source: Harris, 2015

While there are a variety of engineered wood products (EWPs) in European markets, CLT was selected for this research due to its expanding applications, potential to be used for entire buildings, and strong similarities to precast concrete which make it a suitable replacement. Other EWPs have more limited applications, sizes, strength and durability, while CLT can be prefabricated for use as floors, walls, roofs, and shells. Various reports and research articles have confirmed that CLT is also an environmentally preferable choice when compared to steel, concrete, and brick (Evans, 2013). This is due to its renewable nature, carbon storage abilities, low embodied carbon, low air and water pollution, and operational energy efficiency due to thermal insulation properties (Evans, 2013) (WoodWorks, 2014). Considering the many negative environmental impacts of current incumbent building sector materials, expected construction and population growth in Sweden, and the ambitious environmental targets of Sweden, it is unfortunate that this technology has not been more widely deployed.

1.4 Methodology overview

1.4.1 Research design

This research was based on a combination of literature review and qualitative questionnaires, thus providing both secondary and primary data. A single case study approach was adopted which set the focus on CLT deployment in the Swedish building sector. While the literature review was conducted, questionnaires were simultaneously being returned by actors from the Swedish building sector. Once adequate responses were received, the questionnaire responses were analysed using a synthesis matrix and information was triangulated alongside results from the literature review. Ultimately, selected frameworks were also utilised to formulate recommendations suitable for identified barriers. It is important to note that respondents to the questionnaire that were not from Sweden were considered experts related to CLT and were used early in the research only to establish basic knowledge. Due to this separation from the Swedish scope of this research, responses from non-Swedish actors are located separately within the matrix in Appendix B.

1.4.2 Data collection and analysis

First, a literature review was conducted to gather secondary data and establish foundational understanding of the Swedish building sector, timber industry, and municipal and national environmental targets. In addition, a literature review of cross-laminated timber was conducted to enhance understanding of its environmental advantages, technical capabilities, applications, and comparisons to other incumbent building materials.

Next, various building industry actors from Sweden were given questionnaires to identify barriers, drivers, and key actors for CLT in the Swedish building sector. Building industry actors were selected based on their expected ability to provide valuable responses, level of experience in the sector, geographic location, and availability. Questions also focused on potential mechanisms to increase CLT deployment. Building industry stakeholders interviewed included CLT manufacturers, architects, construction companies, consultants, associations, municipal building companies, and regulatory bodies. In total, 23 actors provided written questionnaire responses (See Appendixes A-C).

Triangulation of data collected from literature review and questionnaire responses was the first step of the analysis process. Questionnaire responses were loosely coded based on keywords, and these results can be reviewed in Appendix C. Subsequently, responses were evaluated qualitatively to identify barriers and drivers affecting deployment of CLT in Sweden (See Appendix B). Literature focusing on transition management (MLP), technology innovation systems (TIS), and innovation diffusion was then used to analyse the literature data and questionnaire responses. Specific barriers and drivers found via questionnaire responses were collected and compared to other examples of emerging sustainable technology experiencing low deployment. Successful examples of CLT deployment support in other regions were also used to assist in forming recommendations. Lastly, reviewing various unique factors of the Swedish building and timber sectors also supported the formation of recommendations.

1.5 Limitations

Limited numbers of actor responses were received; therefore, the research results do not accurately represent all building industry actors within Sweden. Since this research was conducted throughout the summer of 2017, the absence of many key actors due to summer holidays was a significant circumstantial limitation in securing questionnaire responses. For qualitative research such as this, purposeful selection of few actors is sufficient, but more responses could have provided more robust results.

A narrow research scope caused delimitations related to generalisability. Generalisability is limited, since CLT served as the sole case study building material. Other bio based or low-carbon building materials may require raw materials, manufacturing, and construction techniques which differ from those of CLT. Other materials may also encounter different barriers. For these reasons, it is advised that the results of this research are carefully applied if other building materials are similar CLT. For example, glue-laminated timber could be another building material which this research could be applied to due to its similarities in raw materials and production while results would be less applicable to recycled aggregate concrete.

Geographic generalisability is also a limiting factor, although intended. Results may be more applicable to specific regions similar to Sweden, based on geographic characteristics such as amount of forest, projected growth in construction, climate, availability of financial investment, and level of industrial development. Building norms, material prices, and environmental targets also vary between regions, so areas with ambitions like Sweden are suggested to be more suitable if applying these results. For example, countries such as Norway, Finland, and Canada could be viewed as similar regions.

It should also be noted that building codes and regulations differ in many parts of the world. Regions with similar performance based building codes and regulations to those of Sweden could be more suitable to generalise this research to than countries with prescriptive buildings codes. For example, the performance based building codes of EU countries inherently make the results of this research more applicable than the USA, which uses prescriptive building codes.

1.6 Ethics and audience

All interviews and questionnaire responses were collected ethically with informed consent. Respondents participated in answering questionnaires voluntarily and confidentiality was respected if requested by the respondent. Questionnaires were sent to relevant building sector actors in Sweden, of which all responses were used. Clear communication of research purpose, scope of work, and rationale for the chosen case study was also provided to respondents. Additionally, all graphics that were not created by the author were used with written permission from the original authors. Frameworks which were used to help synthesise results from the literature review and questionnaire responses served as tools that were adapted to the relevant research topics.

The intended audience for this research is key actors within the Swedish building sector. More specifically, the resulting recommendations of this thesis are aimed to reach Swedish policy makers who influence building codes and regulations, Swedish timber companies, Swedish building companies, and various individual building sector actors. These individual actors include building owners, developers, architects, contractors, and building engineers primarily. As most of the final recommendations are policy or regulation related, it is most importantly aimed to reach key municipal and state decision makers in Sweden.

1.7 Disposition

Chapter 1 introduces this research, defining the problem, research questions, and main objective. The scope and methodology overview is also provided, explaining the research design, data collection, data analysis, and limitations. Lastly, ethical considerations and intended audience are listed.

Chapter 2 presents the context and guiding frameworks of the research. The context includes background information, relevance, and information specific to the scope of research, which focuses on CLT in Sweden.

Chapter 3 provides a general overview of cross-laminated timber (CLT), to establish foundational understanding of its basic characteristics, technical qualities, history, environmental impacts, and comparisons to other building materials.

Chapter 4 holds the literature review where barriers and drivers to deployment of CLT are identified. Some key building sector actors were identified in this section as well.

Chapter 5 presents the results from both the literature review and the questionnaire responses. This section focuses mostly on barriers and drivers, but also highlights key actors, leverage points, and recommendations for how to increase CLT deployment in Sweden.

Chapter 6 presents the analysis of the findings. This section refers to guiding frameworks, using them as tools to enhance understanding of the results and elaborate on key barriers, key actors, and recommendations.

Chapter 7 provides a discussion of CLT best practice examples, sustainable transition examples, and CLT support tool examples. These examples served as a method to withdraw knowledge from other countries, other sustainable innovations, and other tools, further enhancing understanding of how CLT deployment in Sweden could be managed in the future. This also highlighted consistencies from the literature review and the questionnaire responses, as well as contradictions. Recommendations for how to increase CLT deployment in Sweden are presented in the end of this section.

Chapter 8 provides a conclusion summarising chapters 5-7 and Chapter 9 outlines suggestions for further research in this field.

2 Context and theories

2.1 Background

Considering the environmental gravity associated with the current and future building sector, transformative solutions are encouraged rather than incremental improvements (WWF, 2011). Although some transformative solutions in the form of new technologies are available, insufficient political will and market environments are challenges in some regions (WWF, 2011). Fortunately, Sweden is ranked 3rd globally in cleantech innovation due to GDP-related support for clean technologies, meeting demand for new technologies, connecting start-ups to finance, and increasing international investor engagement (Sworder, 2017). It is important to note that Sweden also has high research and development expenditure from public sources, cleantech friendly policies, and many domestic investors which also make it an ideal environment for both emerging and commercialised innovations (Sworder, 2017). CLT could be viewed as a research focus, investment opportunity, and sustainable innovation for Sweden's building sector.

As Sweden is also anticipating strong growth of the building sector, due to rising populations, sustainability of the building sector is a particularly relevant issue for the nation (Naturvårdsverket, 2016). Naturvårdsverket (the Swedish Environmental Protection Agency) also states that there is no clear trend in reducing environmental impacts of the Swedish building sector. They add that it is necessary to improve the building sector beyond energy efficiency via sustainable building design, material choice, and construction methods and that the national environmental quality objective for the built environment will not be met by the 2020 target date (2016). CLT and other low carbon and bio based materials could help Sweden meet these goals.

Sweden's forest-rich landscape, mature manufacturing culture, and ideal innovation environment can also be viewed as underutilised resources. These resources could further boost manufacturing of low-carbon and value-added timber products such as CLT and other engineered timber building materials (Formas, 2012). Since many negative environmental impacts are attributed to the construction sector, specifically cement production, one key mitigation technique is identifying high-impact materials and replacing them with lower-impact bio based materials (Peñaloza, 2017). A recent Club of Rome report also emphasises that investment in new bio based products, specifically from timber, is necessary for shifting to a circular economy in Sweden (Wijkman & Skånberg, 2016). Although generalisations and assumptions should be avoided, Peñaloza established that "increasing use of bio based materials reduces climate impacts of construction" and "mitigation potential is maximised by simultaneously implementing other strategies, such as increased use of low-impact concrete or renewable energy" (2017).

These trends and needs of the building industry in Sweden point towards increased use of low-impact materials, such as CLT. Synergistic benefits and multiple dividends could result from this potential path, such as new "green" jobs, decentralised manufacturing, use of low-quality and damaged wood, reuse of materials, early adopter business opportunities, and streamlined building design and construction processes. Transitioning to low-carbon and bio based building materials like CLT could help Sweden become a more circular and bio based economy (Formas, 2012). This transition could lower environmental impacts of the building sector, while also benefitting the Swedish economy and society.

2.2 Research relevance

Reducing the negative environmental impacts of the building sector in Sweden is a highly relevant issue, due to the growth of population and construction, high impacts of the sector, and various international, national, and municipal environmental targets. While UN Sustainable Development Goals and EC initiatives have placed some focus on reducing environmental impacts of the building sector via improved selection of materials, Sweden is still not on target to meet the 2020 environmental quality objective for "A Good Built Environment" (Naturvårdsverket, 2017). Building design, material selection, and construction methods are each becoming more important due to recent urban growth in Sweden, signalling a need for innovative materials like CLT (Naturvårdsverket, 2017).

With concrete, steel, and brick materials causing a wide range of negative environmental impacts, alternative bio based and low-carbon building materials are appropriate to meet sustainable development demands. Building materials sourced, manufactured, and used in Sweden are key to meeting growth demands and lowering environmental impacts of the building sector simultaneously. Not only could heightened use of CLT revitalise the Swedish timber industry and provide new renewable-based jobs, but it could also help meet many of the Swedish Milestone Targets for the environment. Of Sweden's 24 Milestone Targets, using CLT as a construction material could help 1) reduce greenhouse gas emissions, 2) reduce construction and demolition waste, 3) increase responsible forestry, and 4) further develop sustainable practices and shift to a more bio-based economy (SEPA, 2017). As the largest city in Sweden, Stockholm also has several programmes that focus on urban green growth, building a green economy, and improving recycling and reducing toxic substances (City of Stockholm, 2016). Increased deployment of CLT could contribute to these many goals, since it can be used for both new constructions and additions to existing buildings, can add value to Swedish timber, has reuse potential at end-of-life, and contains no harmful chemicals.

2.3 Definitions of key terms

Cross-laminated timber is a panel consisting of three or more uneven layers of timber beams. Alternating layers of lamellas are placed at 90º angles and bonded together. Panels are bonded using presses and adhesives, and the resulting product has significantly higher strength, durability, and engineering potential than standard single timber beams. CLT panels can be prefabricated to have specific sizes, purposes, fenestrations, and channels for connectors, electrical wiring, and plumbing (Brandner, 2013).

Engineered wood products are the broader group of engineered or "mass" timber panels. These include glue-laminated timber, cross-laminated timber, and laminated veneer lumber. These types of panels are similar, but differ in technical qualities, manufacturing, construction applications, and costs. Overall, they are engineered to have augmented capabilities which standard single timber beams do not have, thus increasing their value, widening their applicability, and increasing their levels of prefabrication (Barber & Gerard, 2015).

Circular economy (CE) is the broad concept of an economic system that seeks to gain more value from resources by use and reuse for as long as possible (Wijkman & Skånberg, 2016). Goals include increasing economic prosperity, providing jobs, and reducing negative environmental impacts associated with GHG emissions, waste, and pollution (Ness & Xing, 2017).

Bio economy refers to an economic system that relies upon biological resources to produce food, energy, chemicals, and materials, while prioritising resource efficiency, emission reductions, sustainability, and biodiversity protection (EC, 2012). Sharing some aspects with the concept of circular economy, the concept of bio economy also implies reduced use of fossil fuels and finite resources (McCormick & Willquist, 2015). The bio economy is mainly aimed to shift economies to become more reliant on renewable and sustainable resources, such as wood, which can replace less renewable materials (EC, 2012).

Low-carbon building materials are defined as building materials which have lower associated GHG emissions, less embodied carbon, and sometimes carbon sequestration capabilities than traditional building materials. A life cycle perspective is implied, since materials such as concrete, steel, and brick are linked with high levels of GHG emissions and significant carbon emissions from their raw material extraction, processing, transport, use, and end-of-life management (Tarantini, Loprieno, & Porta, 2011). Low-carbon building materials conversely refer to materials such as CLT, recycled aggregates, or reclaimed steel, which have lower embodied carbon and lower GHG emissions associated with their production, transport, use, and end-of-life management (Giesekam et al., 2016).

2.4 Sweden

Sweden is a sparsely populated and heavily forested Nordic country known for its advanced industrial and manufacturing practices. Sweden's population is expected to rise significantly in the future and cause urban centres to become denser. The private and public support for clean innovations is also significant in Sweden. Furthermore, Sweden is working vigorously at state and municipal levels to reduce its negative environmental impacts via stringent targets and regulations. Specifically regarding buildings, Sweden is recommended by experts to reduce negative environmental impacts, reduce material consumption, and increase reuse opportunities (McCormick et al., 2013). Sweden serves as a global role model for many good examples or best practices in terms of environmental management. Sweden's planned shifts to a more circular and bio based economy could be the next step for this leading country to act as an international role model for environmental practices.

Working on behalf of the state government, Sweden's national building authority Boverket is currently investigating the benefits of sustainable building materials. Boverket will even be proposing new framework measures regarding materials in 2017 for the national Planning and Building Act (Boverket, 2017). Furthermore, a collaboration between Boverket and the Swedish Environmental Objectives Council is also researching guidance on LCAs for the building sector (Boverket, 2017). Boverket also proposed use of LCAs for all new buildings and renovations by 2020, since roughly 70% of national GHG emissions originate from new construction and renovation (2017). Sweden also has a goal to reuse, recycle, or recover at least 70% of construction demolition waste by 2020 (European Environment Agency, 2016). CLT is one example of a low-carbon and bio material that could help Sweden regarding these developments and goals.

The Swedish Association of Public Housing Companies (SABO) further adds to Sweden's interesting construction industry environment. This non-governmental organisation consisting of 300 companies, manages roughly 20% of the national housing stock, owns ½ the rental sector (over 800,000 homes), and has environmental targets aligning with the EC and Swedish government (SABO, 2008). The organisation also has a 2020 plan with specific focuses, including GHG emission reductions and use of "healthy and renewable materials" which suggest a shift to materials like CLT (SABO, 2008). Looking at not only single building projects, but full precincts and cities is a suggestion from researchers in Sweden that aligns well with this organisation's 2020 plan (McCormick et al., 2013). Since municipal building companies are key decision makers in construction of new multi-story housing in Sweden, they can aptly drive increased use of low-carbon and bio materials in public projects. Companies such as LKF in Lund and MKB in Malmö are examples of these types of companies which could serve as catalysts in transitioning full precincts and cities to low-carbon societies (McCormick et al., 2013). CLT holds massive potential considering these developments, due to its renewability, carbon storage, prefabrication, modularity, and applicability to the housing segment.

Sweden also has abundant timber resources, stringent sustainable forestry practices, and goals to shift to a more bio based and circular economy. Several CLT manufacturers are efficiently combining CLT production with biofuel, heat, and energy production, showing alignment with Sweden's aim to become a low-carbon and bio based society (McCormick & Willquist, 2015). These CLT companies are not located in Sweden (see *Discussion* chapter), but are better capturing the value of timber resources and could serve as guidance for Swedish companies. The bio economy and circular economy are both developing in Sweden, specifically regarding the forestry sector which is expected to stimulate increased timber construction (Peñaloza, 2017). Wooden multi-story construction was even called "the most evident construction-related new business opportunity in the emerging Nordic bio economy" (Toppinen, Röhr, Pätäri, Lähtinen, & Toivonen, 2017). As Sweden uses high amounts of domestic metal ores and exports most of its timber, it is logical to explore domestic production of value-added timber products such as CLT (European Environment Agency, 2016). Furthermore, Sweden is ranked 3rd by the Global Cleantech Innovation Index, suggesting suitability for further research, development, and production of new building material technologies such as CLT.

What links these contextual circumstances together is the potential for bio based and low-carbon building materials, such as CLT, to address them and help reduce the negative impacts of Sweden's building sector. The negative environmental impacts of incumbent building materials and new building demands pose both a challenge and opportunity for Sweden. One expert from the Technical University of Graz also stated that Sweden is one of the most important future markets for CLT and engineered timber products, since CLT has yet to break widely into the multi-story segment, Stora Enso is opening a new CLT plant in late 2018 in Grüvon, and CLT is viewed as a new value-added product to add to timber portfolios (Schickhofer, 2017).

Characteristics of Sweden	**Role(s) of CLT**
Abundant timber	Value-added product, long life (predicted ~80 years per KLH), export opportunities
Effective sustainable forestry	Production could be combined with conservation
Sophisticated industrial sector	Patent-free technology, best manufacturing practices can be mimicked, potential for R&D
Significant cleantech support	Fast project ROI, niche market but growing, open to further domestic development
Ambitious environmental targets	Could help meet national building sector targets (SEPA), municipal initiatives, SABO 2020 targets
Increasing population	10-15% increase of usable interior living space when using CLT, fast construction time, non-toxic
Increasing construction	Low-carbon & bio based material, fast erection, local material, environmental benefits, efficiency
Shifting to bio economy	"Green" jobs, domestic production could lower need for imported CLT, renewable, industrial symbiosis opportunities
Shifting to circular economy	Reduced construction & deconstruction waste, reduced landfilled waste, reuse opportunities at end-of-life

Table 2-1. Synergies between Sweden and CLT

Source: Own elaboration

2.4.1 Swedish building sector

Sweden's building sector has grown steadily since 2014 and has strong expected growth through 2020 (Reportlinker, 2016). Sweden is also experiencing a housing shortage, and thus has a national plan to publicly finance construction of 250,000 new flats by 2020 (Reportlinker, 2016). This is also a significant business opportunity, since a 20% market value increase is predicted between 2015 and 2020 which would bring the industry to roughly 60 billion USD in value (MarketLine, 2016). The residential segment is the most significant, representing 47.9% of construction, while non-residential represents 27.5%, and industrial the remaining portion (MarketLine, 2016). Within the last decade, only about 9% of construction material in Sweden was timber-based and a massive 89.5% was concrete-based (Peñaloza, 2017), showing a significant opportunity to transition to increased use of timber building materials. CLT is interesting in this context, because its prefabrication, technical qualities, and size limitations make it highly applicable to the residential and multi-family building markets.

It is also important to note that the Swedish building industry is highly fragmented, supplier-driven, and risk-averse with many actors wielding decision-making power throughout the building design, construction, and operational phases (MarketLine, 2016) (Giesekam et al., 2016). These actors include building code authorities, owners, developers, architects, contractors, and material suppliers. Notably, the building materials sector in Sweden is concentrated with few, dominant suppliers of traditional materials like concrete, steel and brick. This makes for a difficult market entry path for manufacturers of new building materials, such as CLT (MarketLine, 2016). Furthermore, there is strong reluctance to experiment with unfamiliar building materials in the building sector, because of the unsystematic learning processes of individual actors through project-by-project experience (Giesekam et al., 2016). Even in highly developed countries such as Sweden, there is still only incremental deployment of building material innovation and low exchange of knowledge between academia and the building industry (Giesekam et al., 2016).

Despite the Swedish building sector being a main contributor to environmental stress and resource depletion, there is still a lack of clear national and local public policy support to reduce negative environmental impacts (Hagbert et al, 2013). The strong European-wide operational efficiency focus has also overshadowed building material considerations. Efficiency of lighting, HVAC, and water use has been emphasised, while embodied carbon, emissions, and energy have been less prioritised (Hagbert et al, 2013). Numerous actors of the building sector also caused confusion concerning who should be responsible for mitigation of environmental impacts of building materials (Hagbert et al, 2013). Balancing ranging demands of different building industry actors adds further complexity. Most (roughly 70%) housing units in Sweden are also rented, meaning that it is often unclear which actors are key decision makers in the material selection process (Hagbert et al, 2013). The Swedish building industry is conducting comparative research on life-cycle analysis (LCA) for both concrete and load-bearing wood materials (Schlanbusch et al, 2016). A "screening" LCA of building materials is a potentially valuable tool to help decision makers early in the building design process (Schlanbusch et al, 2016), as seen in the use of EPDs. The construction sector still contributes to a significant share of Sweden's GHG emissions and Boverket confirms that over 1/3 of the building sector's CO_2 emissions come from new construction, indicating a strong need for new materials like CLT (Peñaloza, 2017; Boverket, 2017). Lastly, numerous national plans such as the Sweden Waste Plan 2012-2017, Waste Prevention Programme, and Minerals Strategy among others prioritise the construction industry and its associated consumption patterns, signalling high priority (European Environment Agency, 2016).

2.4.2 Swedish timber industry

Sweden is home to roughly 1% of global commercial forests and provides roughly 15% of global timber (Royal Swedish Academy of Agriculture and Forestry, 2015). Swedish forests experience high productivity and low disturbance rates, due to the dual conservation efforts of general forest management and strict area protection (Royal Swedish Academy of Agriculture and Forestry, 2015). 57% of land in Sweden is considered productive forest, consisting mostly of Norway Spruce (40%) and Scots Pine (38%), which is suitable for CLT production (Royal Swedish Academy of Agriculture and Forestry, 2015; CBI, 2016). Since 1923, standing volume and growing stock of timber have steadily increased (Royal Swedish Academy of Agriculture and Forestry, 2015). These facts exhibit the underutilised timber resources of Sweden, and suggest that increased production of value-added wood products like CLT could be beneficial.

Sweden's forests are owned by a variety of actors, including mostly individuals (50%) and the state government (14%) (Royal Swedish Academy of Agriculture and Forestry, 2015). Head of Swedish Forest Policy at the Forest Industries Federation Linda Eriksson commented that private forest ownership is not seen as a barrier, but in fact a driving force for increased CLT production since forest owners want to increase the value of their timber. Roughly 115 sawmills procure wood from the forest owners, of which 75% is exported (Royal Swedish Academy of Agriculture and Forestry, 2015). 60% of forests are FSC or PEFC certified (see Fig. 2-1) and 70% of timber originates from final felling with 30% originating from thinning practices (Royal Swedish Academy of Agriculture and Forestry, 2015). Overall, Sweden is producing over 24 million m^3 of timber annually and is simultaneously protecting biodiversity, water quality, and social values (Royal Swedish Academy of Agriculture and Forestry, 2015). Furthermore, increased use of wood materials, like CLT, in buildings is a viable mitigation strategy, especially in the case of Sweden where there is extensive forest and steady growth available for increased harvest (Peñaloza, 2017).

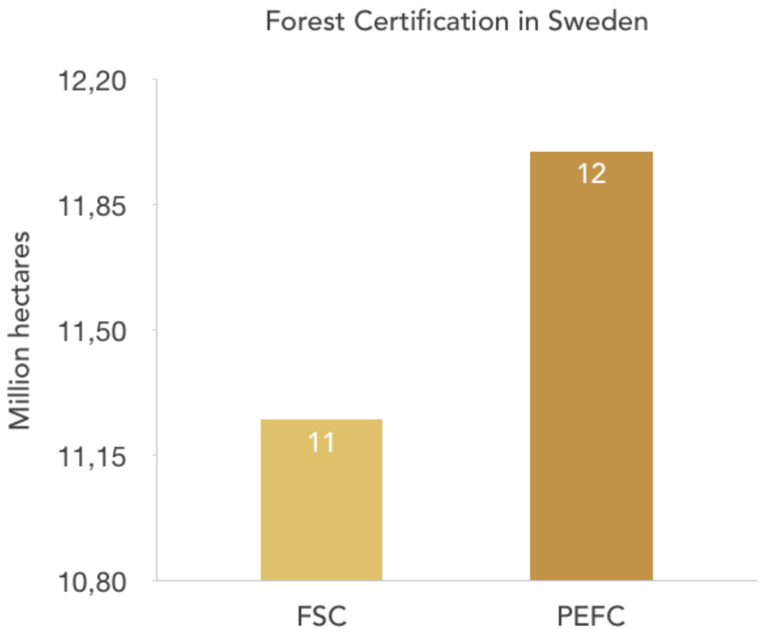

Figure 2-1. FSC and PEFC Certifications of Swedish forests

Source: Adapted from The Swedish Forest Industries Federation, 2015

2.5 Swedish path dependency

Although dominant building materials in Sweden such as concrete, steel, and masonry are entirely adequate for their intended technical purposes, they have many negative environmental impacts associated with them. Cement production alone is estimated to be responsible for about 8% of global GHG emissions (Peñaloza, 2017). Mining accounts for 2% of all GHG emissions in Sweden and total manufacturing accounts for 24%, with cement and steel as some of the most significant contributors (SBC, 2017). 3% of Swedish GHG emissions come from the construction sector, mainly attributed to transport and machinery, which could be decreased if lighter and more easily constructed materials like CLT were used (SBC, 2017). The three dominant incumbent building materials discussed below were selected due to their market dominance in Sweden, significant environmental impacts, and potential to be replaced by CLT.

2.5.1 Concrete

The concrete industry is under close scrutiny, due to the large amounts of CO_2 emissions that are associated with its production (Chen, Habert, Bouzidi, & Jullien, 2010). It is estimated to be responsible for 5-7% of anthropogenic global CO_2 emissions, as well as significant amounts of dust, SO_2, and NO_x emissions (Chen et al., 2010). Many studies confirm that the concrete industry is contributing to issues of global warming, eco toxicity, acidification, photochemical oxidation, and eutrophication (Chen et al., 2010). The cement and concrete (cement combined with sand and other aggregate materials) production processes are also known to be highly energy intensive (Giama & Papadopoulos, 2015). One study also highlighted that reinforced concrete work was responsible for roughly 90% of global warming potential (GWP) attributed to buildings, while ready-mixed concrete and steel rebar were stated to be responsible for roughly 80% of total environmental impacts associated with building materials (Roh et al., 2017). The wide range of negative environmental impacts associated with concrete has made reducing its carbon footprint a high priority for the sector (Yost & Melton, 2012).

2.5.2 Steel

While concrete holds less potential for recyclability in end-of-life scenarios, steel does offer high reuse potential of up to 90% (Zygomalas et al, 2016). Even though steel can be reused upon building deconstruction, there are still many negative environmental impacts associated with its production, use, and recycling. These impacts include intense energy use, abiotic depletion, acidification, eutrophication, ozone layer depletion, photochemical oxidation, and terrestrial and marine toxicity (Zygomalas et al, 2016). The manufacturing processes for both concrete and steel could be further improved through heightened energy efficiency or increased use of renewable energy, but this will still not solve many the environmental problems they are associated with (Zygomalas et al, 2016). The high embodied energy and complex lifecycle of steel also means that EPDs with limited parameters may not provide accurate environmental profiles that are comparable to other structural building materials (Ehrlich, 2015).

2.5.3 Masonry

While steel and cement are largely accountable for many environmental impacts, ceramic and concrete bricks are also significant contributors (Roh et al., 2017). Studies link clay brick production to significant emissions of CO_2, SO_2, NO_x, VOCs, and particulate matter (Giama & Papadopoulos, 2015). Brick production is associated with many of the same environmental impacts as cement, largely contributing to aquatic eco toxicity, acidification, and global warming (Giama & Papadopoulos, 2015). Brick, along with cement and steel, also contributes to natural resource depletion and requires significant amounts of energy for the heating used within its production processes (Maia de Souza, 2016). Although ceramic brick has been estimated to have lower impacts on climate change and resource depletion compared to concrete brick and reinforced concrete, it still has significant negative impacts (Maia de Souza, 2016). Brick production has also been linked to water withdrawal and impacts on ecosystem quality (Maia de Souza, 2016).

Overall, the three mentioned types of materials have notable negative impacts on human health, aquatic and terrestrial ecosystems, ozone depletion, acidification, and other environmental factors. CLT manufacturer KLH states that while CLT panels sequester approximately 0.8 tonnes CO_2/m^3, Portland cement production results in 0.87 tonnes CO_2/tonne and steel production results in 1.70 tonnes CO_2/tonne (KLH, 2013). It is important to note the wide range of products available in each of these three categories, which are complex and have varying levels of negative environmental impacts. For example, recycled steel has less associated impacts than virgin steel regarding raw material extraction and concrete with low-impact mixes or carbon abatement can have lower embodied carbon than standard aggregate concrete (Yost & Melton, 2012). Although complete transition to only wood materials is unlikely, CLT and similar materials can begin to replace and complement traditional materials to reduce sector impacts.

2.6 Guiding framework

Three frameworks were used in this research to analyse literature findings and questionnaire responses. These frameworks include 1) Multilevel perspective 2) Technological innovation system and 3) Diffusion of innovation. Selection of these frameworks is justified mainly through their strong applicability to new technologies or "niche" innovations. They also have been applied to environmental innovations in a variety of industries, for example the adoption of electric vehicles or deployment of solar PV panels. Not only can these frameworks help to identify solutions to barriers, they can also help to clarify the influence of various actors, networks, institutions, and processes within the building sector. They were viewed as the most suitable tools to reflect the complexity involved in the Swedish building sector.

2.6.1 Multilevel perspective

The multilevel perspective (MLP) encompasses niche innovations, sociotechnical regimes, and sociotechnical landscapes which can be understood as the respective micro, meso, and macro levels of a system displayed in Fig. 2-2 (Garud & Gehman, 2012). Niche innovations could be new technologies or practices, which are often developed by fringe actors and often need support from policy and industry (Garud & Gehman, 2012). The regime level is the 'deep structure' and consists of the actors, networks, organisations, rules, and material aspects which guide both actions and perceptions in a system (Geels, 2011) (Garud & Gehman, 2012). These regime components steer trajectories of innovations via fostering routines, regulations, standards, social norms, practices, assets and competencies (Garud & Gehman, 2012). Sociotechnical landscapes also affect innovation transition dynamics, as they are the exogenous environments outside the direct control of niche and regime actors (Geels, 2011) (Garud & Gehman, 2012). Considered the wider discourses and societal settings, these landscape factors often take decades to develop or change (Garud & Gehman, 2012). This framework has proven useful for analysing sociotechnical transitions and systemic changes involving sustainability, therefore it was applied to this research (Geels, 2011).

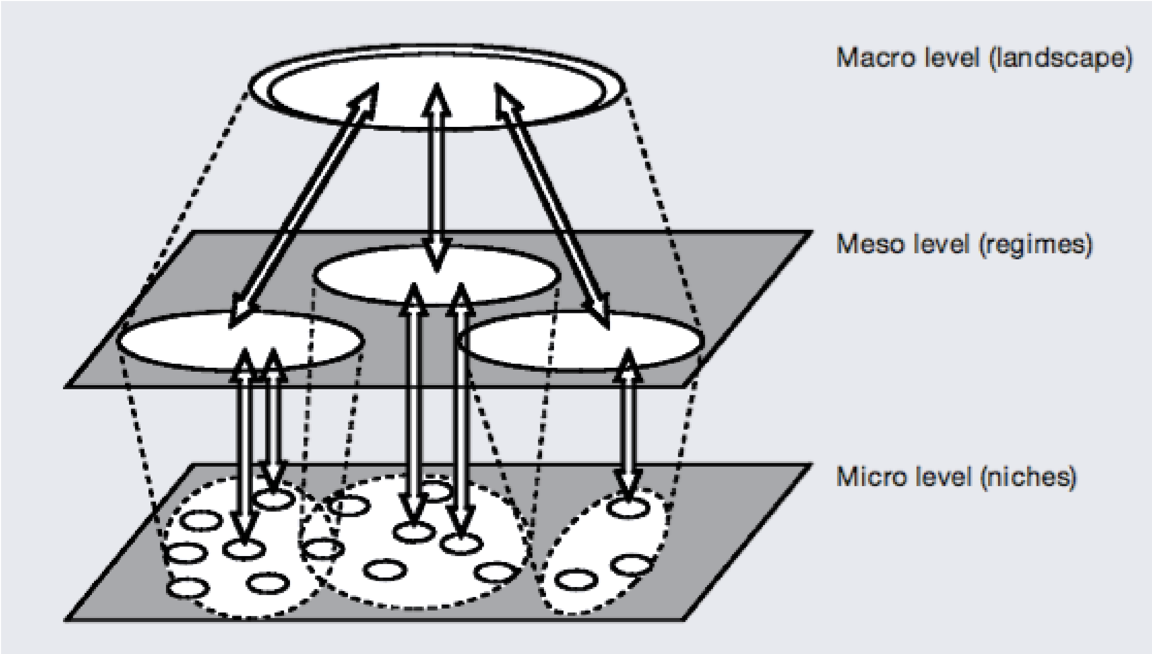

Figure 2-2. Diagram of the Multilevel perspective

Source: Loorbach and Van de Lindt, 2007

2.6.2 Technological innovation system

The technological innovation system (TIS) framework is valuable for identifying barriers and drivers, and is not specific to any technology or sector (Bergek et al., 2015). It is highly focused on technology-specific matters and can be used to analyse technology research, production, and deployment at various stages of development (Bergek et al., 2015; Palm, 2017). It differs from MLP in this sense, since it can be used to analyse development at many stages rather than the speculative transition from niche to mainstream (Palm, 2017). Its goals are to assess key barriers and drivers, provide policy recommendations, and ultimately increase dissemination of innovations (Bergek et al., 2015; Palm, 2017). The framework's inclusion of institutions, networks, and actors allows for valuable analysis of barriers from incumbent technologies, institutional misalignment, market competition, missing actors, insufficient networks, and lack of knowledge (see Fig. 2-3). It was deemed an appropriate choice since these aligned with many identified barriers of CLT (Bergek et al., 2015). Key processes of a healthy TIS include knowledge development and dissemination, guidance, experimentation, market formation, legitimation, and resource mobilisation (Palm, 2017). These factors suggest that the TIS framework is suitable for analysing deployment of a mature technology, in this case CLT, in markets or regions where it is not yet mainstream (Palm, 2017). For example, the Swedish multi-family housing segment.

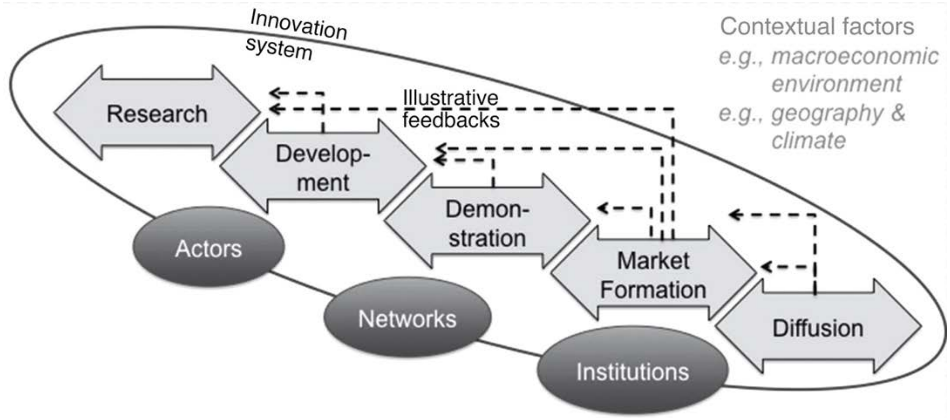

Figure 2-3. Diagram of technology innovation system

Source: (Gallagher, Grübler, Kuhl, Nemet, & Wilson, 2012)

2.6.3 Diffusion of innovation

The diffusion of innovation framework explores various aspects of technology and innovation adoption, such as perceived attributes, rates of adoption, individual innovativeness, decision making, and contextual factors (Botha & Atkins, 2005). Based upon four factors that influence adoption of new innovations, the diffusion of innovation theory blends several perspectives (See Fig. 2-4). These factors are 1) the innovation itself 2) communication channels and methods 3) time and 4) nature of society in which the innovation is introduced (Botha & Atkins, 2005). It is also based upon several sub-theories, which include the decision process model, individual innovativeness, rate of adoption, and perceived attributes (Botha & Atkins, 2005).

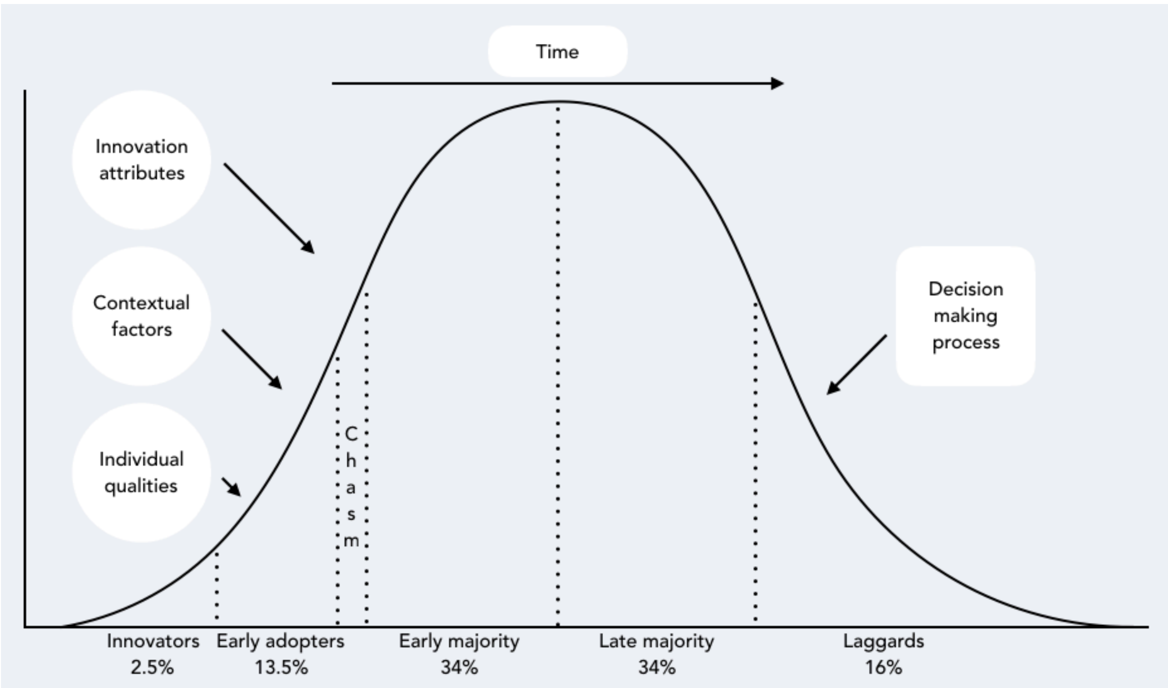

Figure 2-4. Diffusion of innovation theory diagram

Source: Own elaboration, adapted from Athens, 2012

As a broad theory, it examines all aspects of innovation diffusion from how, when, and why innovations are developed to communication, networks, and social systems which affect the ultimate spread of innovations. Unlike the MLP framework, this theory emphasises the mental decision making process of adoption, perceptions of innovations, and promotion (Botha & Atkins, 2005). These additional focuses were deemed valuable to this research, since perceptions, complex decision making processes, and product awareness and promotion are important factors within technology deployment in the building sector (Rogers, 1983) (Laguarda Mallo & Espinoza, 2015; Ogunkah & Yang, 2012). The theory is deployment-focused by nature and categorises adopters based on their characteristics (See Table 2-2), which was also constructive in identifying mechanisms for increased adoption of CLT in Sweden (Rogers, 1983).

Adopter types	*Innovator*	*Early adopter*	*Early majority*	*Late majority*	*Laggard*
Adoption time	1st to adopt	adoption before majority	links early & late adoption (critical mass)	after average adopters	last to adopt
Social system	difficulty entering social system	more integrated in social system	growing social system acceptance	yielding to social pressures	isolated & interaction limited to other laggards
Economics	have significant financial resources	still relative financial investment	less financial risk	economic necessities	economically difficult to catch up to modern innovations
Characteristics	eager to experiment & knowledgeable	high opinion leadership & skill in using innovation	support wide diffusion, but are not leaders	reluctant & sceptical, but following system norms	traditionalists, aligned to outdated technology

Table 2-2. Adopter types and characteristics

Source: Adapted from Palm, 2017

3 Cross-laminated timber: overview

3.1 Basics of CLT

Engineered wood products (EWPs) are a type of manufactured wood product engineered for specific construction purposes and to have certain properties, such as high strength, durability, and consistency (Laguarda Mallo & Espinoza, 2015). One example of innovation in this field is Cross-laminated timber (CLT), often referred to as "X-Lam," "Massive Timber," or "Cross-Lam" (Laguarda Mallo & Espinoza, 2015). This material is notable in the building material sector due to its numerous environmental advantages and innovative laminar structure, which allows it to be used for applications previously dominated by concrete, steel, and masonry (Brandner, 2013). CLT is composed of an uneven number of layered boards that are placed side-by-side, which are then stacked on top of each other at alternating 90° angles (Fig. 3-1; Brandner, 2013). The layered groupings of boards are usually connected by adhesive bonding, thus creating a compact, lightweight, and versatile product (Brandner, 2013). The design and engineering of CLT make it suitable for application as walls, floors, roofs and other large-sized load-bearing building components (Brandner, 2013; CBI, 2016). CLT prefabrication also allows for controlled, in-factory fenestrations, or precise openings cut into panels for windows, doors, skylights or other channels.

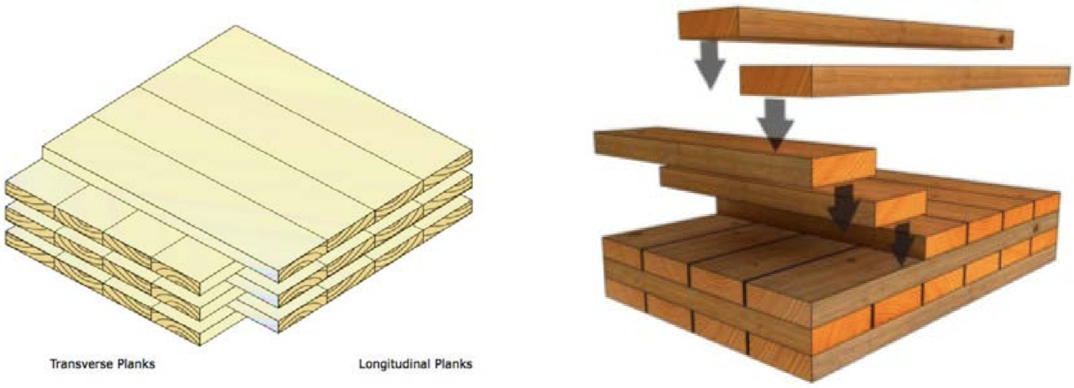

Figure 3-1. Diagrams of CLT panels

Sources: FPInnovations, 2015 (left) & Buck, 2016 (right)

While wood properties are heterogeneous and vary with species, cell arrangement, moisture content and geography, CLT directly addresses this variability and more efficiently utilises timber (Laguarda Mallo & Espinoza, 2015). By stacking wood at alternating 90° angles, CLT diminishes variability in wood and results in a more homogenous, standardised, and reliable product that can utilise damaged, low quality, and small-diameter wood (Laguarda Mallo & Espinoza, 2015). The CLT production process consists of several steps (Fig. 3-2). These simple steps commonly include 1) drying of boards to certain moisture contents of 10-12% 2) strength and stiffness grading 3) trimming and finger-jointing 4) layering and adhesive application to boards 5) pressing and hardening and 6) final cutting and customising (FPInnovations, 2016). Contrasting typical forest industry production which emphasises high-producing commodity operations, CLT is a more sophisticated and value-added product that can more effectively use various species, sizes, and qualities of timber (Muszynski, 2016). CLT is typically made of softwood such as spruce, larch, fir, doug fir, or pine, but exploration of hardwood use could lead to further product developments and new applications for CLT (CBI, 2016).

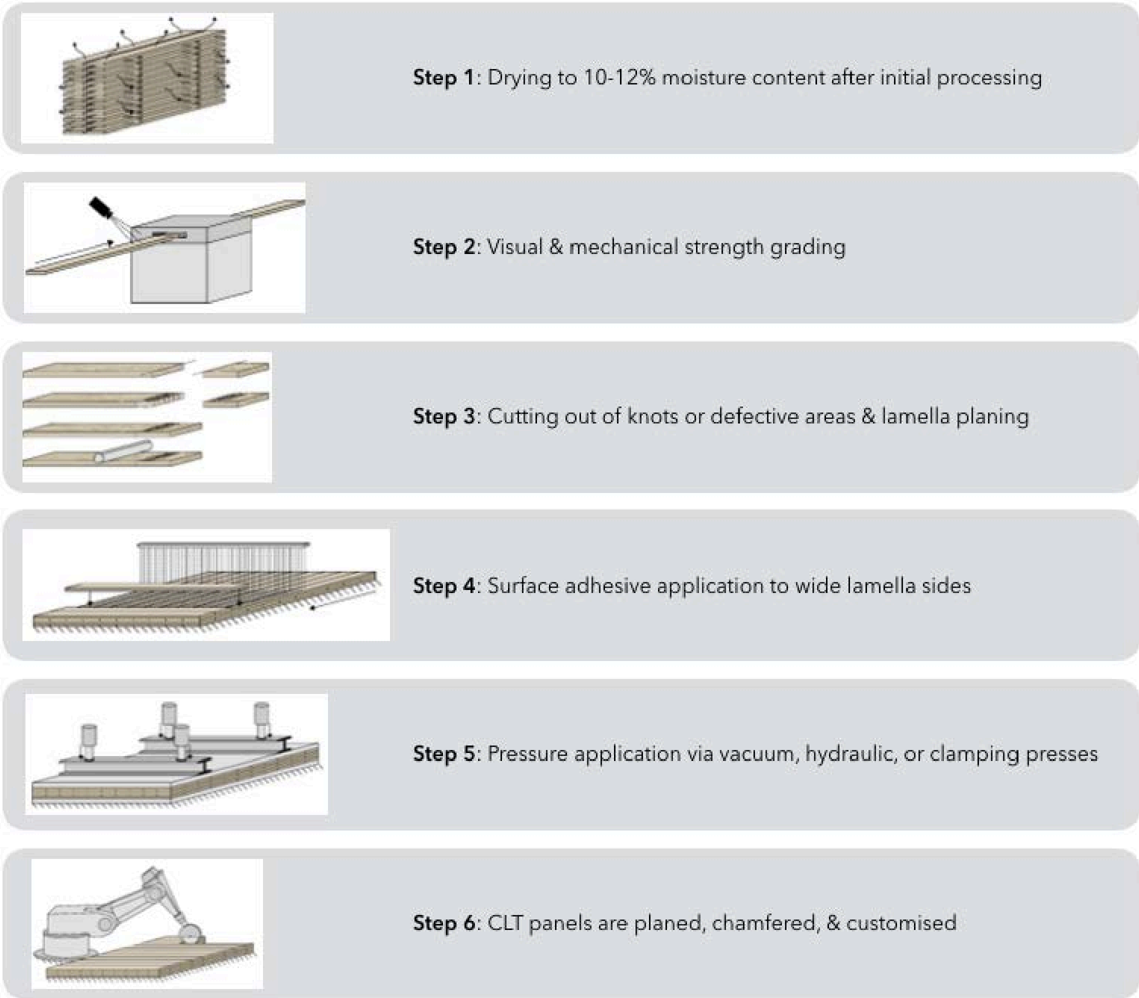

Figure 3-2. CLT manufacturing process

Source: Own elaboration adapted from Brettsperrholz.org, 2017

3.2 History of CLT

Development of CLT began in the early 1990s in Alpine Europe, motivated by desire for solid timber products with minimal shrinking and swelling (Brandner, 2013; Muszynski, 2016). Early ideas also originated from a need to utilise outer layers of logs, or "side boards," which were thought to have little value but in fact have excellent mechanical properties (Harris, 2015). Research and development of CLT was conducted in Austria and Germany in recent decades, where production is now well over 500,000 m^3/a and with Austria responsible for over two-thirds of CLT production globally (Brandner, 2013). Reasons for Austria's CLT success are linked to efficient timber industry, innovation-friendly environment, traditions of solid construction, fast integration of new training, accessible national R&D funding, highly applied R&D "transfer" projects, collaboration with industry, and openness to decentralised industry (Schickhofer, 2017). Production of CLT has risen steadily since the mid-1990s and has been predicted to rise substantially in the coming years, although Austria and Germany will continue to dominate (Fig. 3-3; Brandner, 2013; Muszynski, 2016). The first residential project using CLT occurred in 1993 and the first multi-story project was recorded in 1995 (Fig. 3-4; Brandner, 2013). In 1998, CLT was first approved as a national technology in Austria and in Germany (Brandner, 2013).

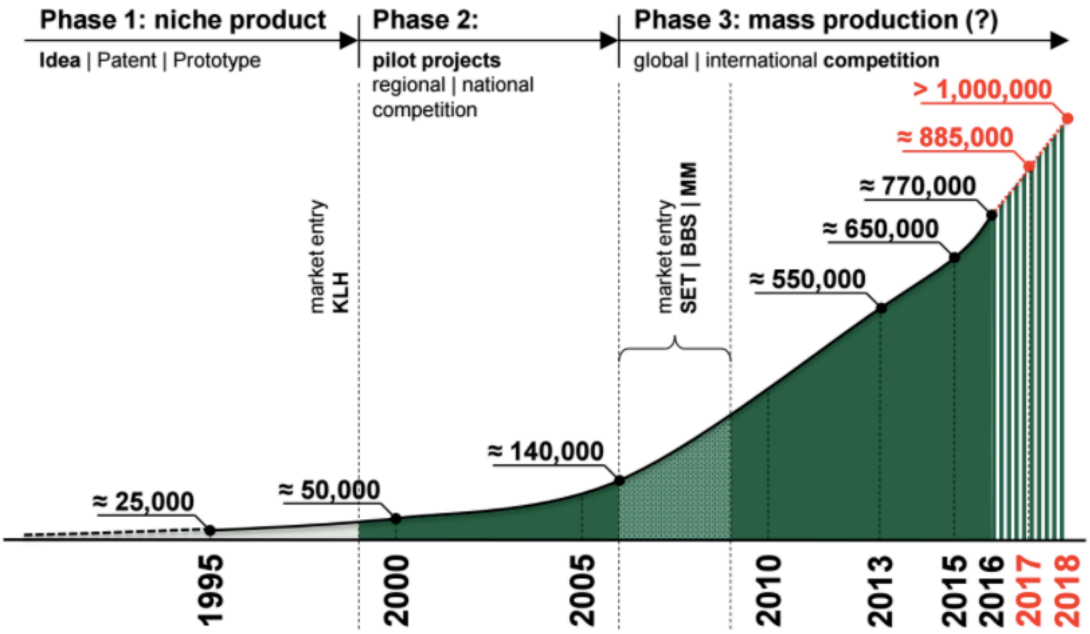

Figure 3-3. CLT production timeline (unit = m^3/year)

Source: Schickhofer, 2017

In 2000, the European Cooperation in Science and Technology (COST) EU framework presented research on CLT in Venice Italy and a plethora of CLT-related research began afterwards (Fig. 3-4; Brandner, 2013). The 2000s brought more research, increased production, and wider market use of CLT, giving rise to the first European Technical Approval (ETA) in 2006 (Brandner, 2013). Since 2010, there has been steady increase in CLT demand, production, and export (CBI, 2016). Belgium and the Netherlands act as large CLT trade hubs, while Austria and Germany still lead in production (CBI, 2016). Austria currently accounts for roughly 65% of CLT production (Schickhofer, 2017). There are currently 48 CLT plants worldwide and global CLT production, shown in Figure 3-3, is estimated to reach over 1 million m^3/year in 2018 (Schickhofer, 2017). In years dotted with economic crises and struggling housing markets, this continuous growth is remarkable. The average price of CLT in the EU is comparable to other materials (roughly 500 EUR/m^3), while one in-depth economic analysis found that CLT was slightly cheaper than traditional concrete and steel materials (Mahlum, Walsh Construction, & Coughlin Porter Lundeen, 2014). The study also stated that the cost of CLT would likely experience decreases, due to increasing production, competition, and economies of scale. Key stakeholders include CLT producers, exporters, importers, distributors, construction companies, and developers (CBI, 2016). Most CLT projects have been single or multi-story buildings for housing, commercial spaces, schools, or offices, with mid and high-rise buildings now becoming more feasible as CLT R&D expands its applicability (Harte, 2016).

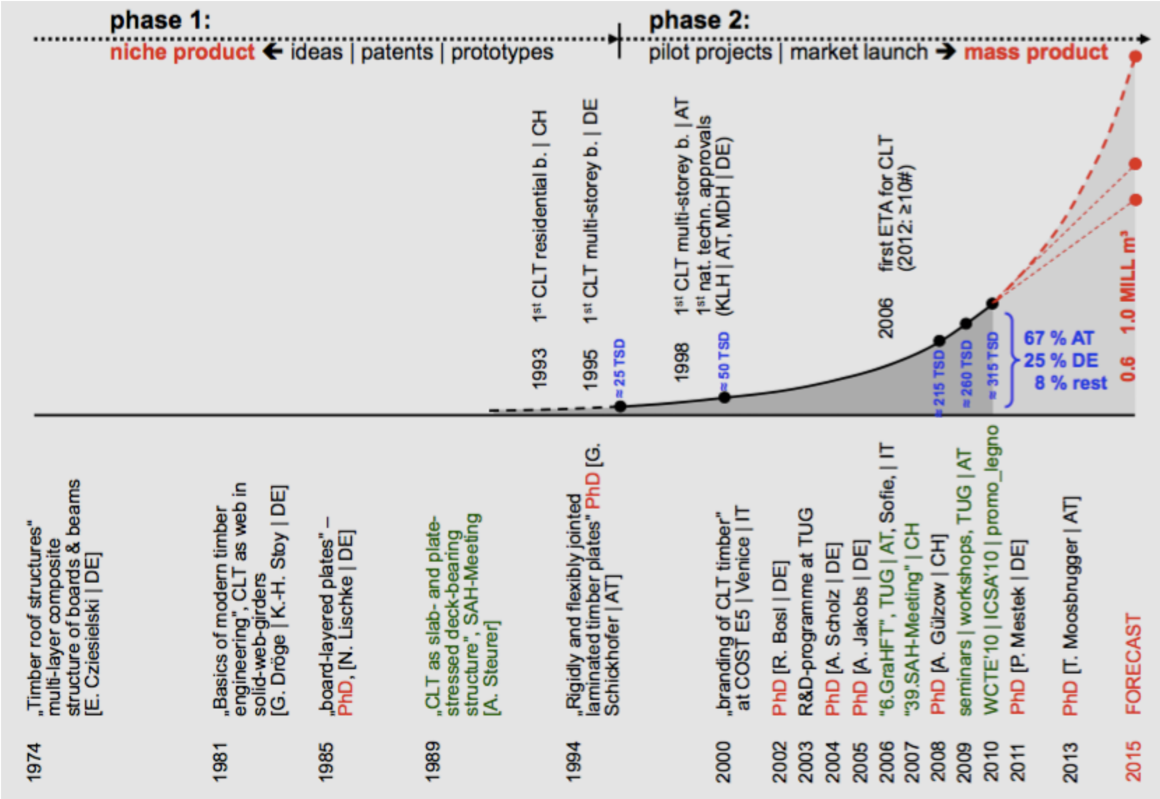

Figure 3-4. History of CLT

Source: Schickhofer, 2013

3.3 Environmental impacts of CLT

There are numerous advantages of CLT regarding mitigation of negative environmental impacts. First, wood acts as a device to store carbon where roughly one m^3 of wood stores around 0.8-1.10 tonnes of carbon as biomass (Laguarda Mallo & Espinoza, 2015)(KLH, 2017). Often quoted as being "carbon-neutral," CLT buildings are in fact capable of being carbon-negative if their carbon sequestration capabilities are accounted for throughout a building's entire lifespan (Salazar & Meil, 2009; Wang et al., 2014). One study showed a negative value of approximately 2,314 tonnes of embodied carbon in a multi-level CLT building (Atlee, 2011). The U.S. CLT Handbook also substantiates this and adds that wood products usually absorb more CO_2 than what is emitted during timber harvest, manufacturing, transport, use, and end-of-life treatment (FPInnovations, 2013). While many factors determining environmental impacts of CLT are contextual, there is generally consensus among academia and industry supporting that it bears many environmental advantages compared to more traditional materials.

CLT is made of wood, which is a natural and renewable resource. Based on urgent needs for GHG emission reductions to avoid dangerous anthropogenic climate change (global temperature change of more than 2°C) (UNFCCC, 2010), CLT presents opportunities to create rapid short-term emissions reductions (FPInnovations, 2013). Additionally, CLT allows for extended timelines of carbon storage for wooden building materials, as it has been shown to have lifespans equivalent to other materials (80 years) and can be reused upon deconstruction (FPInnovations, 2013). Since various species, qualities, and sizes of timber can be used to produce CLT, it also opens a potential new market for the timber industry in Sweden. Influence of the EU Timber Regulation (EUTR) and sustainable forestry certifications such as PEFC, SFI, and FSC is increasing globally, and Sweden's leading forestry position makes it a suitable choice for CLT manufacturing (FPInnovations, 2013). Meanwhile, mining and manufacturing practices for concrete, steel, and brick are not subject to the same types of increasingly stringent regulation or certifications.

CLT can make efficient use of damaged, small-diameter, and generally low-value timber, which is viewed as an under-utilised natural resource (Laguarda Mallo & Espinoza, 2015). CLT is also an efficient building material alternative in terms of both manufacturing and on-site construction speed and simplicity (Laguarda Mallo & Espinoza, 2015). Thanks to their prefabricated nature, CLT panels produce little manufacturing waste, can be customised in factories to reduce on-site labour, are light in weight for easier transport, and can be erected with speed and little on-site waste (Evans, 2013; FPInnovations, 2013; CBI, 2016). Prefabrication also allows for collection and reuse of wood by-products for biofuel, electricity, or heat, which can reduce fossil fuel dependence. The efficiency of transport and construction also helps minimise transport emissions, construction site disturbance, and overall energy use and GHG emissions from construction (Laguarda Mallo & Espinoza, 2015).

The thermal or insulating properties of CLT are also environmentally advantageous, since "the conductivity of softwood lumber is about 0.7-1.0 Btu in/(h x ft^2 x F), compared with 310 for steel and 6 for concrete (Staube, 2005). This means that CLT can aptly retain heating or cooling, with less insulation needs than steel or concrete. CLT provides thermal mass as well, which allows floors, walls, and building enclosure panels to store heat during daytime and release it at night, thus lowering operational energy demands (Cambiaso & Pietrasanta, 2014). Need for additional insulation materials could be reduced, while passive or net-zero building standards could be more easily met by using CLT due to its low coefficient of thermal conductivity and potential air-tightness (Harte, 2016). CLT also requires very little adhesive (roughly 1% of final product), and some companies are now developing adhesive-free panel systems (Brettsperrholz, 2017). Mostly non-formaldehyde PUR adhesives are used in CLT production, reducing harmful VOCs and other chemicals that may be present in other building materials (CBI, 2016). CLT does not adversely affect indoor environmental quality, and if left visible can even positively affect comfort, health, and well-being of occupants (Fell, 2010). Fire resistant coatings such as gypsum bear some potentially negative effects on indoor environmental quality and end-of-life management, but can be avoided with use of sprinkler systems and proper design (FPInnovations, 2013).

The end-of-life benefits for CLT panels are also environmentally significant. Although CLT is estimated to have significant amounts of embodied energy, this energy can be reused upon deconstruction within forms of building material, biofuel, electricity or other products (Laguarda Mallo & Espinoza, 2015). Since the embodied energy of CLT is highly recoverable, its low embodied carbon is what truly makes the material an environmentally superior choice. With concrete, steel, and brick responsible for large amounts of construction and demolition waste that ends up in landfills, there are clear environmental benefits with CLT since it can be reused after deconstruction with little additional processing (WoodWorks, 2014). Overall, LCA results consistently show that CLT offers environmental advantages regarding embodied carbon, air and water pollution, ozone depletion, and other environmental LCA indicators (WoodWorks, 2014).

3.4 Building material comparisons

Many life-cycle analyses (LCAs) have been conducted to compare CLT to other building materials, such as concrete and steel. Robertson et al. compared two five-story office buildings, one made of CLT and one of concrete (2012). They estimated that the wood-based building consumed 15% less energy throughout its lifespan while another comparative study concluded that a CLT-based building would consume 10% less operational energy than a concrete-based building (Chen, 2012). Another comparative LCA study concluded that CLT outperformed concrete in all environmental impact categories, especially in global warming potential, ozone depletion, and eutrophication (John et al., 2009). A British comparative study showed that both concrete and steel-based six-story buildings contained similar amounts of embodied CO_2 (1984 tonnes), while CLT-based buildings of the same size would have less than half the amount of embodied CO_2 (727 tonnes) (Hammond & Jones, 2008). An industry report from CLT producer KLH stated that CLT panels have approximately $1/13^{th}$ the CO_2 emissions of concrete or steel (KLH, 2013). Figure 3-5 shows a robust environmental assessment of various building materials, based on the ΔOI3 indicator which analyses energy consumption, GWP, and acidification potential related to manufacturing (IBO, 2011).

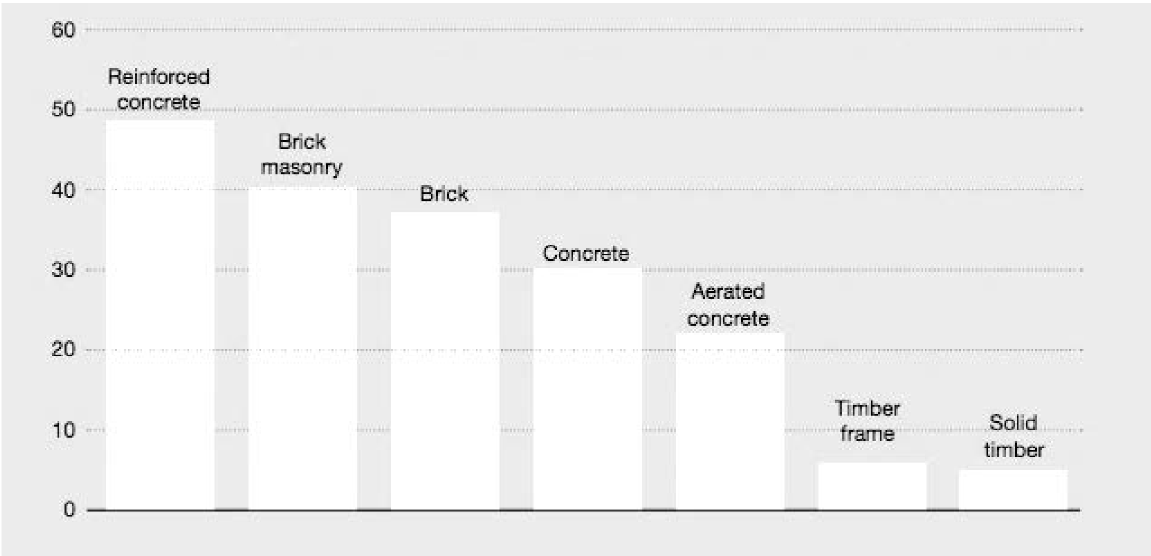

Figure 3-5. Eco Index 3 construction material comparison of single layers

Source: Adapted from Ökoindex3, baubook.at

Harris states that "using criterion for compression, wood panels made of softwood are six times more efficient than concrete panels in terms of weight and three times more efficient than expensive synthetic materials such as graphite-fibre composite" (2015). Use of CNC (computer numerically controlled) technology at the end of CLT production also allows for customisation prior to on-site delivery, reducing energy-intensive, timely, weather-dependent, and costly labour (Harris, 2015). Additionally, insulation, cladding, and other materials and connectors can be more easily screwed to CLT panels compared to concrete (Harris, 2015). Numerous research projects have also highlighted the design for disassembly and recyclability opportunities of CLT panels, compared to other materials which are often landfilled, downgraded to very low-value materials, or reprocessed using significant resources (Thormark, 2006). Horswill and Nielsen add that CLT elements could be more easily reused, recycled, upcycled, or incinerated for energy production at the end of their life (2016).

While mineral and ore-based building materials are made from abundant raw material, they are finite or slowly renewing sources which leads to risks related to scarcity, price fluctuation, and increased land disturbances (Jones et al., 2016). Timber products conversely come from renewable sources, which can be grown repeatedly upon the same plots of land (Harte, 2016). Furthermore, timber extraction and manufacturing has lower energy requirements than equivalent steel and concrete processes (Harte, 2016). It is important to note the carbon sequestration capabilities of CLT, as dry wood is about 50% carbon by weight and several forest rotations can occur during the lifespan of a building (Harte, 2016).

Since CLT is also a lighter weight alternative to steel, concrete, and brick, it can reduce the foundational demands for new buildings, according to Jessika Szyber of Stora Enso. This could result in less foundation material needed, lowering embodied energy and embodied carbon in new buildings which use CLT (Jones et al., 2016). CLT panels are also approximately 30% slimmer than equivalent brick or concrete materials, resulting in an increase in useable indoor floor space or decrease in land use (KLH, 2013). As a very light yet strong building material, CLT also opens possibilities to build up on top of existing buildings, reducing the need to demolition buildings of insufficient height to rebuild taller alternatives. Additionally, the prefabricated nature of CLT, combined with potential customisations and standardisations, make it highly suitable for modularity. Examples of this exist in the form of IKEA and Skanska's Boklok housing, and Stora Enso's Residential Modular multi-story systems (see Fig. 3-6). The climate neutral Jakarta Hotel in Amsterdam is another example of modular CLT systems (Fig. 3-6). Furthermore, British housing company RHP recently unveiled its "LaunchPod" prefabricated CLT modular housing units, where mass production is carried out in a similar fashion to the efficient automotive industry (Legal & General, 2017).

Figure 3-6. CLT modular system render (left) and CLT modules (right)

Source: Stora Enso & Jakarta Hotel

One British study found that buildings using CLT had higher capital costs compared to steel or concrete, but added that this higher initial cost is generally offset by savings in transport and construction (Jones et al., 2016). For example, Horswill and Nielsen claim a roughly 26% higher cost for CLT compared to precast concrete, but without considering the full lifespan benefits of the building (2016). Use of CLT is generally considered cost-neutral when considering both capital costs and savings throughout the entire construction process and building lifespan (Jones et al., 2016). The cost of CLT is comparable to other structural building materials, but what sets CLT apart are financial savings linked to its efficient transport and truckload sequencing, shorter construction times, reduced installation costs, reduced foundation requirements, and associated safety for workers in both manufacturing and construction (Spickler, 2014). Furthermore, a CLT feasibility report showed conservative estimated savings of 4% when using CLT due to quicker construction, efficient transport, and low skill requirements for workforce (Mahlum, Walsh Construction, & Coughlin Porter Lundeen, 2014). The study also noted that increased product familiarity, supply chain development, and economies of scale could further reduce CLT costs. In addition to various environmental and technological advantages, CLT has also shown high aesthetic value in buildings where it positively affects stress, heart rate, and concentration levels of occupants (Harte, 2016). Lastly, many articles, conference presentations, and industry reports highlight the unique and versatile design possibilities that are becoming possible with CLT which indicates expanding applications.

4 Literature review

4.1 Barriers to CLT deployment

While CLT manufacturing and use is growing, there are still challenges it faces while trying to penetrate the building sector in Sweden. As the building sector is highly project oriented and experience-based, deployment of new structural building materials is difficult since most actors trust and use reliable incumbent materials (Laguarda Mallo & Espinoza, 2015). The building sector is also known to be notoriously slow to incorporate new materials and practices. Many barriers defined in literature are perceptual, meaning they are misconceptions or insufficient knowledge regarding costs, risks, regulatory complexities, and technical qualities (Laguarda Mallo & Espinoza, 2015). Perceived costs and risks are significant barriers in nearby Denmark, even though CLT could help Copenhagen's plan to be a CO_2 neutral city by 2025 (Horswill, 2016). As the Swedish building sector is dependent on incumbent material use and construction practices, uncertainty connected to risks and costs are a challenge for new materials such as CLT (Jones et al., 2016).

Durability, maintenance, and fire safety are other important technical factors which act as barriers for CLT deployment (Laguarda Mallo & Espinoza, 2015). Additionally, acoustic performance and seismic resistance are perceived barriers according to many building industry actors (Laguarda Mallo & Espinoza, 2015). Despite showing adequate performance against both fire and moisture in a plethora of studies, there are still misconceptions about CLT (Laguarda Mallo & Espinoza, 2015). Fire performance of timber materials is often perceived as poor, but CLT and other mass timber panels create a stable and predictable charring effect, or pyrolysis (see Fig. 4-1), which effectively limits burning (AWC, 2012). This charring preserves the structural integrity of CLT longer than standard timber, while tight connections between panels allows for desirable containment of fire and smoke (AWC, 2012; Frangi, 2009). Various CLT panels withstood fire testing beyond 180 minutes in one study, which greatly exceeds the 90-minute IBC requirement for heavy timber construction (AWC, 2012; IBC, 2012). Furthermore, full scale fire tests have shown that CLT provides equivalent fire performance to non-combustible materials (Evans, 2013). Fire risks related to various types of connecting mechanisms have also been a barrier for CLT, which is being addressed via ongoing research (Barber & Gerard, 2015). Issues with exposed indoor CLT contributing to fire risk remain, but are more manageable using plasterboard, gypsum coverings, and sprinkler systems (Barber & Gerard, 2015). Further understanding of penetrations for plumbing and electrical services in CLT buildings could also help overcome fire related barriers (Barber & Gerard, 2015).

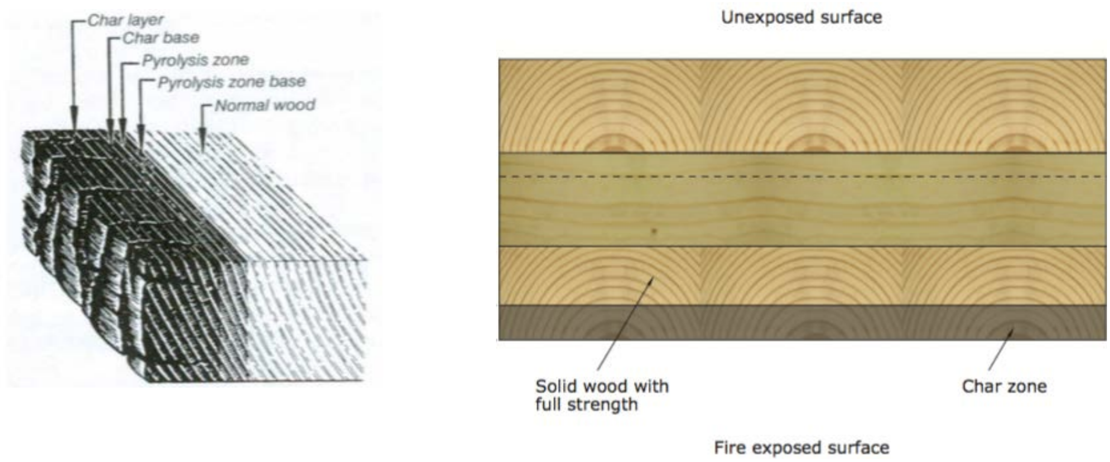

Figure 4-1. Diagram of charring effect for mass timber

Source: Barber & Gerard, 2015

Despite seismic testing (of up to magnitudes of 7.2 on the Richter scale) for multi-story CLT buildings showing negligible damage, seismic performance remains a barrier due to misconceptions (Popovski et al., 2012; Winter et al., 2010). Further research from University of Salerno is exploring how dissipative connectors could even lead to more improvements of CLT's seismic performance (Latour & Rizzano, 2017).

Poor acoustic performance is considered by many to be a barrier, yet one study from Luleå Sweden found that uncertainty in acoustic performance decreased as degree of prefabrication increased (Öqvist et al., 2012). CLT's predictable acoustic performance is attributed to both the controlled environment where prefabrication occurs and the reduced use of uncontrolled on-site labour (Öqvist et al., 2012). Still, attaining high quality acoustic performance for low frequencies in lightweight CLT constructions remains challenging (Öqvist et al., 2012).

Post-construction maintenance is another barrier, coinciding with typical beliefs that wood's organic nature makes it more susceptible to deterioration (Laguarda Mallo & Espinoza, 2015). Wang and Ge highlight that exposure to moisture during transport, construction, and maintenance is a durability concern for CLT, while noting that both time and climate are also important long-term factors (Wang & Ge, 2016). Various water resistant weather barriers and vapour-permeable materials are being tested now to reduce sensitivity to moisture, and have been quite effective (Wang & Ge, 2016). Economic performance of construction projects, related to materials, construction and maintenance, is also viewed as a barrier by many industry actors (Laguarda Mallo & Espinoza, 2015). As a newer, unfamiliar product to many actors, CLT's initial cost and ongoing maintenance costs require further clarification and experimentation through project monitoring (Jones et al., 2016).

Availability of technical information for CLT is viewed as a barrier, yet various CLT manufacturers, timber and building industry associations, governmental organisations, and research institutions provide substantial information (Laguarda Mallo & Espinoza, 2015). Availability of both product and full building level carbon and energy data and benchmarks is low, raising some doubt in CLTs sustainability advantages (Giesekam et al., 2016). The complex material selection process also suffers from unstructured and limited data, which is why an analytical hierarchy process tool has been suggested (Ogunkah & Yang, 2012). This study also found that half of actors did not know or use material selection support tools, therefore such an AHP model would use criteria such as cost, LCA impacts, source, embodied energy, and embodied carbon to environmentally evaluate materials (Ogunkah & Yang, 2012). The products availability itself could also be a current barrier, as production is still low in many regions such as Sweden. This inconvenience requires building industry decision makers to actively seek out the product from few and distant suppliers. While CLT from current suppliers does meet various fire, seismic, and other standards, there is still a lack of cross-product CLT standards which could further systematise production (Brandner, 2013).

Prior to the release of the 2015 IBC, complications related to the incorporation of CLT into building regulations was seen as a large barrier (Laguarda Mallo & Espinoza, 2015). Studies also highlight technical performance, insurance complications, and warranty issues as significant barriers, leading to an emphasis on structural engineers and manufacturers rather than architects (Jones et al., 2016). Jones et al. suggest that the lack of CLT-specific calculation rules in Eurocode 5, and resulting reliance on specialist suppliers and engineers, is also contributing to low deployment of CLT (2016). Eurocode 5 was approved in 2004 and outlines timber structure design using various types of wood materials, but does not include CLT (Jones et al., 2016).

Lack of awareness is also an important barrier, considering the adoption of a new product relies on awareness and training within the target market (King, 1996)(Giesekam et al., 2016). One study showed that many American architecture firms had either not heard of CLT or had very little knowledge about it, potentially contributing to the low production and use levels of CLT in the USA (Laguarda Mallo & Espinoza, 2015). These results indicate that education and training regarding CLT within the architecture community could help increase deployment of CLT (Laguarda Mallo & Espinoza, 2015). Furthermore, jobs connected to CLT engineering, manufacturing, and construction are likely to require new skills and training while also requiring integration into the building design process (Jones et al., 2016). Limited time devoted to construction design phases can also pose as a barrier, since consideration of alternative and new building materials can require additional time or consulting (Giesekam et al., 2016). Swedish research shows that learning and leadership is key to improve awareness, knowledge, and skills regarding CLT and other EWPs (Antikainen et al., 2017).

Perceptions of new products are the key barriers, since beliefs about a product can influence industry actors just as the product's actual performance and qualities can (Giesekam et al., 2016; Laguarda Mallo & Espinoza, 2015). Using a dual Likert scale survey, Mallo and Espinoza's research suggested that increased familiarity with CLT led to more positive perceptions regarding its performance in a variety of categories (2015). Perceived lack of client demand is a further concern (Jones et al., 2016). It is also important to note that companies manufacturing CLT are acting to decrease these barriers and educate the public for obvious reasons. For example, the largest global CLT manufacturer, Stora Enso, is researching and specialty product variations to bring solutions for airtightness, fire protection, soundproofing, moisture resistance, and thermal insulation (Stora Enso, 2017). Overall, lack of awareness, accurate knowledge, and adequate training have been highlighted by industry and academic research as being highly significant barriers to increased use of CLT (Giesekam et al., 2016). Following these factors, questionable durability, lack of product standardisation, limited availability, and fragmented guidelines and design tools are barriers for increased use of low-carbon materials such as CLT (Giesekam et al., 2016).

4.2 Drivers of CLT deployment

The climate or environmental perspective is one of the main drivers for CLT deployment in Sweden. As CLT is a low-carbon and bio based building material, it can be considered as a tool to decarbonise buildings which make up a large part of cities. Neij, Bulkely and McCormick suggest three key areas of action for decarbonising cities in Sweden, including 1) engaging diverse actors 2) increasing experimentation and collaboration and 3) increasing dialogue between practitioners, government, and academia (2015). These overlapping and inter-dependent actions will likely drive a transition to low-carbon building materials, such as CLT, in Sweden's future.

Professor Gerhard Schickhofer from the Institute of Timber Engineering and Wood Technology at the Graz University of Technology has stated that future deployment of CLT should not merely focus on increasing the height of buildings (2017). Rather, Schickhofer claims that it is more important to focus on both expanding CLT application diversity and its qualities (Schickhofer et al., 2017). This suggests that CLT R&D will continue, likely driving new and expanded manufacturing. For example, researchers from Luleå University, SP Technical Research Institute of Sweden, and Träteknik recently discovered that CLT with alternating layers of 45° (shown in Fig. 4-2), rather than 90°, result in heightened bending strength by 35% (Buck, 2016). This could lead to larger spanning sizes of CLT and less material use (Buck, 2016). This type of research could serve to expand applications for CLT, as well as improve its quality which are important drivers for increased deployment.

Figure 4-2. CLT with alternating 45° layers

Source: Buck, 2016

The 2016 bio economy business report from the Swedish Trade & Investment Council highlights Sweden's unique environment of increasing wood biomass supply, sustainably managed forests, advanced technology industries, substantial private and public funding, and strong environmental awareness (Business Sweden, 2016). A growing interest in forming a Swedish bio economy suggests that increased and more efficient use of wood materials will be important for Sweden (Peñaloza, 2016). Shifting to a bio economy and transitioning to low-carbon bio based society implies a change in building materials and is a driver for CLT use. To speed up these trends, clarification of funding sources, educational services, and industrial symbiosis opportunities is necessary for CLT manufacturers. Connecting CLT manufacturers with chemical or textile industries could lead to new synergies and business opportunities, as wood biomass is actively being researched as a key material in both industries (Business Sweden, 2016). Additionally, universities, research institutions, and competence centres for timber building materials should domestically and internationally practice communication to prevent research overlap and disseminate findings.

Increasing standing timber and rising rates of certified forests in Sweden also can be viewed as drivers of CLT deployment, since the material depends directly on these natural resources (Peñaloza, 2016). Strongly driving CLT use in Sweden is mostly CLTs environmental performance, specifically its ability to store carbon, its reliance on renewable resources, and its low-waste nature (Laguarda Mallo & Espinoza, 2015)(Brandner, 2013). In parallel to these environmental advantages of CLT, areas of Sweden are also driving increased deployment via wood construction councils and target-oriented strategies. Such programmes and councils can be seen for example in Växjö, where municipal initiatives are driving CLT deployment (Växjö Kommun, 2013).

Furthermore, economic and practical factors are also driving CLT deployment. Since CLT is associated with efficient transport and on-site construction, these speeds can result in rapid return of investment that is attractive for developers and project investors. CLT manufacturing and construction are simple and produce very little waste, which are viewed as additional drivers. CLT manufacturing can be quite decentralised, as seen in Austria where there are many small-scale producers (Schickhofer, 2017). This is attractive for sparsely populated regions like rural Japan (Eastin & Sasatani, 2016), and perhaps Sweden. The prefabricated and scalable nature of CLT manufacturing also make it a desirable material for prefabricated construction and modular systems as seen with Stora Enso and RHP (Stora Enso, 2017; Legal & General, 2017). The predictability and consistency of quality for prefabricated CLT panels makes it a desirable choice for a construction material, especially for modular construction systems.

Certification schemes, such as Svanen, Miljöbyggnad, and LEED, are also drivers of CLT deployment. In recent years, these systems have broadened their material focuses, shifting from specific suggestions or recycled material requirements to a range of options such as material LCA impact reductions, rapidly renewable materials, and certified timber materials (ReThink Wood, 2014). While certification schemes do not specifically reward CLT use, they do reward credits for use of certified wood, recycled or salvaged wood, material efficiency, and waste minimisation, which all can be achieved through CLT use (ReThink Wood, 2014). These certifications have also been shown to drive increases in sustainable forestry certifications FSC and PEFC, and increases in building material focus, indicating that they would also be significant in uptake of a new timber-based building material such as CLT. The forestry sector's leadership in development of EPDs is another driving factor in favour of CLT and other low environmental impact building materials (ReThink Wood, 2014).

5 Results

5.1 Findings from literature review

Results from the literature review showed that main barriers for increased deployment of CLT related to three general categories. These categories include 1) cognitive 2) technical and 3) financial barriers. For example, the main cognitive barriers identified through the literature review included perceptions regarding technical or economic performance of CLT, awareness about CLT, and practical knowledge or experience regarding CLT. The main technical barriers identified in the literature review were related to CLT fire safety, moisture resistance, acoustic performance, maintenance, lifespan and airtightness. Financial barriers identified included capital costs, uncertain maintenance costs, insurance costs, and costs related to specialty labour required for production or construction of CLT.

5.1.1 Cognitive barriers

Main cognitive barriers included inaccurate perceptions, lack of awareness, and lack of knowledge or skills regarding CLT. Since there are many actors and areas of expertise involved in building industry projects, there are various perceptions and levels of awareness among stakeholders. Few actors have all the skills necessary for understanding and advising CLT use. As CLT is still a relatively new building material with limited existing examples of finished projects, there is still lack of awareness and knowledge among industry actors regarding its costs, applications, durability, sustainability and other factors. This knowledge and experience gap results in doubt among building industry actors, preventing them from using a new material like CLT. The building industry in Sweden is notably path-dependent on traditional concrete, brick, and steel materials, due largely to the wood ban that was repealed in the mid-1990s.

5.1.2 Technical barriers

Several technical features are still viewed as barriers to increased uptake of CLT in the building sector. Fire performance, moisture resistance, sound insulation, and maintenance are still barriers, despite abundant academic findings showing adequate performance of CLT in many of these categories. Companies, such as Stora Enso and Euclid Timber Frames, are producing product variations and specialty products to overcome technical performance barriers regarding fire, moisture, thermal insulation, and acoustics. Ongoing research at universities and competence centres is also addressing some technical issues, such as tighter connection systems, expanding applications, maintenance practices, adhesive-free options, and shell and spatial structures (Schickhofer, 2017).

5.1.3 Financial barriers

While CLT has been shown to have higher up-front costs than incumbent building materials (Horswill & Nielsen, 2016), it has also been shown to have financial savings that can balance these higher capital costs and make it financially competitive long-term. Despite this longer term cost competitiveness, CLT is still viewed as more costly to purchase initially, more difficult to find and procure, and more costly to maintain (Giesekam et al., 2016). If building sector actors are given the option to use an unfamiliar building material which costs the same or more than well-respected incumbent materials, then it is rational that they select the cheaper and safer options in most cases. This could especially be the case when environmental requirements of building projects are minimal or completely absent. Overall, both capital and long-term costs related to CLT are very important barriers.

5.2 Findings from Swedish questionnaire responses

The following responses were collected from the questionnaire. For a list and description of respondents, please see Table 5-1. A comprehensive list of responses is located in Appendix B, while Appendix C contains graphs featuring the most common responses regarding barriers, drivers, key actors, and suggestions.

5.2.1 Barriers

The responses showed that many barriers to higher deployment of CLT within the Swedish building sector matched those barriers which were identified in the literature review. The main barriers identified via the questionnaire responses included capital cost, uncertainty, risk, lack of knowledge, fire performance, moisture risk, lack of experience, and architect or engineer-specific knowledge. One researcher also highlighted the ban on wooden structures higher than two stories in Sweden, which lasted from the 1830s until 1995. This may have been a significant barrier, considering it likely shaped building industry trends, standards, and perceptions still influencing current practices. This also could have caused setbacks for the wood building materials industry in general, considering wood could only be used for 1-2 level buildings for many years. Path dependency toward incumbent materials, like concrete, stone, brick, and steel, is another barrier. Incumbent building materials benefit from existing market dominance, alignment with regulations, well established value and supply chains, and both knowledge and reliability among industry actors.

Key barriers: lacking knowledge and skills; technical weaknesses or limits; path dependencies; capital and long-term costs; uncertain maintenance and insurance costs (see Fig. I in Appendix C).

5.2.2 Drivers

Drivers for increased deployment of CLT within the Swedish building sector included environmental performance and climate perspective, long-term financial savings, rapid and clean construction, waste reduction, light weight, transport ease, housing demand, value addition to timber, abundant timber, suitability for modular systems, and design flexibility. Additional drivers for increased deployment included increasing domestic production in Sweden, sharing good examples of manufacturing, and communicating examples of CLT use.

Key drivers: growing importance of climate perspective; carbon sequestration; renewable source; waste minimisation; growing demand; prefabrication and customisation; promising technical qualities (see Fig. II in Appendix C).

5.2.3 Actors

Several important building industry actors were also identified through questionnaire responses. Respondents highlighted clients, owners, contractors, engineers, construction companies, architects, municipal building companies, and modular building manufacturers as having significant importance in increasing deployment of CLT within the Swedish building sector. Building certification schemes, the national building code authority, and timber industry actors were also listed as key actors. Furthermore, the importance of building or project owners and developers, both private and public, was shown to be significant since they wield power to steer building projects at very early stages through inclusion of environmental requirements embedded in contracts and tenders.

Key actors: owners; clients; engineers; architects; contractors; municipal building companies (SABO); Boverket; LEED, Miljöbyggnad, Svanen; material databases; timber and building associations; researchers (see Fig. III in Appendix C).

5.2.4 Suggestions

Respondents had a wide variety of suggestions to boost deployment of CLT in Sweden. Knowledge, skills, and experience regarding CLT could be improved via better dissemination of accurate information, use of guides or handbooks, and education at both professional and university level. Communication of environmental, economic, and social benefits of CLT could also influence materials suppliers, building project actors, certification bodies, and building authorities. Voluntary measures such as increased green procurement, increased material focus in certifications, and increased use of material comparison tools were also recommended to boost CLT deployment. One important suggestion was inclusion of more environmental and material-focused targets within project contracts and tenders. Early design phase evaluation of materials, reliant on LCA, LCC, EPDs, and other tools, could further drive deployment of CLT in Sweden. New Boverket or municipal requirements for low-carbon, bio based, or timber materials could also stimulate more use of CLT. Creation of cross-supplier standardisations was also recommended, since it could clarify what CLT products are available for consumers regarding sizes, applications, costs, and customisations.

Key suggestions: environmental requirements embedded in contracts and tenders; Boverket requirements for low-carbon or bio based materials; requirements for early design material evaluation; improved information dissemination; professional and academic education; national or municipal initiatives (see Fig. IV in Appendix C).

	Organisation	Role
	Stora Enso	Finnish and Swedish wood product, biomass, paper, packaging, and pulp company. Largest CLT manufacturer.
	Martinsons	Largest Swedish CLT and glu-lam product manufacturer. Nordic leader in prefabrication and building systems.
	Boverket	Swedish national board of housing, building, and planning. Create, evaluate, and manage regulations and policies.
	Lund Municipality Building Company	Aims to acquire, own, build, and manage quality lumber-based housing in Lund and rent at reasonable costs.
	Sweco	Swedish construction and engineering consultancy focused on designing and building sustainable, efficient structures.
	Vasakronan	Sweden's largest real estate company that develops, owns, and manages commercial and retail property.
	Swedish Green Building Council	Guides sustainable building in Sweden, via education, council influence, and Miljöbyggnad certification.
	Swedish Forest Industries Federation	Supports R&D in timber-related policy, industry, bio innovation, wood products, and the building sector.
	Swedish Tree	Spreads knowledge regarding wood materials and wood building, aimed at increasing use of wood in Swedish building
	Tham & Videgård Architecture	Popular and award-winning Swedish architecture firm.
	Research Institutes of Sweden	Aims to support SMEs via R&D in bio economy, materials, certifications, and other fields.
	Lund University	Swedish R&D on timber materials, timber engineering, adhesives, joints, and construction.
	Linköping University	Significant Swedish R&D on value-added timber, timber construction, national policies, and consumers.

Table 5-1. Respondent organisations and roles

Source: Own elaboration

6 Analysis

6.1 Multilevel perspective

Niche – How could CLT education and experimentation improve?

Respondents identified significant barriers for new bio based and low-carbon materials at various sociotechnical levels. First, at the micro or niche level, CLT is an interesting case due to its environmental advantages as well as its innovative application for engineered timber, sophisticated manufacturing, and new potentials for both design and construction. CLT could be considered both a new technology and a new practice, due to its unique manufacturing and on-site construction practices. The transport and construction practices for CLT are fast, simple, and efficient, while the engineering and CNC technology used in CLT manufacturing are considered by some to be costly or complex. Respondents mentioned that lacking knowledge and skills among building industry actors, such as developers, architects, engineers, and contractors, is also a barrier for increased CLT deployment in Sweden (see Fig. 6-1). Respondents considered ongoing CLT R&D as a pathway for improved design, expanding applications, design flexibility, and enhanced premanufactured and modular building systems. Lastly, further CLT research, testing, and standardisations were highlighted by respondents as necessary to help this niche technology transition to mainstream use in Sweden.

Regime – How could practices and rules support CLT?

At the regime level, the building sector is highly complex due to its project-based nature and wide variety of actors. This sociotechnical level is highly linked to many barriers identified by respondents. The actors present in this level are fragmented, have differing expertise, and have varying perceptions, knowledge, and awareness regarding CLT. These actors could be considered architects, engineers, contractors, owners, construction companies, certification bodies, and building authorities. Since these actors and their various networks are what generally guide building industry actions and perceptions, it is important to note that this level lacks clear communication and education regarding CLT. Building sector regulations, routines, and norms that are formed in this sociotechnical level could steer the trajectory of the building industry in Sweden. Regime actors could influence the building material selection process, and work to bridge the important gap between CLT suppliers and end users (see Fig. 6-1). Market dominance by concrete, steel, and brick industries remains a barrier for increased CLT use in Sweden.

Landscape – How are exogenous factors affecting CLT?

At the landscape level, exogenous factors such as the increasing population and construction in Sweden, paired with Sweden's rich timber supply and ambitious environmental targets, could drive CLT deployment. Conversely, the Swedish ban on timber buildings above two stories between the 1830s and 1995 is a barrier that caused a technology "lock-in" for the building sector. Since wood was not used for decades, the building industry developed strong habits of using mainly concrete, steel, brick or stone. Furthermore, the manufacturing for those materials also expanded and developed over those years, making it difficult for CLT and other bio based or low-carbon building materials to experience similar development and market penetration. Incumbent building materials have established high capacity manufacturing, reliability, stable cost, and well-known construction practices in Sweden, which remain barriers for CLT. Taking designed actions in the regime and landscape levels could create the disruptive changes necessary to reduce the environmental impacts of the building sector in Sweden. By using actions in both private and public sectors to target key barriers, the building industry could speed up and steer a transition towards low-carbon and bio based materials like CLT.

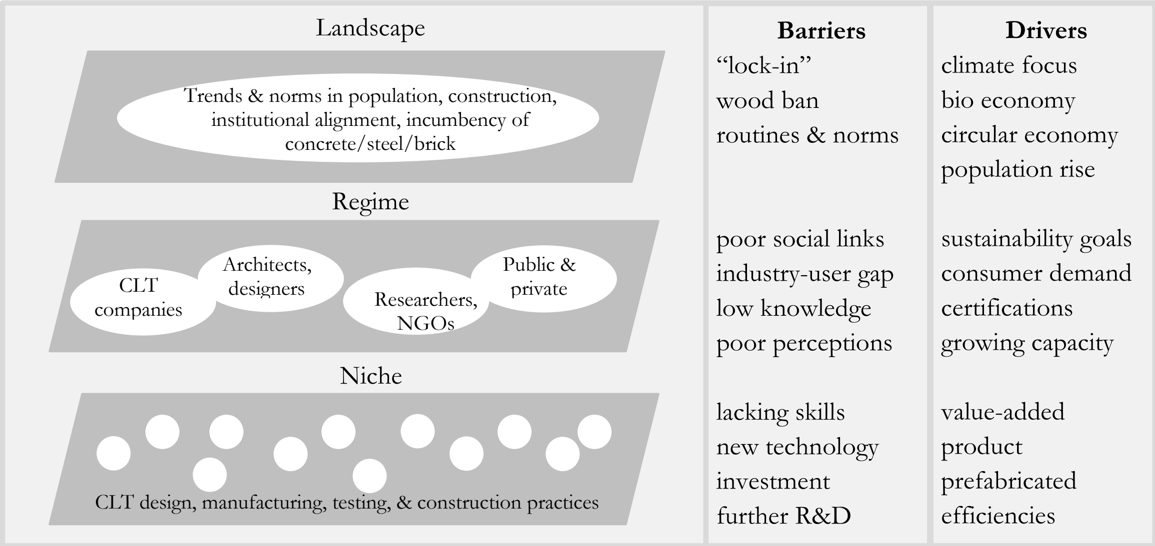

Figure 6-1. MLP diagram for CLT in Sweden

Source: Own elaboration

6.2 Technology innovation system

The technology innovation system framework was used to assess barriers and drivers, then explore means to increase dissemination of new technology, CLT in this case. Many identified barriers fit into this framework, suggesting their importance (see Table 6-1).

Who are the important actors?
Barriers for increased deployment of CLT include missing actors, lack of necessary competencies, and insufficient levels of knowledge and awareness. The gap mentioned earlier between CLT manufacturers and end users could be reduced if there were actors to occupy this void. For example, government lobbyists, procurement officers, consultants, and other actors could fill this role and serve as catalysts to create improved communication between these two groups. New and expanded competencies are also key for both CLT manufacturers to properly engineer and prefabricate desirable products, and for building industry actors to know how to design, construct, maintain, and deconstruct buildings using CLT. More knowledge specifically of how to design and construct hybrid CLT concrete buildings will be influential in increased deployment of CLT for structures beyond 12 stories.

Which networks and links are important?
TIS networks could include links between actors, methods of information exchange, and could be both formal and informal. Examples, of these could be NGOs, advocacy groups, industry associations, journals, events, and other methods of communication. The importance of these networks should not be overlooked. While institutions do determine industry rules, laws and regulations, and do very much influence norms, networks are key to establishing stronger links between CLT manufacturing and CLT use. Targeting networks could also increase deployment of CLT via improved communication among the wide array of actors, including academia where CLT research is being conducted. Improving information exchange regarding CLT awareness, knowledge, and competencies is also a barrier. Institutions could also be influenced via these networks to adapt rules, regulations, and standards via advocacy or lobbying.

Why is institutional alignment for CLT poor?

Lastly, the incumbent building materials in Sweden have dominant roles in the building sector due to their long-standing production, reliability, certainty and knowledge among actors, and developed supply chains and construction practices. What can be better understood with the TIS framework is the fact that they also benefit from strong alignment of institutions and regulations in their favour. While new technologies such as CLT, on the other hand, must struggle to develop this alignment. Well established building materials, such as concrete, steel, and brick have been highly standardised over time and therefore have proven reliability. These materials have shown repeatedly that they meet building regulations and material requirements, thus reinforcing their continued use among industry actors. This is a significant barrier for CLT, since it must compete for recognition within both the building sector market and within building industry institutions and authorities.

Actors	Networks	Institutions
Missing actors for industry-end user gap	Complexity of actors in project based industry	Recent lifting of wood ban (1995)
Little industry representation	Poor links & communication	Path dependencies of concrete, steel, and brick
Lacking skills & competencies	Nascent advocacy & lobbying	Less established manufacturing processes
Knowledge needed (CLT concrete hybrid design & construction)	Fragmented dissemination of research results	Less alignment with & influence on industry regulations
	Lacking clear communication of benefits	Less proven project experience

Table 6-1. Barriers to CLT deployment in Sweden using TIS categories

Source: Own elaboration using TIS categories

Methods to improve system function

Findings suggest both demonstration and market formation may benefit from targeted measures. Improved education and skill-building among studying and professional building designers, architects, engineers and other actors were mentioned as pathways to more CLT demonstration. Increased experimental and highlighted CLT projects were also stated as needs for Sweden. Many barriers identified by respondents relate to the TIS functions, or key processes as well. For example, the function of knowledge could benefit from further development and communication regarding CLT. Increased knowledge of manufacturing methods, building design, technical applications, and suppliers of CLT could help to increase the deployment of CLT within Sweden. Guidance via financial incentives or regulatory requirements could also influence the deployment of CLT. As CLT is still a nascent product with fewer years of production established than incumbent materials, experimentation of product variations, technical applications, and business models could serve as deployment drivers. For example, if CLT manufacturers begin creating new business models of a more integrated or digitalised nature, they may be able to streamline construction processes and sell packages of both products and services. Increased social acceptance and legitimisation of CLT could also be reached via lobbying, NGO advocacy, and governmental support. Resource mobilisation may also aid increased deployment of CLT, just as renewable energy benefitted from the mobilisation of funding for subsidy and feed-in tariff programmes.

6.3 Innovation diffusion

Advantages and disadvantages at adoption phases

The diffusion of innovation framework focuses on understanding and influencing adoption rates. Since this framework categorises adopters by their characteristics, it served as a tool for clarification of the advantages and disadvantages of adopting CLT at various times (see Table 6-2) and for clarification of roles building industry actors could play to overcome barriers identified through questionnaire responses.

Since initial CLT innovation occurred in Alpine Europe in the 1990s, it is likely that established CLT manufacturers such as Stora Enso, KLH, Hasslacher, and Binderholz are fulfilling the innovator roles. With that in mind, these companies produce CLT outside of Sweden, suggesting the innovator roles within Sweden could still be unfulfilled. While the Martinson timber company recently opened a CLT manufacturing facility in Sweden, it is one of few examples and is of much lower capacity than the mentioned companies. While innovators experience trouble entering social systems, in the case of CLT they could collaborate with municipal and private developers who have strong sustainability initiatives for their new buildings. Furthermore, new CLT manufacturers in Sweden could adopt manufacturing best practices from other successful companies to avoid unnecessary experimentation. CLT is also an un-patented technology and standard manufacturing practices are quite open to the public.

While early and majority adopters may begin manufacturing or using CLT after innovators, they could still reap benefits from this. Early adopters require less innovation, less experimentation, are more integrated with social systems, serve as more effective role models, and often hold high levels of opinion leadership. This means that once a technology, such as CLT, becomes more standardised in both production and use, then early and majority adopters can avoid risks and costs related to R&D, experimentation, and market penetration. While innovators for CLT could be considered mainly manufacturers, they could also be building industry actors which are aware, knowledgeable, and supportive of CLT use in building design and construction. Early adopters such as architects, engineers, construction teams, developers, and municipalities could be highly influential role models in the case of CLT in the Swedish building sector. With new housing demands high and insufficient domestic CLT supplies in Sweden, early and majority adopters of CLT could reap benefits of a new market devoid of much competition.

Late adoption of CLT and other low-carbon and bio based building materials could be problematic for Swedish actors, considering environmental targets for the building sector, transition to a bio economy, and development of a more circular economy. Laggards could suffer from stronger competition, economic pressures, and social pressures. While there is less risk and uncertainty, late adoption leaves actors misaligned to new technologies and with outdated practices and skills; disconnected from industry trends. Economic strain due to this misalignment and late transitions of building material manufacturing, building design methods, or construction techniques could also occur. Falling out of leading industry roles and losing competitive advantages are other possible consequences of late CLT adoption in Sweden.

Adopter typologies	Innovators & early adopters	Early majority	Late majority	Laggards
Advantages	Sweden net imports CLT, showing market demand	Less financial risk	Domestic & export opportunities	Decentralised & export opportunities
	Few domestic CLT competitors	More developed market	Developed market & social acceptance	Market acceptance
	Many municipal housing companies	Construction & population growth	Most design, manufacturing, & use issues solved	All issues solved, technology is mainstream
	Low-carbon or bio based materials niche; build links to timber industry	Expanding niche market; expand links to timber industry	Developed supply & value chains	Integrated timber & building industries; bio economy & CE developed
Disadvantages	Nascent manufacturing	Supplier competition growing	High competition	Alignment to old technologies
	Nascent use in construction	Remaining resistance to new materials	New, additional innovation required	Full range of products exist
	Poor awareness & perceptions	Time & experience required for change	Missing supplier to user links	Lacking knowledge & skills
	Financial risks & uncertainties	Residual risks & uncertainties	Rapid or large investments	Missed economic opportunities

Table 6-2. Advantages and disadvantages of CLT adoption phases

Source: Own elaboration based on Palm, 2017

A look at the decision-making process

Like key processes of the TIS framework, the diffusion of innovation framework describes adoption as a five-step decision making process. More linked to cognitive decision making, these steps include 1) gaining knowledge 2) changing attitudes 3) activity leading to adoption or rejection 4) implementation of innovation and 5) confirmation of decision leading to more adoption or reversal (Palm, 2017). Since the main identified barriers from questionnaire responses from Swedish building industry actors related to awareness, knowledge, skills, path dependencies, costs, and technical qualities, it suggests that intervention at the knowledge and persuasion stages of the process could increase deployment of CLT. For example, due to the immature nature of the CLT industry, many building industry actors still lack knowledge, skills, and CLT project experience. Poor perceptions and fragmented awareness regarding CLT also suggest that education and better communication of its advantages and applications could help. Correct, unbiased CLT information must be available to building sector actors prior to material selection to guide the complex decision making process. Prior to the implementation of new innovations, such as CLT, the decision phase occurs and is quite complex and habit or routine-based in the case of the building industry. Each building project is unique and involves various actors, phases, materials, skills, and labour. Rather than experiment with new building materials, uncertainty and fears drive continued use of familiar building materials. Disruption of habitual material selection could lead to increased implementation of CLT in new construction projects. Learning from successful construction projects and manufacturing companies could also lead to increased deployment, by guiding both the implementation and confirmation phases.

Attributes of CLT that could influence adoption

Several attributes are also influential in the rate of adoption for innovations, according to this theory. These innovation attributes are bulked into five types, including relative advantage, compatibility, complexity, trialability, and observability.

Despite CLT's environmental and efficiency advantages over competition, incumbent building materials dominate Swedish markets. Existing habits, routines, reliable prices, proven quality, and knowledge among industry actors are advantages of traditional materials, which CLT will need to catch up to. Incumbent building materials also have an advantage due to their existing infrastructure, alignment to regulations, and well-developed supply chains. It could be helpful for increasing deployment of CLT in Sweden if its various advantages are better communicated to influential policy makers, industry actors, and investors to spur transition.

Compatibility with both formal and informal aspects of the building industry can still be viewed as barriers for CLT. Since building codes in Sweden are performance based, they do allow for the use of new building materials. But with that said, they do not promote or favour any specific materials which reinforces use of traditional incumbent building materials. Certification programmes are becoming more material-oriented, and have expanded credits and weighting towards low-impact materials further driving CLTs compatibility with the sector. Informally, some Swedish actors still consider CLT incompatible with fire safety. Overall, changes in building design and construction are needed to increase CLT compatibility with the sector.

Complexity of CLT is both perceptual and actual. Perceptions of CLT based on traditional single timber beams may be very inaccurate, since it is a different, more complex product with heightened qualities. While CLT is made of timber, its layered composite structure amplifies technical characteristics and essentially transforms timber into a much stronger, solid material. CLT manufacturing is more complex than for standard timber beams, and can be both a barrier and a driver. CLT production requires machinery (presses, adhesive portals, CNC routers), engineering, and design which can be considered barriers. The sophisticated manufacturing of CLT is also an opportunity, since precise panel prefabrication reduces on-site labour, minimises waste, and increases transport and construction efficiency.

Significant CLT testing and research on seismic, acoustic, fire, and other technical capabilities is being conducted. But, these tests are taking place in controlled settings, and what is lacking are real building projects in different geographic areas, climates, and of various designs. Rather than building sector actors being eager to trial new materials, it is likely that habits, knowledge, costs, and client demands drive selection of traditional materials. Increased collaboration between academia and industry could result in more project-based trialability, and better highlight the array of applications and legitimacy of CLT. Municipal and other public projects were also mentioned by respondents as good opportunities to trial CLT in Sweden.

Observability is improving, due to highlighted CLT projects, dissemination of research, conferences and events, and increased publications regarding CLT. If these highlighted success stories of CLT reach the necessary building industry actors within Sweden, this could drive increased deployment of CLT. Research results and successful projects may require additional support to reach actual building industry professionals. Specifically, research results could benefit CLT manufacturing companies, project owners, building design teams, and construction teams. Spreading knowledge and solutions could reduce barriers related to technical performance, costs, applications, and design of CLT, thus helping it become a more competitive building material.

7 Discussion

The *Discussion* chapter consists of five sections. These sections represent the process which was used to formulate the final recommendations. First, selected frameworks were used to further discuss questionnaire responses. Secondly, CLT manufacturing best practices were examined. Thirdly, sustainable transition examples were compared to CLT and the building sector. Fourthly, CLT support systems from around the world were highlighted and discussed. Lastly, final recommendations were revealed in prioritised categories.

7.1 Synthesis of frameworks

Multi-level perspective

At the niche level, more knowledge is necessary to boost CLT manufacturing and use within Sweden. Increasing knowledge specifically among architects, engineers, contractors, owners, and project developers was highlighted by multiple respondents. Suggestions for this task included university and professional education, dissemination of guides and handbooks, and events and outreach. Respondents suggested more R&D to expand CLT applications, better understand hybrid CLT, concrete, and steel designs, and learn how to produce CLT of larger spans and sizes. Goals of increasing domestic production, increasing availability, and lowering capital costs of CLT were also suggested by respondents, which could be reached via adoption of best production practices, mobilised investment, and tax breaks or incentives. More owner-directed environmental requirements embedded within early stages of building projects were also recommended.

Within the regime level, both the Eurocodes (specifically EC 5) and the Boverket Building Regulations (BBR) were mentioned by respondents as key authorities. Eurocode 5 could more explicitly mention CLT, upon review and updating of all 10 Eurocodes to integrate bio and low-carbon materials. More guidance regarding hybrid building design, using CLT, concrete, and other materials, could also help CLT deployment. Increased material consideration at early stages was also recommended by shifting to more feedback-based integrated design processes (IDP; see Fig. 7-1), where owners take an active role and the architect(s) manage team members (Kubba, 2012a). Rather than acting as sole decision maker, the architect(s) work with BIM experts, engineers, construction managers, and consultants to align goals and streamline decision making (Kubba, 2012a). Kubba and respondents also suggest design-stage material evaluations (using EPDs for environmental impacts and LCC for financial costs), including everything from raw material extraction to maintenance and end-of-life treatment (2012a). Certification schemes, like Svanen and Miljöbyggnad, could increase material focus, while material databases, such as Sunda Hus or Byggvarubedömingen, could better link CLT suppliers and users.

According to respondents, landscape level factors will also drive increased CLT use in Sweden through consumer demands, the transition to bio economy, and the increasing climate perspective. State and municipal environmental targets and sustainability initiatives will also drive the building sector towards increased use of low-carbon and bio materials, such as CLT. The housing shortage and rising population in Sweden was an important driver, according to respondents, since rapid housing solutions and densified urban housing could benefit from increased use of CLT. Increased CLT projects and increasing publicity for CLT were also mentioned as drivers for increased deployment via knowledge transfer. Lastly, changes at the landscape level for a conservative, complex sector such as the building industry are predicted to take long periods of time therefore actions targeting barriers at this level could be of high importance.

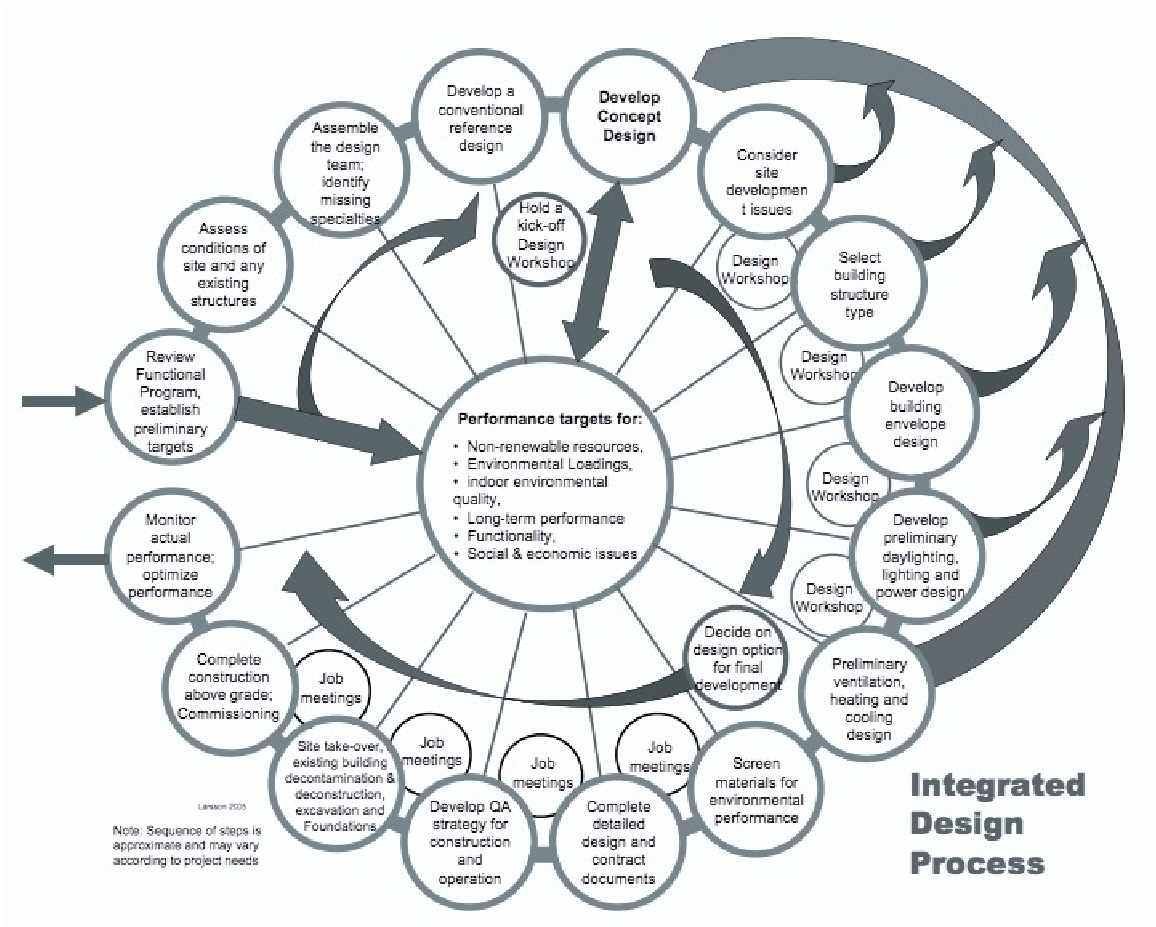

Figure 7-1. Diagram of Integrated Design Process

Source: Larsson, 2009

Technology innovation system

Institutions such as building authorities, national and municipal governments, and certification schemes should seek to increase alignment with low-carbon and bio based building materials, such as CLT. Integrating low-carbon and bio based materials into industry regulations, recommendations, and green procurement initiatives could lead to higher CLT adoption in Sweden. Further standardising domestic CLT production and construction practices could also increase legitimisation of CLT. With the strong position that incumbent building materials hold in the Swedish building industry, life-cycle analysis, life-cycle costing, environmental product declarations, and other environmental assessment tools to make the market a more aware and level playing field could also benefit CLT.

Network related actions, like increased communication and collaboration between timber and building industry actors, could be an ideal method to clarify market demands for CLT and clarify opportunities for timber companies. Since incumbent building material companies are known to have significant lobbying power and dominant industry positions, bio based and low-carbon materials such as CLT will need to further develop these. For example, associations, NGOs, and other organisations may help CLT manufacturers penetrate the market, reach key building sector actors, and influence policies and regulations. These groups could also serve as networks to disseminate knowledge and provide free tools or guidance, which were suggestions from respondents.

Actors must better link CLT suppliers and users. Actors such as architects, certification authorities, consultants, and contractors could act as these links. The concept of improved networks could also be applied to the building process. Since respondents stated needs for embedded environmental requirements in project contracts and increased early stage focus on full life cycle impacts of building materials, the IDP is one example of how a more holistic decision making process and material selection process could be achieved. Building professionals need to more accurately assess building materials by using reliable tools like EPDs or LCAs at early design stages, which would favour CLT and other low-carbon materials (Spiegel at al., 2012). Spiegel and respondents highlighted the influence of owners, architects, consultants, and material suppliers, suggesting their importance in increasing CLT deployment (see Fig. 7-2). Contractors were also mentioned by respondents as having strong influence over owners, architects, and engineers, therefore if their knowledge and skills regarding CLT increases they could trigger shifts in material selection.

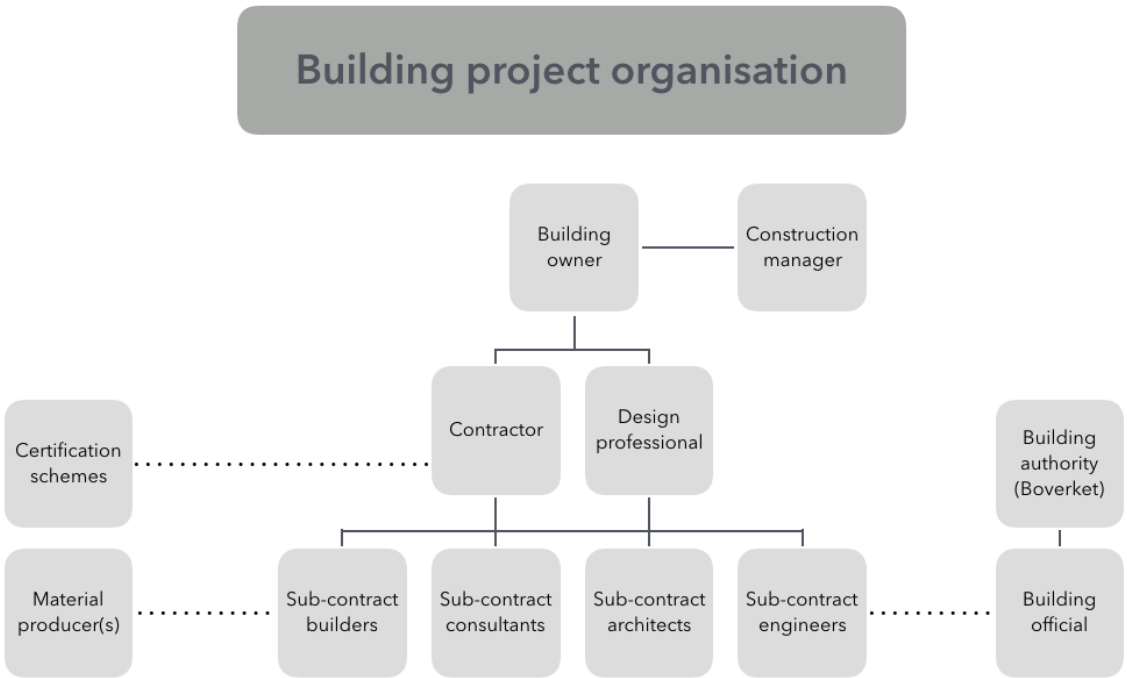

Figure 7-2. Key actors of the construction process

Source: Own elaboration

Innovation diffusion

If advantages of early adoption become more attractive or are better communicated, then this could drive deployment of CLT in Sweden. Additionally, if disadvantages of early adoption are diminished, then investment, manufacturing, and use of CLT could be boosted. For example, if financial risks, lack of manufacturing knowledge, under-developed supply chains, and lack of CLT-specific skills could be reduced, then early adoption could increase. Communicating early adopter advantages of a growing domestic market, few domestic competitors, large number of municipal building companies, and low-carbon and bio based material niche could attract early adopters and investors. For example, events or business reports could communicate these advantages to timber industry actors (potential CLT producers) and building industry actors (potential CLT users). Educating insurers and financers could also be considered an important factor to overcome fears of collateral or insurance risk, according to Swedish CF Møller architect Ola Jonsson. Alternatively, communicating the risks of late adoption could display risks associated with lacking a demanded product, increased competition, and misalignment to new technologies and practices. Lagging behind industry trends and the increasing climate focus could be additional risks that drive early adoption.

Per respondents, the knowledge and persuasion stages of the decision-making process for innovation adoption are most in need of solutions. Low awareness, inaccurate perceptions, and lack of knowledge must be met with education using accurate, unbiased, and understandable information regarding CLT. Furthermore, domestic supply chains for CLT must become more developed, a more level playing field must be created for building materials, and real life projects using CLT must be observable and well-documented. These responses apply more to the implementation stage for CLT. CLT projects of varying building types in different climates and geographic locations are key to display its benefits and applications in localised settings.

Summary of synthesis

These three frameworks were used to analyse and discuss questionnaire responses. The frameworks enhanced understanding of Swedish building industry actors, networks, communication, technology adoption, and the numerous complexities of the building sector. The MLP theory and responses suggested that increasing climate focus, heightening regulations, standards, and certifications, and linking knowledge to manufacturers and users are key for CLT deployment. Responses viewed through the TIS framework suggested use-oriented mechanisms, such as material carbon taxes, owner requirements, early design stage LCAs and EPD use, education, linking suppliers and users, and increasing materials focus in BBR and certifications. The innovation diffusion perspective indicated that communication of early adopter benefits and late adopter risks could push CLT deployment. Additionally, respondents highlighted key actors like contractors, architects, engineers, suppliers, and owners, which this framework helped to identify roles and responsibilities for that could boost CLT deployment. Overall, the frameworks provided the initial analysis of responses and helped to understand which recommendations could best support CLT deployment in Sweden.

7.2 Best practices: CLT manufacturing

These three examples of CLT manufacturing are aimed to highlight best current practices and act as guidance for Sweden's expanding CLT industry. Guidance and dissemination is important to increasing deployment of CLT, and these examples provide exactly that (Antikainen et al., 2017). The example companies are interesting due to their various product portfolios, manufacturing practices, investments, vertical integration, and various service and product packages. Since Swedish demand for CLT exceeds domestic supplies, this section could help show pathways for Sweden's CLT manufacturing future. Main findings from these examples include wide and expanding product ranges, specialty products, vertically integrated organisation, environmental certifications for facilities and timber, ongoing R&D and collaboration with academia, and efficient combined production of EWPs, biofuels, heat, and power. Other key takeaways are the concepts of internal industrial symbiosis, panel customisation, heightening prefabrication, digitalisation, and expanding sizes and applications of CLT. While this examination of Stora Enso, Binderholz, and Hasslacher Norica Timber did not strongly influence recommendations, it does enhance understanding of ideal CLT manufacturing systems and could be very valuable to the producers of Sweden's growing CLT industry.

Stora Enso

Finnish and Swedish pulp, paper, biomaterials and wood materials producer Stora Enso has two large scale CLT manufacturing sites in Austria, leading the CLT industry in terms of production capacity at around 150,000m^3/year (Stora Enso, 2017b). Little information is available publicly regarding their CLT manufacturing processes, but they produce CLT panels using presses and CNC router technology. CLT panels are up to 2.95 x 16m, vary in numbers of layers, and vary in thickness. This allows for CLT panels to serve a wide range of structural purposes for end users. Timber layers are bonded using formaldehyde-free and low-VOC adhesives of polyurethane (PUR) and Emulsion Polymer Isocyanate (EPI), accounting for less than 1% of the final product (Stora Enso, 2017a). Both visible and non-visible wood options for industrial, commercial, and residential use are available, relying on round wood of fir, larch, and two species of pine.

Guides, certifications, and technical documents are available online, further clarifying the various CLT products offered. Guides in numerous languages clearly communicate the applications of CLT and its technical specifications regarding load bearing, fire resistance, seismic performance, acoustics, moisture resistance, and thermal qualities. Stora Enso collaborates with academia to continuously improve CLT designs and expand applications. For example, the SISMO and WUFI projects focused on seismic testing, connector evaluations, and creation of free CLT design and engineering tools (e.g. Calculatis). Their CLT manufacturing is also certified under ISO 9001, ISO 14001, FSC and PEFC. Conformity certificates for the ETA, the EUTR, and other regulations are also available. An EPD document also clarifies the manufacturing, environmental and health impacts, and LCA of their CLT. A 2017 timber construction report from Stora Enso highlights their interest in further digitalising the CLT industry using BIM, virtual reality, and 3D printing. Stora Enso recently invested 45 million EUR in a CLT manufacturing facility in Grüvon, Sweden where it will produce 100,000m^3/year by late 2018 or early 2019 and aims to earn 50 million EUR/year when running at capacity (IPW, 2017).

Figure 7-3. Stora Enso CLT customisation in Austria

Source: Zukunftsinstitut GmbH, 2017

Binderholz

This German timber company combines CLT manufacturing with biofuel and energy production (see Fig. 7-4). They use virtually 100% of timber within the value chain to create three general products. Suitable timber is processed into panels, wood pieces are turned into biofuel pellets or briquettes, and by-products are burned in a combined heat and power (CHP) plant to produce renewable energy. Akin to a bio refinery, they produce heat, power, and fuel, but wood products rather than chemicals. Binderholz also offers engineering and consulting services, providing packaged support to building industry actors. Binderholz is integrating digital building information modelling (BIM) into its design processes, which reduces complexity and errors for large building projects with large teams. Timber meets PEFC standards and facilities meet various ISO standards.

Binderholz uses automated timber quality sorting, four-colour scanners, and strength testing. CLT panels are available in categories based on surface qualities, and in sizes up to 3 x 22m. Spruce, larch, fir, and pine are used for their CLT panels, profiled by their respective applications, strengths, technical qualities, and size ranges. Wood beams are kiln dried, bonded with PUR, auto-pressed, and customised using automated CNC machinery. Binderholz collaborates with insulation, door, and window companies to further increase prefabrication and expand their portfolio. Adhesive supplier tests for panel bonding quality, internal audits of production, and final product inspections all occur regularly by internal staff and external institutes. A "Processing guide" for CLT users explains transport, unloading, lifting, use of cranes and scaffolding, installation, connectors, screws, anchors, joints, and sealants.

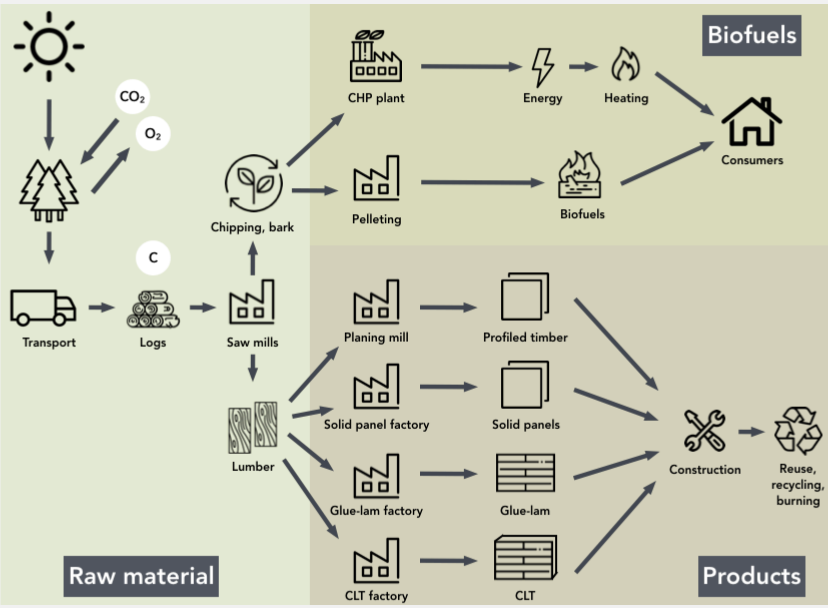

Figure 7-4. Resource efficiency manufacturing model (Binderholz GmbH)

Source: Adapted from Binderholz, 2017

Hasslacher Norica Timber

Austrian producer Hasslacher Norica Timber manufactures a variety of EWPs, including CLT. In addition to panels of various timber types, thicknesses, and dimensional sizes, they also manufacture specialty products including thermal planks, façades, round columns, ceiling systems, and other unique goods aimed to enhance wood building systems. This company also provides "CLTdesinger" digital software to consumers, which was developed and is maintained by Graz University of Technology's timber building competence centre. Pre-dimensioning tables and mechanical properties are also publicly available. Mills, saws, and CNC router machinery is used to customise panels with fenestrations, electrical and sanitary channels, and spaces for connectors.

A high pressure Kallesoe Machinery press is used in their CLT manufacturing, which increases efficiencies via shorter pressing times and higher capacity. This machinery also allows omission of adhesives and wood where building envelope fenestrations have been planned, reducing adhesive use and wood waste. CLT can be made at various thicknesses and up to 3.2 x 20m. Hasslacher offers similar species as Stora Enso and Binderholz, but stands out by offering Swiss stone pine, birch, and hardwoods upon request. All timber is PEFC and FSC certified, showing that sustainable forestry certifications are used by leaders of the CLT industry. Lastly, Hasslacher goes beyond Binderholz by generating more energy than it uses, via wood by-products used in a CHP plant, solar PV installations, and a hydropower plant.

7.3 Similar sustainable transitions

These two examples were used to explore sustainability innovations which have experienced rapid growth and deployment in recent years. Electric vehicles and solar PV panels were selected due to their significant barriers and difficulties when trying to penetrate respective transport and energy sectors. Since these sectors are also recognised to be burdened with path dependencies, existing infrastructure, and reliance on routines and current technologies, they can provide helpful insights for decarbonisation of the building sector. The examples suggest that increased innovation deployment can be reached via green procurement, business models, and market instruments supporting new innovations. While these examples were not key in formulating final recommendations, they did serve as successful archetypes which were kept in the background to guide the process.

Transport: Electric vehicles

Figure 7-5. Electric vehicle charging

Source: Creative Commons

Electric vehicles (EVs) experienced significant barriers, comparable in many ways to the various barriers CLT is experiencing. While EVs are an innovation example from the transport sector and not the building sector, relevant barriers of existing infrastructure and path dependencies are common to both sectors. First, existing infrastructure of the transport sector was historically aligned with internal combustion engine (ICE) vehicles and has only recently begun to shift via expanded placement of EV charging stations (Steinhilber, Wells, & Thankappan, 2013). Path dependency of ICE vehicles manifests in regulations, consumer demands, industry openness to new business models, and manufacturing trends (Bohnsack, Pinkse, & Kolk, 2014). Nascent and developing technology of EVs is another reason for slow commercialisation and fragmented deployment (Steinhilber et al., 2013). Similar to engineered timber panels such as CLT, there are still further technical improvements that can be made to these technologies which may have been a barrier for early adoption (Bohnsack et al., 2014).

Lacking economies of scale could also be considered a common barrier for both EVs and CLT, since smaller-scale production lines of experimental products are less cost-effective than large-scale manufacturing of well-established products. EVs are no doubt a beneficial technology in terms of environmental impacts, but unfortunately they do not bear any significant benefits for the energy sector (Steinhilber et al., 2013). CLT differs regarding this challenge, since it bears environmental advantages for the building sector and provides value addition for the timber sector. EVs also relied on both governmental and regulatory measures to increase deployment, suggesting that similar measures could boost deployment of CLT and other low-carbon or bio based building materials (Steinhilber et al., 2013). Positive social environments, driven partly by decarbonisation of industries and rising environmental awareness, was also a requirement for EVs to increase deployment (Steinhilber et al., 2013). New business models and green public procurement (GPP) are also considered tools that are boosting EV deployment.

Energy: Solar PV panels

Figure 7-6. Residential solar PV panels

Source: Creative Commons

The idea of decentralised energy production that is implied with the deployment of solar PV panels could be a significant barrier for this technology. Decentralised residential adoption of solar PV technology could be highly disruptive to traditional, centralised energy production. As energy production has historically been a centralised and fossil fuel-powered industry, the existing infrastructure favoured existing technology based around coal, nuclear, and natural gas plants. This type of barrier relates to the path dependencies of materials within the building sector, which revolve around manufacturing and use of concrete, steel, and brick. Effects of peers have also been regarded as important barriers that should be considered ex ante when designing or comparing new policy alternatives for solar PV (Rai, Reeves, & Margolis, 2016). Installation, operation, and maintenance are considered barriers, since they are concerns that drive private individuals away from adoption of solar PV (Rai et al., 2016). Despite falling technology and installation costs for solar PV panels, lack of information, installer influence, and peer influences remain barriers (Rai et al., 2016). This finding suggests that even after CLT manufacturing and user costs fall, the material might still face barriers.

Within Sweden, PV installation firms with typically small, local focus often lack the specialisation necessary for wider deployment of PV technology (Palm, 2017). Key actors, such as architects and construction companies were also only marginally involved in PV deployment (Palm, 2017). A lack of business models and adoption choices was another identified barrier. This suggests that larger national or regional PV companies and more education and involvement of key actors could have boosted PV deployment. Direct purchasing was most common, while leasing and investment opportunities were low (Palm, 2017). Low national energy prices, high costs of panels, and poor economic profitability and ROI in Sweden were identified as the important barriers to residential PV panel adoption (Palm, 2017). A 2009 investment subsidy served as a support tool for PV adoption in Sweden, but once budget caps were reached the rise in PV deployment stopped and caused problems for installation firms (Palm, 2017). Additionally, new applications for this subsidy experienced long waiting times due to undetermined policy decisions for funding (Palm, 2017). These findings suggest innovations benefit from consistent and reliable financial support tools, lowered costs, and fast ROI.

7.4 CLT support examples

These examples are aimed to highlight good examples of organisations, policies, regulations, financial mechanisms, and business models which support CLT deployment. Drawn from throughout the world, the examples are meant to display potential pathways for Sweden and reference existing ideas that could align with respondent suggestions. This analysis of current CLT support systems uncovered roles and responsibilities, methods, and categories, which helped to transform questionnaire responses into final recommendations.

Organisations

The Japan CLT Association specifically focuses on CLT deployment, increasing efficient use of timber, and forming a recycling-oriented society. Acting as a support body for CLT, its business centre helps to form technical standards and hybrid standards, disseminate knowledge, fund and steer R&D, expand CLT applications, and provide design support for projects. Other useful tools the association provides are supplier locations and contact information, completed project profiles, an events calendar, technical reports, and guiding example documents.

The Canadian Wood Council (CWC) consists of several associations which support increased and sustainable use of wood products. The CWC is integrated with both national and provincial building code committees, allowing extensive participation in the development of new codes and more equal political representation with non-wood industries like steel and concrete. The council is also involved in development of product standards, engineering design standards, and testing standards. Lastly, the CWC supports increased deployment via manuals, software, field advising, and transferring knowledge to key building sector actors such as builders, architects, and engineers.

The Växjö Municipal Council in Sweden formed a Wood Construction Strategy in 2013, which focused on creating requirements for timber based material use for most frames in all new public constructions. Additionally, it established a Wood Construction Council consisting of actors with various expertise and serving a range of roles. Targets include increasing collaboration between industry and academia, testing products and practices, educating building sector actors, increasing engagement of the private building sector, and increasing R&D regarding mass timber building acoustics, construction, maintenance and life-cycle costing (Växjö Kommun, 2013). The programme liaises closely with businesses and organisations in the Småland region, such as the Centre for Building and Living with Wood (CBBT) which provides R&D funding. The strategy targets are evaluated and updated annually by the Council (Växjö Kommun, 2013).

Municipality highlight: Växjö, Sweden

- Wood Construction Strategy (formed 2013)
- Explores wood construction & climate perspectives of construction
- Combines forestry, timber manufacturing, building, & academia
- Increase pilot projects, R&D, & dissemination of knowledge
- Wood Construction Council designates roles

Targets:
-Develop building lifecycle costing tools
-Reduce construction & maintenance costs
-R&D for acoustics & maintenance
-50% new builds wood based by 2020

Figure 7-7. Limnologen building in Växjö, Sweden

Source: Växjö Kommun, 2013

Policies
A "wood encouragement" policy being developed in Tasmania will require all public construction and renovation projects to consider timber materials as first-choice during the early building design stages, according to State Treasurer Peter Gutwein. This follows recent changes in national construction codes, which allow for increased use of timber products such as CLT in taller buildings. While not requiring use of CLT or other engineered timber products, policies such as this are both raising awareness and creating social pressure to use low-carbon and renewable materials as a preferred choice.

The Wood First Act of 2009 implemented by Canadian province British Columbia was created to require the use of wood as a primary building material in all provincially funded new construction and additions. Paired with funding from the B.C.-established Forestry Innovation Investment (FII), the Wood First Act promotes value-added timber building materials directly through GPP. This could be a pathway to spark innovation, increase public deployment of CLT and other EWPs, and increase market demand for potential manufacturers.

Finland and Denmark have recently begun requiring use of BIM on all public building projects (Kubba, 2012b). This can indirectly support increased deployment of CLT, and other low-carbon or bio based building materials. Since BIM increases likelihood of a sustainability focus at early building design stages, collaboration of project actors, and evaluation of building material options, it can therefore lead to more awareness and use of low-carbon and bio based materials. It is also viewed as a tool that allows project actors to easily access important building material data and accurately compare options. If this practice is paired with strong focus on embodied carbon, GHG emission reductions, or renewability of materials, then it could greatly influence deployment of CLT.

Regulations and codes
Changes in building codes can help new building materials break into the industry and increase their legitimisation. Both city-level building code changes, such as Seattle's 2012 incorporation

of CLT, and larger scale changes like the 2015 IBC change to incorporate CLT both increase the awareness and legitimacy of the building material. China's Ministry of Housing and Urban Development notably passed a new technical standard for multi-story and high-rise timber buildings, taking effect in October 2017 (*GB/T51226 – 2017*). This standard increases the maximum height of timber buildings to five stories from the previous three stories, and allows for new timber-based construction of up to 18 stories if local authorities and seismic zones allow.

The Finnish Ministry of Foreign Affairs Wood Construction Working Group recommended lobbying to the EU to establish a Commission-level directive focused on embodied carbon, embodied energy, and LCA impacts of building materials (Ministry of Foreign Affairs Finland, 2010). In addition to this EC-level directive, the group recommended an increased and more explicit focus on timber construction within climate policy of international organisations such as the UN, WTO, UNFCCC, and IPCC (Ministry of Foreign Affairs Finland, 2010). International cooperation between governments was also suggested to increase deployment of timber building materials via uniformity among international building codes and regulations (Ministry of Foreign Affairs Finland, 2010). This could help timber-friendly regulations and codes reach internationally to developing countries, and help establish new markets (Ministry of Foreign Affairs Finland, 2010).

A UNEP and DTU low carbon development report for the building sector also recommends use of carbon budgeting, combining operational and embodied carbon (Lütken & Wretlind, 2016). Cities, companies, and clients could place these types of budgets within already existing project approval processes. Cities are highlighted as catalysts, where a few pioneering cities could test this type of system relying on supplemental tools such as EPDs and the EN 15978 standard for building LCAs (Lütken & Wretlind, 2016).

Financial mechanisms

Regional financial benefits, such as the OregonBEST cleantech grant, also can help fund experimental research, new projects, or serve as investment for new manufacturing facilities. The grant of roughly 200,000 USD was devoted to a CLT based project, ongoing CLT research, and helped to create one of the first CLT manufacturing lines in the USA.

Additionally, state or EU funding could be another source of financial support. For example, the U.S. Department of Agriculture has awarded several million dollars to timber based experimental projects and research. 80 billion EUR was also mobilised in 2014, as part of the EU Horizon 2020 Research and Innovation programme which focuses largely on sustainability. Overall, reducing economic barriers via financial mechanisms like subsidies, grants, and taxes could help increase CLT deployment akin to EVs and PV panels.

Business models

Cree by Rhomberg has created a unique new business model, which revolves around integrated procurement of materials, building design, and construction. By creating a new system of "customised industrialisation" for new constructions, Cree has created a market niche. The company designs low-impact LifeCycle Towers of a hybrid timber and concrete design, using prefabricated CLT panels and a concrete building core. They do not produce materials, thus can support different suppliers and better meet unique consumer demands. LifeCycle Towers can be customised, since they have no partition walls inside and utilise prefabricated module roof, wall, floor, and core components.

As mentioned earlier, some CLT manufacturers are using a business model which involves timber processing, CLT production, biofuel production, and combined heat and energy production. This allows utilisation of low quality and by-product, mid-grade, and high-grade wood material. While being highly efficient from an environmental and natural resource perspective, these business models also allow for a more diverse portfolio of products which extend beyond the building sector to the energy and fuel sectors. As market prices fluctuate in these various sectors, this diversity could help CLT companies become more resilient and withstand financial crises.

7.5 Recommendations

Recommendations for how to increase deployment of CLT within the Swedish building sector have been categorised into five groups, based on their nature. These categories include 1) informational 2) voluntary 3) financial 4) regulatory and 5) business model-related recommendations. Recommendations outlined below are based primarily on questionnaire responses. Examples of best CLT manufacturing practices, sustainable transitions, and CLT support systems also served as guiding concepts, but were relied upon less since they were not specific to Sweden. Although these recommendations are framed specifically at supporting CLT deployment in Sweden, many could be applied to or altered slightly to support other low-carbon and bio based building materials. Implementation of recommendations is also suggested to follow the three phases of reinforcing market adoption and behavioural change, which are 1) remove barriers and support innovators, 2) create incentives, and 3) create requirements (Athens, 2012). These phases are more successful when done in succession (Athens, 2012). For example, initial financial support and spread of research or development helps disseminate knowledge and build awareness. Incentives are next used to reduce scepticism and increase market adoption voluntarily. Lastly, mandatory requirements are used once building markets have sufficiently tested and approved adoption of a product or service.

Before reaching the recommendations, a look at the value chain of CLT can clarify locations of barriers and potential leverage points for measures to drive increased deployment. The manufacturing, sales, and construction and use stages were identified as main leverage points for measures that could be implemented to increase CLT deployment in Sweden (see Fig. 7-8). The maintenance and end-of-life (deconstruction and reuse) stages were identified as leverage points currently needing more research, development, experience, and ongoing monitoring. More experimental projects and projects of a wider variety of building typologies were identified as important paths for addressing the needs of the final two stages. Perhaps voluntary, financial, and regulatory measures could be implemented in the maintenance and end-of-life stages in the future, once more research and experience is developed over the coming years.

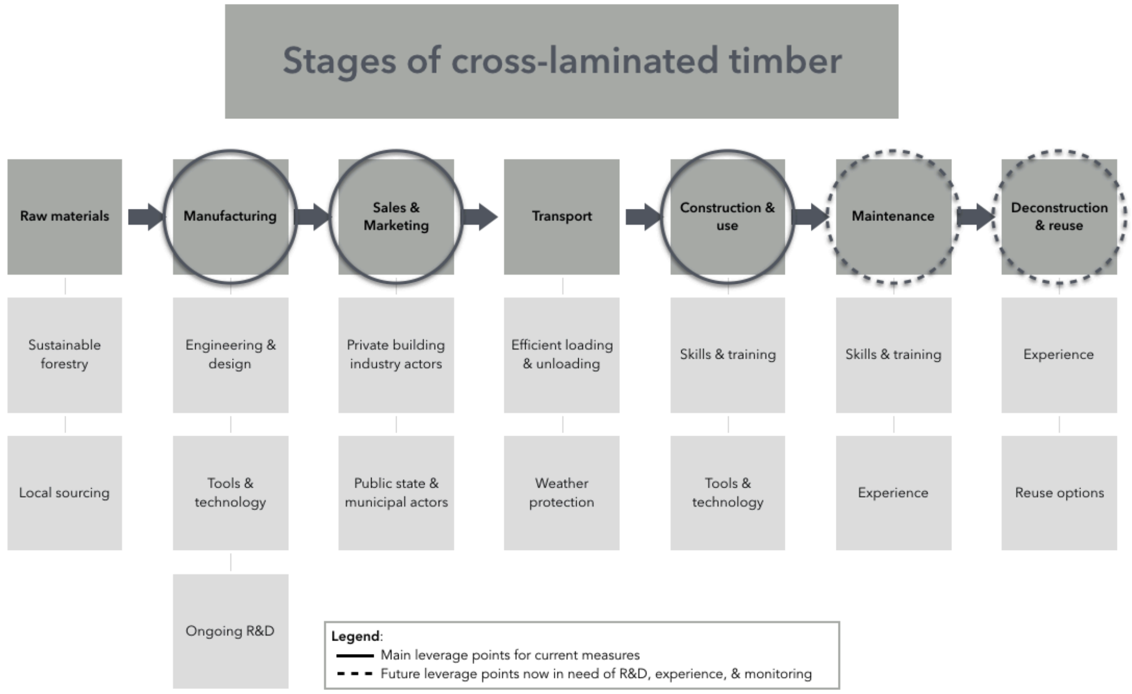

Figure 7-8. Value chain diagram of CLT in Sweden

Source: Own elaboration

7.5.1 Informational tools

These recommendations refer to actions that enhance education, training, and skill building for manufacturing and use of CLT. Respondents from Svenskt Trä (Swedish Tree) suggest more events and seminars, as well as increased dissemination and use of their various Swedish guides and handbooks for EWP construction. These guides align with BBR and Eurocodes.

To "upskill" future generations of building industry actors, it is important to also include CLT and other low-carbon building materials in professional and university level courses for architects, engineers, and building designers. Training, workshops, and seminars aimed at building industry professionals could enhance CLT knowledge among current actors. These programmes could be run by industry associations such as the Trästad, or research institutes such as the SP Technical Research Institute of Sweden. Associations could also aim to take a role like that of the Japan CLT Association, which focuses specifically on CLT materials, provides technical support, and offers many communication and education related resources nation-wide. These organisations recently have brought CLT and timber construction more into the political sphere, via seminars and discussions at Almedalen. This type of lobbying and cooperation among municipalities, builders, and researchers could be tuned up and better linked to Sweden's growing number of environmental targets. Lastly, Swedish organisations could become more integrated with national and municipal building regulations, such as the CWC.

Educating timber industry actors of the potential business opportunities could help clarify the benefits of CLT manufacturing and its projected market growth. Clear communication of best manufacturing practices, technologies, funding sources, business models, and industrial symbiosis opportunities to timber industry actors is also recommended. If this information was provided to timber companies, they may be more likely to invest in CLT manufacturing infrastructure. Lastly, but importantly, working to educate building insurance companies regarding technical safety of CLT panels is key to break down barriers related to heightened insurance costs associated with timber based buildings.

7.5.2 Voluntary measures

Voluntary green building certification schemes relevant in Sweden, such as Miljöbyggnad, LEED, and BREEAM, could potentially increase deployment of CLT. Increased percentage weighting or additional credits for building materials that meet certain embodied carbon, renewability, or LCA criteria could boost deployment of low-carbon and bio based materials such as CLT. Early design stage requirements for building material environmental evaluations using EPDs or LCAs could also result in higher adoption of low-carbon and bio based materials like CLT.

Technology and innovation procurement from both public and private building industry actors could help communicate to CLT manufacturers what products and applications are desired. This tool could be used to transform the building market and guide CLT manufacturers to improve CLT designs, create new specialty products, and better use their customisation abilities. Increased low-carbon and bio based building material focus within building project contracts and tenders is also recommended, driven by building owners. If building owners or project managers initially include environmental requirements for building materials, then this could lead to increased CLT deployment. More explicit building material focus within international and national level climate policy could also increase CLT deployment, since these policies often act as guides or influences on regional and city-level construction practices.

7.5.3 Market based instruments

Both disincentives and supportive financial mechanisms are recommended. Public or private grants for CLT research and manufacturing is recommended. Tax reductions or subsidies to CLT manufacturers and users are also recommended to make CLT more capital cost competitive, therefore increasing the likelihood of timber companies investing in manufacturing and of users being willing to pay for the product.

Alternatively, negative instruments such as carbon tax on building materials is recommended, so materials with high embodied carbon pass on increased costs to consumers and thus make them less desirable choices. Taxing non-renewable building materials could be a similar option to this measure, and could result in more positive outcomes for CLT. Lastly, setting maximums or "caps" on the embodied carbon or emissions of construction projects could be another method to decrease reliance on traditional building materials, such as concrete, steel, and brick. Many of the responses and resulting recommendations in this category align with recommendations of Antikainen et al., bolstering their validity (2017).

7.5.4 Regulations

Increased use of "green" procurement is recommended for both public and private construction, renovation, and addition projects. With Sweden's influential municipal housing sector and National Agency for Public Procurement, GPP requirements for low-carbon, bio based, and local building materials is strongly recommended. Antikainen et al. support this recommendation, by stating that public procurement of timber building materials is a key policy (2017). A Harvard Business School study found that cities that require LEED certification in public buildings experience twice the LEED adoption in the private sector (Melton, 2012). This suggests that a combined increase in GPP and increase in building material focus in certifications could lead to higher CLT deployment publicly and privately. As certifications like Miljöbyggnad and Svanen have been shown to improve building operational performance and not significantly affect material selection, it is recommended to heighten their focus on sustainable materials (Tarantini et al, 2011). Building material databases, which are influential when using BIM, could also better incorporate CLT and engineered timber products.

Furthermore, increased requirements regarding building material environmental analysis and comparison at early design stages could help increase CLT deployment. By requiring building material data for embodied carbon, embodied energy, or LCA impacts, construction projects would be pressured to use or at least become more aware of alternative building materials. Requirements for building materials that have maximum levels of embodied carbon, embodied energy, or LCA results could also promote deployment of CLT and other low-carbon or bio based materials. Alternatively, requiring certain percentages of building materials to be wood-based could boost CLT deployment. Lastly, requiring use of building materials which fulfil certain eco-design or end-of-life reuse criteria could lead to increased CLT deployment, due to its renewability and retained deconstruction value. Municipalities in Sweden could also form target-based wood building strategies or wood building councils, following suit of Växjö.

7.5.5 Business models

As a few leading CLT manufacturers have implemented highly efficient and resilient manufacturing models, it is recommended that Swedish manufacturers follow suit. To better utilise high, mid, low-grade, and by-product wood materials, it is recommended that developing or expanding CLT manufacturers in Sweden explore opportunities to combine CLT production with heat, power, and biofuel production. As Sweden also aims to increase wood material use within both chemical and textile industries, it is recommended that CLT and EWP manufacturers explore industrial symbiosis opportunities with these sectors.

Higher levels of prefabrication and customisation of CLT panels is also recommended to reach higher economies of scope, as modular construction, reuse of materials at end-of-life, and more efficient construction processes are all important factors within Sweden. Like Cree by Rhomberg, vertically integrated business models which include CLT based building design, transport, and construction are recommended. Since rapid and sustainable construction of housing is needed in Sweden, integrated business models like this could satisfy environmental and social needs while also rolling out fast construction. If CLT manufacturing and design can also be integrated with this business model, then that is even more beneficial since fewer actors are involved and potential for error or supply chain hold-ups is reduced. Integrated systems could also offer consistent advising and consultation to building industry clients, making CLT part of attractive and streamlined environmental packages. Investment in new manufacturing and expansion of existing manufacturing is recommended lastly, as means to reach higher economies of scale and higher production capacities as mentioned by respondents.

8 Conclusion

CLT provides a highly attractive pathway for Sweden to reduce environmental impacts of its building sector. By transitioning to low-carbon and bio based materials, Sweden could reduce a wide range of negative environmental impacts (refer to sections 3.3 and 3.4). Increased CLT deployment could help Sweden shift to a bio based and circular economy, increase the value of its timber, and meet various pending targets. There are three main targets CLT would contribute to. First, CLT could help reach the Naturvårdsverket (SEPA) building sector goals of GHG emission reductions, waste reduction, elimination of hazardous materials, end-of-life material reuse, and densification of existing infrastructure to preserve green space (Naturvårdsverket, 2012). Next, CLT aligns with governmental goals for long-term sustainable structures, good indoor environments, and adoption of life-cycle perspectives for buildings. Lastly, the recent legal commitment to reach net-zero GHG emissions by 2045 will require the help of CLT and other low-carbon building materials, since it can replace concrete and steel which are heavily responsible for GHG emissions of the Swedish building sector.

The recommendations are suggested in a sequence of "programme phasing," which relies on three stages of informational measures, supportive incentives, and regulations. See Figure 8-1 for prioritised actions in each of these phases, based on the analysis of questionnaire responses. It is a pity that wood materials are not the default within Sweden, but these recommendations aim to support a transition towards such new building trends.

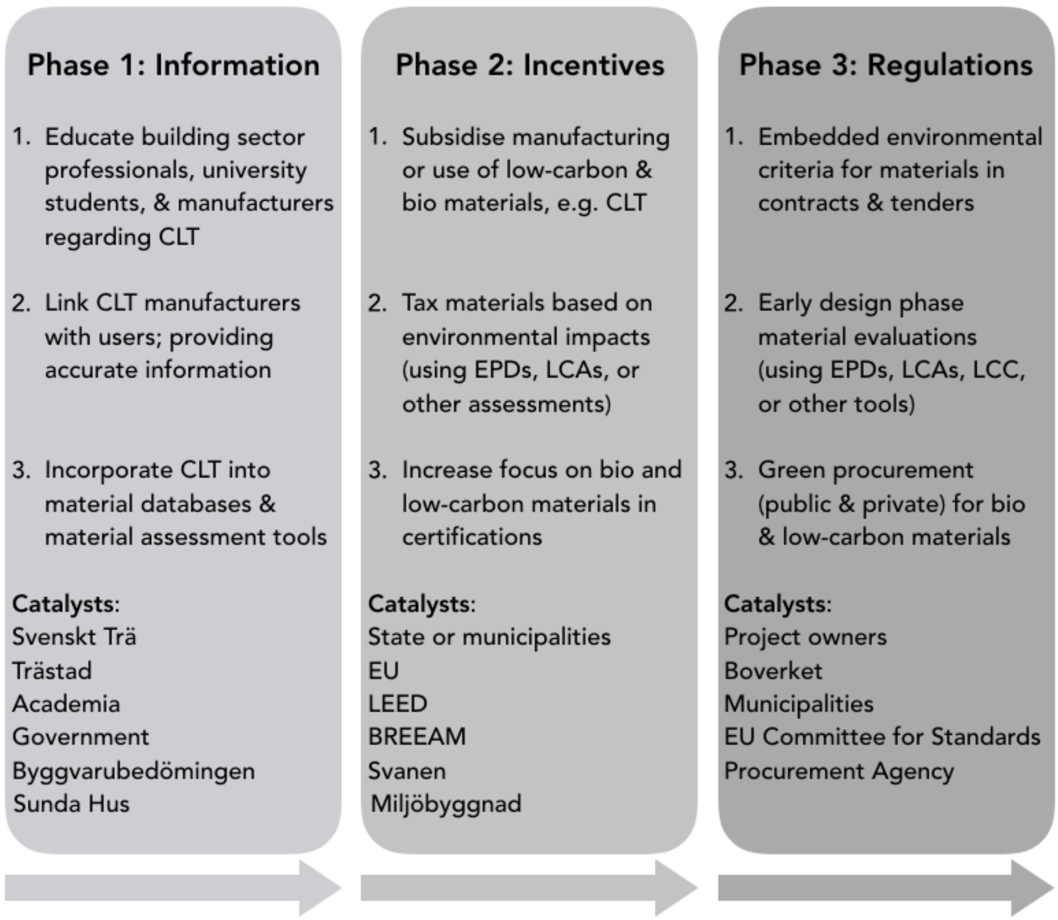

Figure 8-1. Programme phasing diagram with prioritised actions

Source: Own elaboration, adapted from Athens, 2012

Recommendations from respondents emphasised the importance of early design phase material assessment. Using environmental assessment tools, like EPDs, LCAs, and LCC, is highly recommended early in building design processes. Unfortunately, these material selection processes are driven mainly by costs and experience, so this is where owner requirements, certifications, building regulations, and other measures are suggested to be implemented. In parallel to these measures, cost reductions for CLT manufacturing and use could disrupt these habits of material selection and influence building industry actors to adopt CLT (also creating a more level playing field among building materials). Additionally, the three examples of CLT manufacturing best practices provided guidance for Sweden's growing CLT production industry. Examples of other sustainable technologies and CLT support tools added valuable external insights, which Sweden can learn and borrow from.

There are many opportunities for key building sector actors to implement measures which favour low-carbon and bio based building materials. This could trickle down and indirectly support CLT deployment. As staff of Boverket highlighted, there is still need to identify necessary policy levers and implementation methods to increase CLT deployment in Sweden. Hopefully, this research helped identify these leverage points and possible measures. One important development during the final revision of this research also poses an opportunity for Sweden. That is the unveiling of the new EC framework for sustainable building design and construction, titled Level(s). The voluntary framework was released September 2017 and aligns with many Swedish goals regarding resource efficiency, life cycle perspective of buildings, emission reductions from construction, use of bio based materials, and circular economy (Dodd et al., 2017). It is therefore recommended that Sweden's companies, associations, and municipalities register to test this framework and work to coordinate sector efforts among clients, design teams, construction companies, and other key actors.

It is in the best interest of actors from the Swedish government, timber industry, and building industry to support increased deployment of CLT in Sweden and abroad. As shown in Figure 8-2, increasing deployment of CLT could positively impact all three spheres of the triple bottom line. Increased deployment of CLT and similar EWPs would bring Sweden environmental benefits, new revenue and employment to the bio based timber industry, fast and low-carbon housing solutions, and new export opportunities. Environmental benefits of CLT could help the Swedish building sector reach environmental targets at municipal and state levels. It will also help associated sectors, such as the transport and energy sectors, reduce their negative environmental impacts via indirect emissions (see *Introduction*). With increased CLT production and use in Sweden, skilled jobs will be created in manufacturing, building design, and construction. If neighbouring countries also shift towards bio and low-carbon building materials, attractive export opportunities for Swedish CLT could develop. With needs for rapid housing construction and temporary housing to accommodate rising populations and refugees, CLT would also be a suitable technology in meeting those demands.

Figure 8-2. Triple bottom line diagram for CLT in Sweden

Source: Own elaboration

As CLT is just one emerging low-carbon and bio based building material, it is encouraged to also explore other building materials that could replace environmentally impactful materials, such as recycled materials and other bio materials. Since CLT is unlikely to completely replace all traditional building materials, it is recommended to increase hybrid building design so that materials are used as efficiently as possible (such as using minimal concrete for foundations or central lift cores). It is also vital to understand that CLTs environmental impacts are affected by many factors, such as the timber source, transportation, manufacturing energy amount and source, application, and forest management practices. For example, if CLT used in Sweden is manufactured domestically using local timber which is PEFC or FSC certified, then of course it would be an environmentally superior option to uncertified CLT imported from a distant country. Manufacturing practices, adhesives used, distance of transport, and other factors influence the environmental footprint of CLT, producing a range of products with varying environmental impacts – making it vital to have data regarding the entire value chain.

In conclusion, CLT is only one type of engineered timber panel, which are in turn only one type of low-carbon bio material. CLT was selected for this research as a proxy building material to represent low-carbon and bio materials, because of its relevance to Sweden. Factors such as the housing demand, abundant timber, ambitious environmental goals, strong public and private support of clean technologies, and developed industrial sector of Sweden were drivers for this decision. Recommendations were created with CLT in mind, but could be useful or adaptable for other building materials. While the CLT perspective is an interesting and relevant case study for Sweden, it is recommended that traditional building material companies work to reduce their environmental impacts while key building industry actors simultaneously shift to more use of emerging bio and low-carbon materials. Technology transitions take time, especially within the building sector, therefore the sequenced recommendations are aimed to steer and speed up adoption of CLT and other bio or low-carbon building materials in Sweden.

Critical reflections

Upon reflection, barriers from respondents generally matched those identified from literature. Thus, the research could have initially been more focused on how to boost drivers and support CLT deployment. Since key building industry actors were identified as project owners, architects, engineers, contractors, the national building authority Boverket, municipalities and their respective building companies, and certification bodies, these actors could have been targeted more as the ideal candidates for questionnaires. An initial interview, followed by follow-up interviews, could have yielded more results as well. Lastly, perspectives from forest owners and timber companies would have complemented and expanded this research.

Post-defence notes

Peers, IIIEE staff, and opponent Søren Lütken provided valuable feedback during the defence of this thesis. Regulatory pressure was identified as a key tool to drive the demand for knowledge and skills regarding CLT manufacturing and use. A transition to new building materials was recognised to potentially create a need for new construction skills, but also a void for existing skills that could become obsolete. Therefore, it is important to consider job loss and the effort to educate existing professionals within the construction industry. Financial disincentives, such as fees or taxes on embodied carbon, were determined to be a more suitable initial policy than subsidies. These disincentives could help the Swedish municipalities or state generate funds which could later be used to support subsidies or other post-disincentive measures. Lastly, the European Commission launched a building sector framework on 28-09-2017 called Level(s), which is a new tool for sustainable design and construction that Sweden could voluntarily test. This research was not associated with or supported by any funding, organisations, or companies. No conflicts of interest interfered with the research conducted.

9 Future research

Findings from the literature review and questionnaire responses suggest that studies specific to different disciplines could be useful in further establishing the legitimacy of CLT in the sector. For example, sustainable forestry scenarios applied to CLT for the Swedish building sector could help enhance understanding of forest management requirements and capacities. Economic feasibility studies for potential CLT manufacturers, clear architectural and engineering studies exploring new CLT applications, and further research on products, design, or services for fire resistance may also help legitimise CLT especially with the insurance sector.

Responses also suggested that technical qualities regarding seismic performance, weather resistance, moisture resistance, new applications, and maintenance still require further research and development. A respondent from Cree suggested further research on similar topics of fire safety, lifecycle benefits, design and use flexibility, maintenance, durability, and end-of-life scenarios for CLT. Respondents from Boverket stated that further technical information, improved methods of dissemination, and more focus on suitable policy levers to expand CLT deployment are areas for further research. These research areas suggest that a cooperation between Boverket and Svenskt Trä could be beneficial, since the latter organisation is already educating actors, providing technical guides, and aligning CLT information with regulations for wood grading and construction. A respondent from TU Graz also suggested further CLT research on connection systems, shell and spatial constructions, expanded spans, and new lightweight and hybrid hardwood applications. A respondent from Rambøll's Building department added that methods of educating and training contractors requires more research, as they are key influences on clients, architects, and engineers of building projects. Additional R&D is also needed for larger-spanning CLT to enter commercial and industrial segments, increasing the sophistication and flexibility of prefabrication, and re-densification applications where CLT is used as an addition to existing buildings.

In summary, further research is needed on identifying leverage points and policy instrument implementation. Research focused on how to create CLT of larger spanning sizes, for new applications, and with more sophisticated prefabrication is also recommended. Respondents also highlighted that more accurate and understandable technical and environmental data (EPDs, LCAs, LCC) is needed for CLT, to provide building material assessments. Further research on how to increase economies of scale, economies of scope, and reduce costs for CLT may also help increase deployment.

Bibliography

American Wood Council. (2012). Preliminary CLT Fire Resistance Testing Report. American Wood Council. Retrieved July 10, 2017, from http://www.awc.org/Code-Officials/2012-IBC-Challenges/Preliminary-CLT-Fire-Test-Report-FINAL-July2012.pdf

Antikainen, R., Dalhammar, C., Hildén, M., Judl, J., Jääskeläinen, T., Kautto, P., Koskela, S., Kuisma, M., Lazarevic, D., Mäenpää, I., Ovaska, J., Peck, P., Rodhe, H., Temmes, A. & Thidell, Å. (2017). Renewal of forest based manufacturing towards a sustainable circular bio economy. Finnish Environment Institute. ISBN 978-952-11-4684-8

Athens, L. (2012). *Building an Emerald City: a Guide to Creating Green Building Policies and Programs*. Washington DC: Island Press.

Atlee, J. (2011). Selecting safer building products in practice. *Journal of Cleaner Production 19*(5), 459-463. doi.org/10.1016/j.jclepro.2010.09.001

Barber, D., & Gerard, R. (2015). Summary of the fire protection foundation report - fire safety challenges of tall wood buildings. *Fire Science Reviews, 4*(1). doi:10.1186/s40038-015-0009-3

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B. & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions 16,* 51-64. doi.org/10.1016/j.eist.2015.07.003

Bohnsack, R., Pinkse, J., & Kolk, A. (2014). Business models for sustainable technologies: Exploring business model evolution in the case of electric vehicles. *Research Policy, 43*(2), 284-300. doi:http://dx.doi.org/10.1016/j.respol.2013.10.014

Botha, N. and Atkins, K. (2005). An assessment of five different theoretical frameworks to study the uptake of innovations. 2005 NZARES Conference.

Boverket. (2017). Construction Building Codes and Permits: current assignments. Retrieved July 10, 2017, from http://www.boverket.se/sv/byggande/uppdrag/

Brandner, R. (2013). Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report. *Focus Solid Timber Solutions - European Conference on Cross Laminated Timber (CLT),* 3-36. University of Bath.

Buck, D., Wang, A., Hagman, O., and Gustafsson, A. (2016). Bending Properties of Cross Laminated Timber (CLT) with a 45° Alternating Layer Configuration. *BioResources* (2), 4633. doi:10.15376/biores.11.2.4633-4644

Business Sweden. (2016). Bio economy in Sweden Sector Overview: Business opportunities in a bio economy growth market. The Swedish Trade & Invest Council. Retrieved July 25, 2017 from http://www.business-sweden.se/globalassets/invest-new/reports-and-documents/bioeconomy-in-sweden---sector-overview-2016.pdf

Cambiaso, F., Pietrasanta, M. (2014). Innovative timber construction: sustainability and high performance building skin. IA*CSIT International Journal of Engineering and Technology 6*(1), 47-54. DOI: 10.7763/IJET.2014.V6.664

CBI. (2016). CBI Product Factsheet: Cross Laminated Timber (CLT) Western Europe 2015. CBI Ministry of Foreign Affairs. Retrieved June 14, 2017, from https://www.cbi.eu/sites/default/files/market_information/researches/product-factsheet-western-europe-cross-laminated-timber-2016.pdf

Chen, C., Habert, G., Bouzidi, Y., & Jullien, A. (2010). Environmental impact of cement production: detail of the different processes and cement plant variability evaluation. *Journal of Cleaner Production, 18*(5), 478-485. doi:10.1016/j.jclepro.2009.12.014

Chen, Y. J., (2012). Comparison of Environmental Performance of a Five-storey Building Built with Cross-laminated Timber and Concrete. University of British Columbia, Department of Wood Science.

City of Stockholm. (2016). Stockholm Environment Programme 2016-2019. Retrieved June 21, 2017, from http://international.stockholm.se/globalassets/rapporter/the-stockholm-environment-programme-2016-2019.pdf

Dodd, N., Cordella, M., Traverso, M., & Donatello, S. Unit B5. (2017). Level(s) – A common EU framework of core sustainability indicators for office and residential buildings. European Commission Joint Research Centre. Retrieved October 2, 2017, from http://susproc.jrc.ec.europa.eu/Efficient_Buildings/docs/170816_Levels_EU_framework_of_building_indicators_Parts.pdf

Dodoo, A., Gustavsson, L., & Sathre, R. (2014). Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems. *Energy and Buildings, 82*, 194-210. doi:10.1016/j.enbuild.2014.06.034

Eastin, I. & Sasatani, D. (2016). Japan CLT Roadmap: Lessons for North America. UNECE Timber Market Committee Meeting UN Palais des Nations, Geneva. Oct. 19, 2016. Retrieved July 28, 2017 from https://www.unece.org/fileadmin/DAM/timber/meetings/20161018/coffi74-item3c-01-eastin.pdf

Ecorys. (2014). Resource efficiency in the building sector final report. Directorate-General for Environment European Commission. Retrieved June 28, 2017, from http://ec.europa.eu/environment/eussd/pdf/Resource%20efficiency%20in%20the%20building%20sector.pdf

Ehrlich, B. (2015). Wood, Concrete, and Steel – And Their Incomparable EPDs. *Environmental Building News (24),* 8. Aug. 2015. www.BuildingGreen.com

European Commission. (2014). Brussels, 1.7.2014 COM(2014) 445 final. Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions on Resource Efficiency Opportunities in The Building Sector. Retrieved June 19, 2017, from http://ec.europa.eu/environment/eussd/pdf/SustainableBuildingsCommunication.pdf

European Commission. (2012). *Innovating for sustainable growth: a bio economy for Europe*. Luxembourg: Publications Office of the European Union. https://publications.europa.eu/en/publication-detail/-/publication/1f0d8515-8dc0-4435-ba53-9570e47dbd51

European Commission. (2017). Sustainable buildings. Green growth and circular economy - Environment - European Commission. Retrieved June 28, 2017, from http://ec.europa.eu/environment/eussd/buildings.htm

European Environment Agency. (2016). Sweden Country Profile. More from less — material resource efficiency in Europe 2015 overview of policies, instruments and targets in 32 countries. Retrieved July 24, 2017 from https://www.eea.europa.eu/publications/more-from-less

Evans, L. (2013). Cross Laminated Timber: Taking Wood Buildings to the Next Level. *Engineering News Record,* Oct 14, 2013. Retrieved June 19, 2017, from http://www.rethinkwood.com/sites/default/files/Cross-Laminated-Timber-CEU.pdf

Fell, D. (2010). Wood in the human environment: Restorative properties of wood in the built indoor environment. PhD dissertation, University of British Columbia.

Formas. (2012). Swedish Research and Innovation Strategy for a Bio-based Economy. ISBN 978-91-540-6068-9. Retrieved June 24, 2017, from https://biobs.jrc.ec.europa.eu/sites/default/files/generated/files/policy/Strategy_Biobased_Economy.pdf

FPInnovations (2013). CLT Handbook U.S. Edition. FPInnovations, Montreal, Canada. ISBN 978-0-86488-553-1. Retrieved May 17, 2017, from www.fpinnovations.ca

Frangi, A., Fontana, M., Hugi, E., Joebstl, R. (2009). Experimental analysis of cross-laminated timber panels in fire. *Fire Safety Journal 44*(8), 1078-1087.

Gallagher, K. S., Grübler, A., Kuhl, L., Nemet, G., & Wilson, C. (2012). The Energy Technology Innovation System. *Annual Review of Environment and Resources, 37*(1), 137-162. doi:10.1146/annurev-environ-060311-133915

Garud, R. and Gehman, J. (2012). Metatheoretical perspectives on sustainability journeys: Evolutionary, relational and durational. *Research Policy 41,* 980-995. doi:10.1016/j.respol.2011.07.009

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*(1), 24-40. doi:10.1016/j.eist.2011.02.002

Giama, E., & Papadopoulos, A. M. (2015). Assessment tools for the environmental evaluation of concrete, plaster and brick elements production. *Journal of Cleaner Production, 99*, 75-85. doi:10.1016/j.jclepro.2015.03.006

Giesekam, J., Barrett, J. R., & Taylor, P. (2016). Construction sector views on low carbon building materials. *Building Research & Information, 44*(4), 423-444. doi:10.1080/09613218.2016.1086872

Hagbert, P., Mangold M., and Femenías P. (2013). Paradoxes and Possibilities for a 'Green' Housing Sector: A Swedish Case. *Sustainability,* 5.5, 2018-035. Web.

Hammond, G.P., Jones, C.I., 2008. Embodied energy and carbon in construction materials. Proc. Institut. Civ. Eng. *Energy 161(2),* 87-98.

Harris, R. (2015). Cross laminated timber. 141-167. doi:10.1016/b978-1-78242-454-3.00008-1

Harte, A. M. (2016). Mass timber - the emergence of a modern construction material. Civil Engineering Research in Ireland Conference (CERI 2016). NUI Galway.

Horswill, D. and Nielsen, T. (2016). Can CLT Construction Help Copenhagen Become the World's First Carbon Neutral City? *Structures and Architecture – Cruz (Ed),* 153-160. ISBN 978-1-138-02651-3

Horx-Strathern, O., Varga, C., & Guntschnig, G. (2017). The future of Timber Construction CLT – Cross Laminated Timber: A study about changes, trends and technologies of tomorrow. Zukunftsinstitut Österreich GmbH. Retrieved October 4, 2017 from http://www.clt.info/wp-content/uploads/2017/06/Stora-Enso-The-future-of-timber-construction-EN.pdf

International Building Code. (2012). Chapter 7: Fire-resistance-rated Construction. International Code Council. Retrieved June 18, 2017, from http://www2.iccsafe.org/states/newjersey/nj_building/pdfs/nj_bldg_chapter7.pdf

IBO. (2011). IBO-Guidelines to calculating the OI3 indicators for buildings. Version 2.2, June 2011. IBO – Austrian Institute for Healthy and Ecological Building. Retrieved June 29, 2017 from http://www.ibo.at/documents/OI3-LeitfadenV22_06_2011_english.pdf

IPW. (2017). Stora Enso invests in cross-laminated timber (CLT) production in Grüvon, Sweden. Retrieved August 2, 2017 from http://www.ipwonline.de/ipw/Home/News/11417

John, S., Nebel, B., Perez, N., & Buchanan, A.H. (2009). Environmental Impacts of Multi-Story Buildings Using Different Construction Materials. Report. Department of Civil and Natural Resources Engineering. University of Canterbury, Christchurch, New Zealand.

Jones, K., Stegemann, J., Sykes, J., & Winslow, P. (2016). Adoption of unconventional approaches in construction: The case of cross-laminated timber. *Construction and Building Materials, 125*, 690-702. doi:10.1016/j.conbuildmat.2016.08.088

Khasreen, M., Banfill, P., & Menzies, G. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability*, *1*, 674-701. doi:10.3390/su1030674

King, W. (1996). Adoption and diffusion research in marketing: an overview. In: Proceedings. Fall Conference. American Marketing Association, 665-684.

KLH. (2013). Environment and Sustainability. Version 01/2013. Retrieved June 28, 2017, from http://www.klh.at/en/download/public/Kreuzlagenholz/KLH_Environment_and_Sustainability_en.pdf

Kubba, S. (2012a). Chapter 3 - Green Design and the Construction Process *Handbook of Green Building Design and Construction* (pp. 105-144). Boston: Butterworth-Heinemann.

Kubba, S. (2012b). Chapter 5 - Building Information Modelling *Handbook of Green Building Design and Construction* (pp. 201-226). Boston: Butterworth-Heinemann.

Laguarda Mallo, M. F., & Espinoza, O. (2015). Awareness, perceptions and willingness to adopt Cross-Laminated Timber by the architecture community in the United States. *Journal of Cleaner Production, 94*, 198-210. doi:10.1016/j.jclepro.2015.01.090

Larsson, Nils. (2009). The Integrated Design Process; History and Analysis. International Initiative for a Sustainable Built Environment (iiSBE). Retrieved Sep. 8, 2017 from http://www.iisbe.org/system/files/private/IDP%20development%20-%20Larsson.pdf

Latour, M., & Rizzano, G. (2017). Seismic behaviour of cross-laminated timber panel buildings equipped with traditional and innovative connectors. *Archives of Civil and Mechanical Engineering, 17*(2), 382-399. doi:10.1016/j.acme.2016.11.008

Legal & General (2017). Legal & General Modular Homes: Our Vision. Retrieved August 23, 2017 from https://www.legalandgeneral.com/modular/our-vision/

Lütken, S. & Wretlind, P.H. (2016). City Based Carbon Budgets for Buildings. UNEP DTU Low Carbon Development Programme Partnership. May, 2016.

Maia de Souza, D. Lafontaine, M., Charron-Doucet, F., Chappert, B., Kicak, K., Duarte, F., & Lima L. (2016). Comparative life cycle assessment of ceramic brick, concrete brick and cast-in-place reinforced concrete exterior walls. *Journal of Cleaner Production, 137,* 70-82. doi.org/10.1016/j.jclepro.2016.07.069

Mahlum, Walsh Construction Co., & Coughlin Porter Lundeen. (2014). CLT feasibility report: A study of alternative construction methods in the pacific northwest. Retrieved August 9, 2017 from http://www.seattle.gov/dpd/cs/groups/pan/@pan/documents/web_informational/p2174864.pdf

Malakahmad, A., Kok, J., & Gardezi, S. (2016). Carbon footprint reduction in building construction by less usage of ore-based materials. Proceedings of the International Conference on Civil, Architectural, Structural and Constructional Engineering, Dong-A University, Busan, South Korea, August 21-23, 2015. 179-183. doi:10.1201/b19961-41

MarketLine. (2016). Industry Profile: Construction in Sweden January 2016. Retrieved June 16, 2017, from *Business Source Complete*, EBSCO*host.*

McCormick, K., Anderberg, S., Coenen, L., & Neij, L. (2013). Advancing Sustainable Urban Transformation. *Journal of Cleaner Production, 50*, 1-11. DOI: 10.1016/j.jclepro.2013.01.003

McCormick, K., & Willquist, K. (2015). The Bio economy: An Introduction to the World of Bioenergy. Lund University. ISBN: 978-91-87357-17-6

Melton, P. (2012). LEED in Public Buildings Sparks Private-Sector Demand. *Environmental Building News (21),* 12. Dec. 2012. www.BuildingGreen.com

Ministry of Foreign Affairs Finland. (2010). The international promotion of wood construction as a part of climate policy: Working Group Report. Retrieved July 25, 2017 from http://formin.finland.fi/public/download.aspx?ID=73389&GUID={4A54694C-4244-4D67-8909-EDB5724153C6

Muszynski, L., Hansen, E., Geisel, J., Fernando, S., Schwarzmann, G., Rainer, J. (2016). The Global CLT Industry: Preliminary Results, 2016. *Solutions Forest Business, 14*(4). Oregon State University Wood Science & Engineering Department.

Naturvårdsverket. (2016). 15. A Good Built Environment. Miljömål.se – om hur miljön mår och arbetet med Sveriges miljömål går. Retrieved June 28, 2017, from http://www.miljomal.se/Environmental-Objectives-Portal/Undre-meny/About-the-Environmental-Objectives/15-A-Good-Built-Environment/

Naturvårdsverket. (2012). Sweden's environmental objective – An Introduction. Swedish Environmental Protection Agency. ISBN 978-91-620-8620-6

Neij, L., Bulkeley, H., & McCormick, K. (2015). Cities and climate change: The great decarbonisation challenge. Climate in Focus (pp. 1-4). Retrieved July 11, 2017 from http://portal.research.lu.se/ws/files/6410449/8194692.pdf

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology, 21*(3), 572-592. doi:10.1111/jiec.12586

Öqvist, R., Ljunggren, F., & Ågren, A. (2012). On the uncertainty of building acoustic measurements – Case study of a cross-laminated timber construction. *Applied Acoustics 73*, 904–912.

Oscarsson, J. (2016). Production of CLT in Southern Sweden. *Smart Housing Småland.* Retrieved July 2, 2017, from http://smarthousing.nu/en/projekt/production-of-clt-in-southern-sweden/

Palm, A. (2017). Residential solar photovoltaics deployment: barriers and drivers in space Lund: IIIEE, Lund University. ISBN 978-91-7753-123-4

Peñaloza, D. (2017). The role of bio based materials in the climate impacts of construction: Effects of increased use of bio based materials in the Swedish building sector. Doctoral Thesis, KTH Royal Institute of Technology. ISBN 978-91-7729-418-4

Popovski, M., Karacabeyli, E. (2012). Seismic behaviour of cross-laminated timber structures. World Conference on Earthquake Engineering 15, 1-10.

Rai, V., Reeves, D. C., & Margolis, R. (2016). Overcoming barriers and uncertainties in the adoption of residential solar PV. *Renewable Energy, 89*, 498-505. doi:http://dx.doi.org/10.1016/j.renene.2015.11.080

Rebane, K., & Reihan, A. (2016). Promoting building materials that have lower embodied carbon and energy in public procurements. *Management of Environmental Quality: An International Journal, 27*(6), 722-739. doi:10.1108/MEQ-07-2015-0154

Reportlinker. (2016). Construction in Sweden - Key Trends and Opportunities to 2020. Retrieved June 16, 2017, from http://www.prnewswire.com/news-releases/construction-in-sweden--key-trends-and-opportunities-to-2020-300370169.html

ReThink Wood. (2014). Green Building and Wood Products. *Architectural Record, June 2014*. Retrieved August 25, 2017 from http://www.awc.org/pdf/education/gb/ReThinkMag-GB100A-GreenBuildingWoodProducts-150501.pdf

Robertson, A.B., Lam, F.C., & Cole, R.J. (2012). A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete. *Buildings 2*(3), 245-270.

Rogers, E. M., & Shoemaker, F. (1983). Diffusion of innovation: A cross-cultural approach. Third Edition. *New York*. ISBN 0-02-926650-5

Roh, S., Tae, S., Suk, S. J., & Ford, G. (2017). Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea. *Renewable and Sustainable Energy Reviews, 73*, 135-144. doi:10.1016/j.rser.2017.01.081

Rotmans, J., Kemp, R., & van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight, 3*(1), 15-31. doi:10.1108/14636680110803003

Royal Swedish Academy of Agriculture and Forestry. (2015). Forests and Forestry in Sweden. Retrieved on June 23, 2017, from https://www.skogsstyrelsen.se/globalassets/in-english/forests-and-forestry-in-sweden_2015.pdf

SABO. (2008). SABO Companies Moving Towards 2020 – creating value for municipalities, housing areas and tenants. Retrieved on July 20, 2017 from http://www.sabo.se/om_sabo/english/Documents/SABO%20companies%20moving%20towards%202020%20%E2%80%93%20creating%20value%20for%20municipalities,%20housing%20areas%20and%20tenants.pdf

Salazar, J., Meil, J. (2009). Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. *Journal of Cleaner Production, 17*(17), 1563-1571.

SCB. (2017). Greenhouse gas emissions increased during all quarters of 2016. Statistika Centralbyrån. Retrieved June 27, 2017, from http://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/environmental-accounts-and-sustainable-development/system-of-environmental-and-economic-accounts/pong/statistical-news/environmental-accounts--emissions-to-air-q4-2016/

Schickhofer, G., Flatscher, G., Ganster, K., Sieder, R. & Zimmer, S. (2017). A Status Report from the CLT Hotspot in Europe: Austria. Institute of Timber Engineering and Wood Technology, Graz University of Technology. Sola City Conference, Tokyo, Japan. March 21, 2017.

Schlanbusch, R. D., Fufa S. M., Häkkinen T., Vares S., Birgisdottir H., & Ylmén P. (2016). Experiences with LCA in the Nordic Building Industry – Challenges, Needs and Solutions. *Energy Procedia,* 96, 82-93. Web.

Spickler, K. (2014). 5 myths about cross-laminated timber: A CLT expert clears up several common misconceptions and myths surrounding the use of wood as a building material. *Building Design & Construction, February 2014.* Retrieved August 8, 2017 from http://editiondigital.net/publication/?i=195063#{"issue_id":195063,"page":24}

Spiegel, R. & Meadows, D. (2012). Green Building Materials: A Guide to Product Selection and Specifications. 3rd Edition. ISBN 978-0-470-53804-3

Staube, J. F. & Burnett, E. F. P. (2005). *Building Science for Building Enclosures.* Building Science Press, Westford, MA, United States. ISBN 978-0-975-51274-6

Steinhilber, S., Wells, P., & Thankappan, S. (2013). Socio-technical inertia: Understanding the barriers to electric vehicles. *Energy Policy, 60*, 531-539. doi:http://dx.doi.org/10.1016/j.enpol.2013.04.076

Stora Enso. (2017a). Approvals & Documents: Technical Applications (CLT). Retrieved July 11, 2017, from http://www.clt.info/en/media-downloads/approvals-documents/technical-applications/

Stora Enso. (2017b). Capacities by mill in 2017. Retrieved July 19, 2017 from http://annualreport.storaenso.com/2016/capacities-by-mill-in-2017/

Sworder, C. Salge, L. Van Soest, H. (2017). The global cleantech innovation index 2017. World Wide Fund for Nature. Retrieved June 27, 2017, from citationmachine.net/items/confirm

Thormark, C. (2006). The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment, 41*(8), 1019-1026. doi:10.1016/j.buildenv.2005.04.026

Toppinen, A., Röhr, A., Pätäri, S., Lähtinen, K., & Toivonen, R. (2017). The future of wooden multi-storey construction in the forest bio economy – A Delphi study from Finland and Sweden. *Journal of Forest Economics.* doi:10.1016/j.jfe.2017.05.001

United Nations. (2016). SDG 11 Sustainable Cities and Communities. Retrieved July 1, 2017, from http://www.un.org/sustainabledevelopment/wp-content/uploads/2016/08/16-00055K_Why-it-Matters_Goal-11_Cities_2p.pdf

United Nations Environment Programme. (2016). The 10YFP Programme on Sustainable Buildings and Construction. Retrieved July 2, 2017, from http://www.scpclearinghouse.org/sites/default/files/10yfp-sbc-brochure-en.pdf

Växjö Kommun. (2013). Växjö the modern wooden city: Växjö Municipality's Wood Construction Strategy. Approved by Växjö Municipal Council, 26 August 2013-08-26. Retrieved on August 8, 2017 from http://www.vaxjo.se/upload/www.vaxjo.se/Kommunledningsf%C3%B6rvaltningen/H%C3%A5llbarhetsgruppen/Milj%C3%B6dokument%20och%20broschyrer/Tr%C3%A4bygnadsstrategi_ENG_webb.pdf

Wang, L., & Ge, H. (2016). Hygrothermal performance of cross-laminated timber wall assemblies: A stochastic approach. *Building and Environment, 97*, 11-25. doi:10.1016/j.buildenv.2015.11.034

Wang, L., Toppinen, A. & Juslin, H. (2014). Use of wood in green building: a study of expert perspectives from the UK. *Journal of Cleaner Production*, *65*, 350-361. doi.org/10.1016/j.jclepro.2013.08.023

Wijkman, A. & Skånberg, K. (2016). The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency. Club of Rome. Retrieved July 2, 2017, from https://www.clubofrome.org/wp-content/uploads/2016/03/The-Circular-Economy-and-Benefits-for-Society.pdf

Wilmott Dixon. (2010). Briefing Note 33: The Impacts of Construction and the Built Environment. WD-Rethinking Ltd. Retrieved July 1, 2017, from https://www.willmottdixon.co.uk/asset/9462/download

Winter, W., Tavoussi Tafreshi, K., Fadai, A. & Pixner, T. (2010). Development of wood based sustainable construction methods for high-rise buildings under lateral loading. *High Rise Towers Tall Buildings*, 1-8.

WoodWorks. (2014). Multi-Story Wood Construction: A cost-effective and sustainable solution for today's changing housing market. *Engineering News-Record,* March 26, 2012; Updated February 2014. Retrieved June 28, 2017, from http://www.awc.org/pdf/education/des/ReThinkMag-DES515A-MultistoryWoodConstruction-140210.pdf

Wu, P., Feng, Y., Pienaar, J., & Xia, B. (2015). A review of benchmarking in carbon labelling schemes for building materials. *Journal of Cleaner Production, 109*, 108-117. doi:10.1016/j.jclepro.2015.07.067

WWF. (2011). Enabling the transition: Climate innovation systems for a low-carbon future. World Wildlife Fund for Nature. ISBN 978-91 89272-19-4

WWF. (2013). Urban solutions for a living planet. World Wildlife Fund for Nature. Retrieved June 28, 2017, from http://www.wwf.se/source.php/1491525/Urban%20solutions_summary_2013.pdf

Yost, P. & Melton, P. (2012). Setting Carbon Footprint Rules for Concrete. *Environmental Building News (21),* 11. Nov. 2012. www.BuildingGreen.com

Zygomalas, I., Kaziolas, D., Stavroulakis, G., & Baniotopoulos C. (2016). Quantification of the influence of life cycle parameters on the total environmental impact of steel-framed buildings. *International Journal of Sustainable Engineering (9)5*, 329–337. http://dx.doi.org/10.1080/19397038.2016.117835

Appendix A: Questionnaire guide

1. What are the main barriers preventing wider deployment of cross-laminated timber (CLT) in the Swedish building sector?

2. Which building sector actors are most influential or important for increasing the deployment of CLT in the Swedish building sector?

3. How does CLT compare to other building materials from your professional perspective, for example regarding environmental impacts, cost, availability, technical properties, and other factors?

4. What might influence key building sector actors to focus more on the building material selection process and transition to using more low-carbon and bio based materials, such as CLT?

5. What are the significant leverage points where measures are necessary to support low-carbon and bio based materials, such as CLT?

6. What could help increase CLT deployment in the Swedish building sector?

Note: Summarised responses are compiled in the matrix in Appendix B. Complete questionnaire responses were received via email and are available from the author upon request in Word or PDF format.

Appendix B: Questionnaire response matrix

Classification	Name & title	Organisation	Barriers	Key actors	Drivers	Comparison	Suggestions
CLT manufacturing	*Technical Manager*	*Martinsons*	• Moisture during construction • Fire standards • Final cost	• End users • Construction companies	• Environmental concern • Developing market demand • Promise due to geometric & technical properties	• Similar regarding technical properties • Close price & availability • Environmentally superior	• Early building process evaluations • Authority requirements • Evaluation of environmental impacts of materials
	Jessika Szyber Business Development Manager of Building Solutions	*Stora Enso*	• BBR classification of wood • BBR not allowing visible wood • Lack of knowledge • Panel thicknesses • Additional risks	• Constructors • Contractors • Municipalities • Project developers & private owners	• Low cost • Key in modular systems • Efficient construction • Fast project ROI	• Cost effective • Better thermal properties • Less transport & on-site construction • Light weight & reduced foundation • Little waste • Little noise & site disruption	• LCAs at early project phase • Free tools • New product development • Increased domestic production • Regulation solutions
Construction	*Group Manager for the Structures Department*	*Sweco*	• Lack of knowledge • Low architect-specific knowledge • Uncertainty • Early design phase inconsideration • Wall thickness • Uncertain lifespan	• "Single players" • Architects • Clients • Early designers	• Environmental focus • Increasing demand in Sweden • Companies with wood construction goals • New wood application • Applicability to multi-story	• Faster delivery & construction time • Lower costs (1/2 of prefab concrete) • Lighter weight for transport ease • Lower environmental (LCA) impacts • CLT young compared to steel & concrete	• Increased awareness & knowledge • Incorporation early in design process • More producers • More project examples
	Head of CSR	*Vasakronan*	• Narrow mind-set of decision makers	• Residential segment • Commercial	• Debate of non-renewable materials	• Low environmental impacts	• Increased focus on full lifecycle

			• Unwillingness to use new, unproven materials • Limitations of CLT spans & sizes • Fire safety • Moisture & mould • Acoustics	segment important for future	• Growing numbers of good examples	• Similar costs • Faster construction time & ROI • Different design possibilities • Different acoustics	environmental impacts of buildings • Expanded POV beyond operational efficiency • Commercial projects • More materials focus in certification schemes (e.g. LEED and BREEAM)
Municipality	*Construction Manager*	*Lund Municipal Building Company (LKF)*	• N/A	• Modular home manufacturers	• Communication of environmental advantages • Competitive price • Long-term sustainability • Environmental impacts	• N/A	• Communication of price advantages • Quality assurance • Environmental requirements for new building materials
Government	*Managers of Sustainable Buildings & Products*	*Boverket (National Swedish Building Authority)*	• Poor information distribution • Lack of technical information • Path dependencies • Lack of skills & experience • Regulations misaligned to traditions (wood ban)	• Builders • Clients • Wood industry	• Controlled & industrialised manufacturing • Efficient construction • Minimal waste • Building certifications • Environmental policies & requirements	• Requires extra focus on: fire safety, acoustics, & moisture • More consideration of building location	• Project leader environmental policies • Requirements of environmental classification systems, i.e. SGBC • Public procurement requirements • Owner directives • Low-waste construction • Industrialised construction • Lower costs

Associations	*Head of Swedish Forest Policy*	*Swedish Forest Industries Federation*	• N/A	• Forest owners • Timber industry	• Forest owners desire to increase timber value • Increasing sector interest • Big industry actors Stora Enso's & Martinson's new CLT mills pressuring others	• Ideal product to increase utilisation of sawn timber	• N/A
	Mikael Eliasson Head Director (& additional staff)	*Svenskt Trä*	• Low capacity & finances of timber companies • Limited industry interest • Lack of knowledge • Maintenance requirements • Uncertainty	• Forest owners • Timber companies • R&D foundations • Civil engineers & architects	• Climate perspective • Population growth • Increases in high-rise building • Abundant timber • Factory production • Efficient transport & on-site construction	• Faster construction • More prefabrication	• Increased production capacity • Increased standardisation • Aligned regulations • Education of professionals & students • Seminars • Handbooks
Certifications	*Evelina Strandfeldt Policy & Marketing Manager*	*Swedish Green Building Council*	• N/A	• Building material databases, i.e. Sunda Hus or Byggvarubedömi ngen	• Inclusion of CLT products & building methods in certain databases	• N/A	• Increased recognition of CLT products & methods in building material databases • Add CLT to environmental assessment tools

								for construction
Architecture	*Mikael Stenqvist Architect SAR/MSA*	*Tham & Videgård Architecture*	• Low availability in South Sweden • Can have long transport times • Fire safety difficulties in multi-story buildings	• Policy makers	• Low cost • Good aesthetics & “feel” • Generally good availability • Design flexibility • Adoptability	• N/A	• CO_2 emissions legislation • Life-cycle costing • Energy policies for new building entire lifespans • Local production & expertise
	Fredrik Furrer Architect & MSc in Sustainable Urban Design	*Lund University*	• Low experience in construction • Low knowledge among industry • Need example projects • Use of adhesives	• Large developers • Municipalities • Policy makers	• Increasing life-cycle focus of architecture firms • Abundance of low-value timber	• Adhesives could be weakness, if detrimental to IEQ • Can utilise wood species which are most cheap or abundant	• Decrease capital & long-term costs compared to other materials • Minimise dimensions (if thickness is issue) • Easier fire protection measures • Municipal policies • Labels for Swedish sourced & manufactured products

Research & Academia	*Diego Peñaloza PhD researcher*	*Research Institute of Sweden (RISE): Built Environment*	• Conservative sector • Economic dominance of concrete • Doubts • Fire safety • Insurance related costs	• Large building companies, i.e. • Skanska • Vasakronan • Riksbyggan • NCC	• Housing crisis • Needs for rapid construction	• Lower environmental impacts • Prefabrication potential • Fast & simple construction	• Low-carbon requirements in Boverket building regulations • Increased use of EPDs • Commissioned projects from construction companies
	Erik Serrano Director of Structural Mechanics	*LTH Lund University*	• Slow recovery from Swedish ban on wood in construction • Path dependencies	• N/A	• Performance-based code (EU) • Growing focus on climate change • Sustainable forestry practices	• Carbon storage • Can be sourced from sustainably managed forests • Equivalent safety levels (loads, fire, seismic, etc.)	• N/A
	Tomas Nord Researcher & Professor of Industrial Development & Economics	*Linköping University*	• Lack of knowledge • Low use by engineers, contractors, & architects • Procured as single product, not system • Needs standardisations for meeting acoustics, strength, safety requirements	• Clients • Engineers • Architects	• Rising consumer demands • Climate risks • No negative health impacts	• Better environmental performance • Demand exceeding capacity in Sweden • Good weight to strength ratio • Comparable costs	• Increase information • Guide usage • Increase engineer & architect knowledge • CLT courses • More projects • Increase availability • Mimicry of existing building systems • More cost

			• Cost • Technical difficulties with energy buffering, flank transmission, & 10+ story weight				research
Actors from outside of Sweden							
Category	**Name**	**Job title**	**Barriers**	**Key actors**	**Drivers**	**Comparison**	**Suggestions**
Academia	*Brent Lawrence Graduate Researcher Wood & Science Engineering*	*Oregon State University*	• Scepticism in business & public community • Perceived fire risk • Perceived seismic risk among architects & engineers • Low demand • Lack of trained professionals	• CLT producers • Private investors • Government • Building authorities • Architects • Engineers	• Technical research • Timber innovation building acts	• N/A	• GPP • Loans & finance tools for producers • Training
Associations	*Researcher & member of LCA Alliance*	*University of British Columbia & LCA Alliance*	• N/A	• Municipalities (e.g. Provinces of British Columbia & Quebec "Wood First Act" & "Chartre du Bois" policies)	• Accessible, accurate and inexpensive tools to evaluate environmental impacts of materials • Eco-design	• Significant embodied energy, but much can be recovered at end of life	• Use existing tools, such as Tally, Green Globes, Athena, and BEES • Better understanding of material selection in building design process

	Timm Locke Director of Forest Products	*Oregon Forest Resources Institute (OFRI)*	• Lack of understanding • Lack of information • Few manufacturers • Costly labour • Low market demand • Lack of labour • Perceived limitations of timber supply • Under-developed supply chain	• Industry associations & educators • Building material procurers • Government & building authorities • Manufacturers	• Municipal and city-level initiatives • Education of industry actors • Fast • Low cost	• From renewable resource • From low-quality, damaged, and abundant wood species • Precisely prefabricated	• N/A
Construction	*Lars Riemann Executive Director of Buildings Department*	*Ramboll Global*	• Subjected to fewer tests • Viewed as less durable than non-organic materials • Perceived fire risks • Limited spans • Material selections are conservative to avoid risk & liability	• Contractors (influence on architects & engineers) • Fire authorities • Research institutions • Clients & owners • Policy makers & code officials	• Expected cost decreases due to economies of scale & design • Expected increase in applicability & spans • Hybrid designs	• Carbon storage • Indoor environmental quality • Renewable • Same or higher cost	• Universities & institutes testing & recommending • Building codes prescribing low-carbon & bio based materials as default
	Principal Structural Engineer	*Ramboll UK*	• Limited applicability	• Suppliers (suggested) • End-users (suggested)	• Competitive cost • Many suppliers offering various products	• Comparable costs • Widely available • Lower carbon	• Increased suppliers providing range of products and

					• Expanding to new applications	footprint	different prices • LCAs, embodied energy, or embodied carbon considered at early design stage
	Director of Technical Operations	*Cree by Rhomberg*	• Consumer reservations & uncertainty • Debate over performance concerning: fire safety, durability, maintenance, sustainability • Complex decision making process	• N/A	• High potential for prefabrication • Opportunities to further digitalise manufacturing, design, & construction	• N/A	• Tools to simplify & guide material selection • More business models combining renewable materials, prefabrication, building design & construction

Appendix C: Questionnaire result graphs

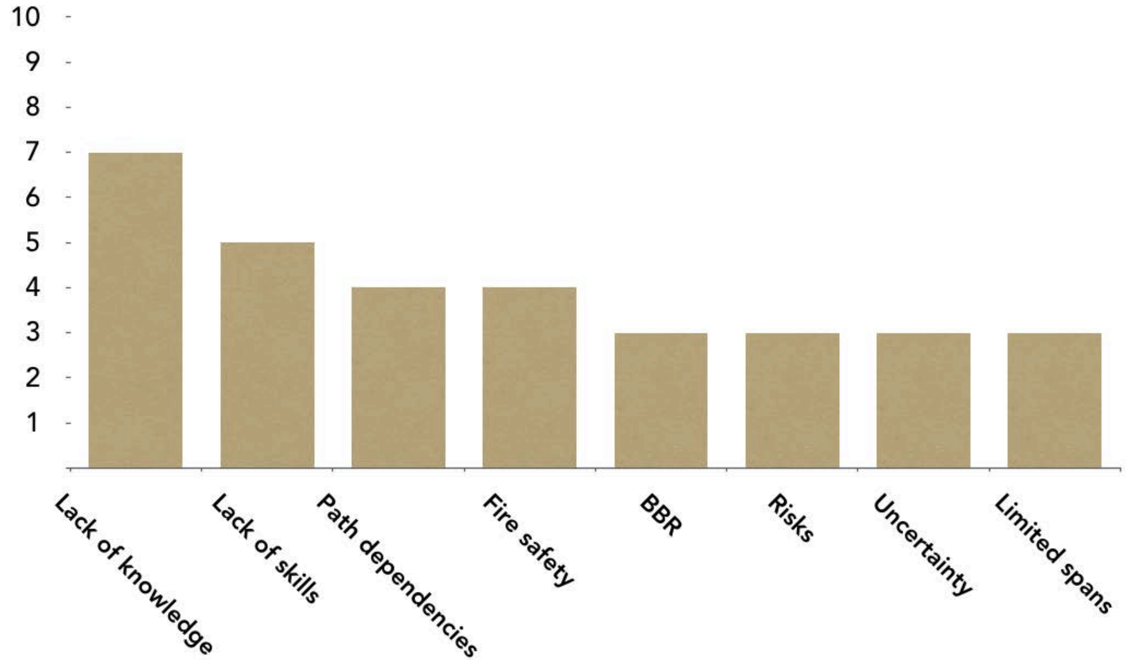

Figure I. Respondent results regarding barriers of CLT deployment

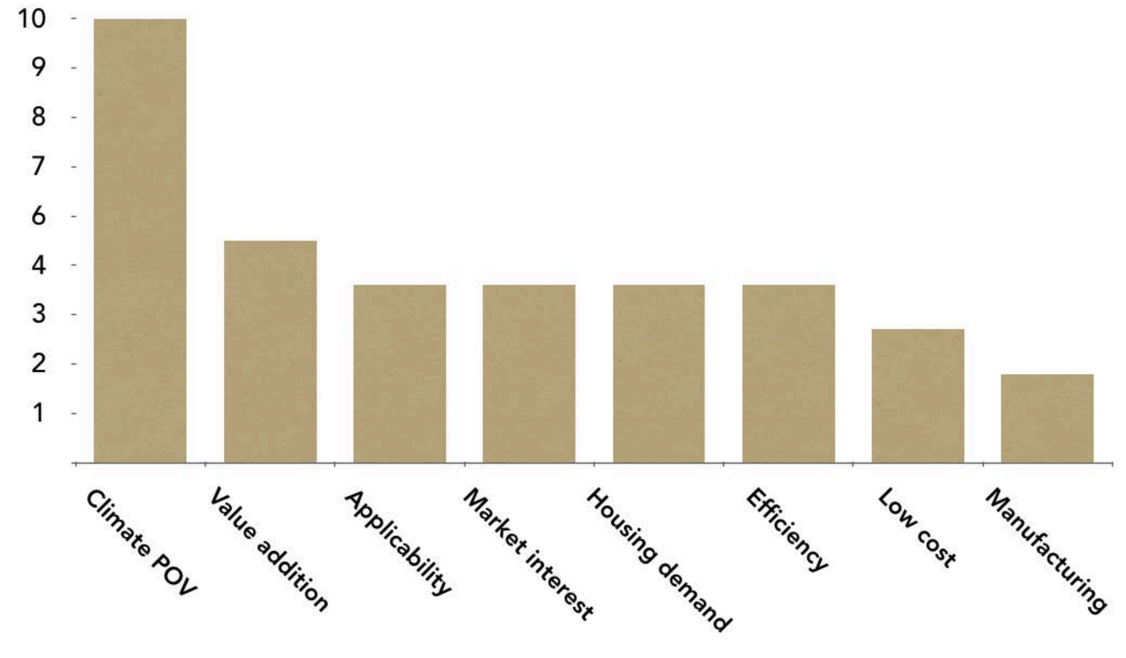

Figure II. Respondent results regarding drivers for CLT deployment

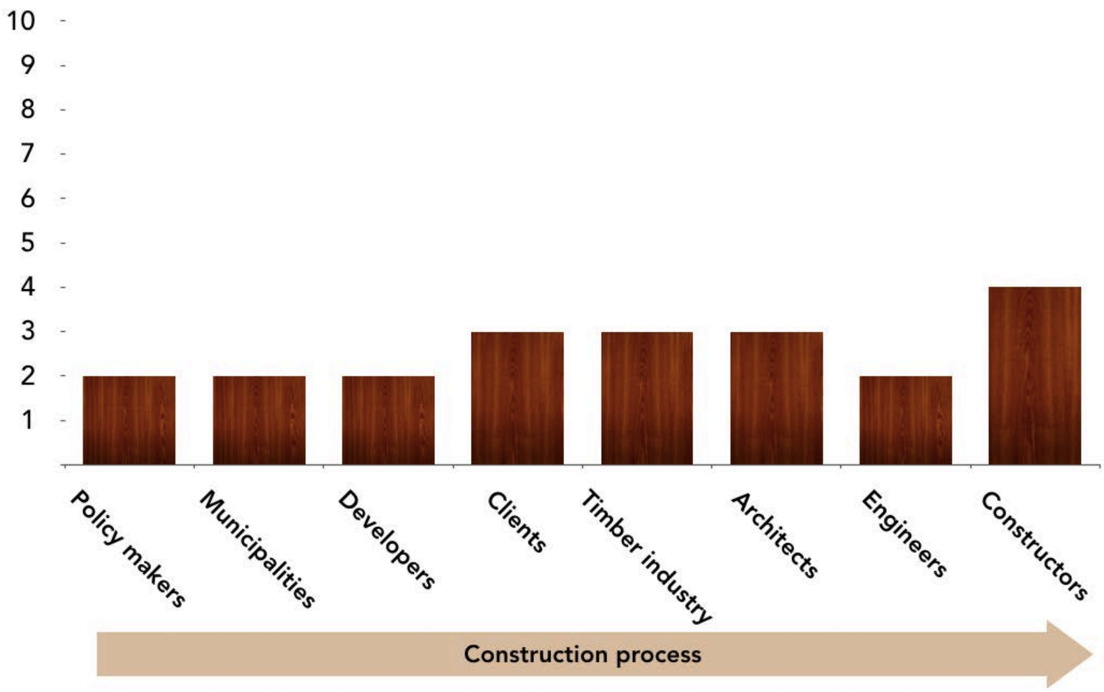

Figure III. Respondent results regarding key actors of CLT deployment

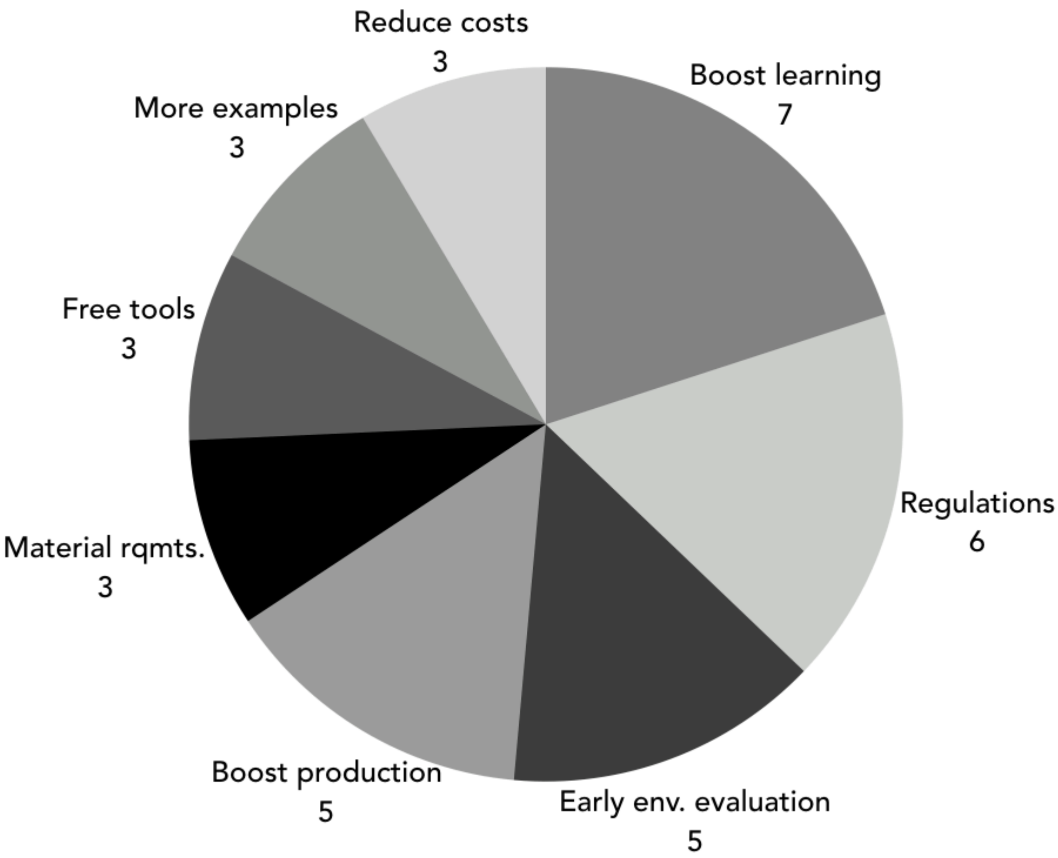

Figure IV. Respondent results regarding suggestions to increase CLT deployment