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# Economic assessment of a wood building: Life Cycle Cost and Stakeholders' Decision-Making

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**Abstract of master's thesis**

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**Abstract**

The strong trend in urbanization and population growth rises building construction demand following with increased contribution to the global environmental impact. Wood construction is considered to be a key solution to future cities with greater environmental performance and it has the highest potential of meeting all three sustainability criteria, including environmental, social and economic benefits. Therefore, the question of cost-efficiency of wood buildings as the main alternative to traditional construction to combat climate change is at the front of construction development.

The aim of this thesis is to assess economic efficiency of a wood building and add to the literature related to the economic optimization strategy of modern wood construction. In order to get deeper knowledge of wood construction development, the thesis examines the construction industry key stakeholders' decision-making aspects.

The thesis proposes a research methodology based on the integration of two approaches. First, Life Cycle Cost (LCC) assessment method is performed on the case of a wood building to demonstrate the impact of different cost indicators on building's economic efficiency. Further, the LCC method involves economic performance assessment to examine the cost competitiveness of a wood building compared to a concrete building. Second, the thesis conducts the online survey and individual interviews with the construction industry key stakeholders to determine what potential benefits and obstacles of wood buildings influence stakeholders' decisions to implement wood construction.

The thesis summarizes three main study results. First, the Life Cycle Costs assessment indicates cost-reducing opportunities for wood building related to material's lightweight, prefabrication, and fast installation, which allow decreasing the construction costs. Whereas, recycling and reuse advantage of wood building materials at the end-of-life bring income generation opportunity and impact on the overall cost-efficiency of the wood construction. These results show that wood buildings are able to demonstrate economic efficiency throughout the life cycle. Next, the economic performance assessment reveals the minimal difference in Net present value of costs for the wood building compared to the concrete building. The similarity in economic performances is due to quick wood construction period, adjusting the timing of revenue flow and additional income resulting from wood component reuse, recycling, and energy recovery. These indicate the cost-competitive opportunities for wood buildings in comparison with alternative buildings. Lastly, the results of the online survey and individual interviews confirm that key stakeholders seem to recognize potential benefits of wood buildings and demonstrate growing interest towards the wood construction practice. However, the long-term prevalence of traditional materials in the industry, as well as inconsistency in the academic literature, indicated as obstacles influencing stakeholders' decision-making to adopt wood in building construction.

Based on the thesis results, three suggestions for continuing this study are put forward. First, further research is required to demonstrate the LCC method as involving tool to bring the knowledge about the interdependence of building's economic aspects. Second, to improve the knowledge on correlating processes contributing to the economic performance of wood buildings, more case studies need to be examined. Third suggestion stresses the need for further research to communicate the knowledge concerning wood buildings technical and economic performance to the construction industry stakeholders.

**Keywords** Life Cycle Cost (LCC), economic assessment, economic efficiency, cost efficiency, wood construction, wood buildings, stakeholders decision-making

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p.s. Happy Birthday, Dad!

Helsinki, May 27, 2018.

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# 1 INTRODUCTION

This chapter introduces to the reader the research field and describes what issues it intends to investigate within the scope of the study. This is followed by the aim and objectives of the thesis.

## 1.1 Background and Problem Definition

Today, wood construction has evolved considerably, especially in terms of technical development and is considered to be a key solution to future cities with greater environmental performance (Pei et. al., 2017; Valsta et al., 2017). Studies have shown modern wood materials to have the highest potential of meeting all three sustainability criteria, including environmental, social and economic benefits (e.g. Pajchrowski et al., 2014; Falk, 2009; Mahapatra et al., 2016; Panitkov, 2012, Gustavsson et al., 2005). The main environmental benefit of wood construction is the mitigation of greenhouse gas emissions due to wood properties that enable the storing of carbon (Gustavsson et al., 2005; Werner and Richter, 2007; Valsta et al., 2017). Social benefits consist of potential health outcomes, such as overall well-being, comfortability and improved psychological condition of end-users experiencing wood materials in the built environment (Burnard et al., 2015; Strobel et al., 2017; Bysheim et al., 2016). The economic benefits of wood construction, including prefabrication and industrialization processes, are expected to provide a standardized workflow. This may result in a significant reduction of construction costs (Koppelhuber, J. et al., 2017; SFS-EN 16309 + A1, 2014; Fregonara et al., 2016; Schaltegger and Wagner, 2017).

In addition, the demand for more resource efficient construction is rising and concerned clients are growing interested in lifetime costs and the impacts of their buildings. Supported by policy structures to improve living standards and to conform to climate mitigation strategies, the use of wood in the construction sector is being promoted more often (Jones et al., 2016; Jochem et al., 2016; Hynynen, 2015).

Nevertheless, the price of wood materials at the time of research, like Cross Laminated Timber (CLT), is higher per square meter of a completed building than conventional materials (Jones et al., 2016; WoodWorks; Stora Enso, 2017). Further, it has been suggested that higher costs for wood construction can be related more to business issues rather than strictly to technical variables (Giesekam et al., 2014; Jones et al., 2016). For example, the lack of standardized building processes, costing systems, and associated performance may be reflected in price by adding risk premiums, making wood construction systems more expensive to the end client (Jones et al. 2016; VTT, 2017; Koppelhuber et al., 2017; Cazemier, 2017).

Moreover, according to previous research (e.g. Burrows and Sannes, 1999; Gold and Rubrik, 2009; Jochem et al., 2016) one of the main decisive factors of wood construction implementation is the material price, constituting 50% to 60% of the total construction cost (Safa et al., 2014), whereas environmental criteria may merely provide additional value to key stakeholders (Jochem et al., 2016).

Even if higher initial capital costs flatten out by reduced building programmes due to a high rate of wood buildings prefabrication and industrialization, thereby making wood construction cost-neutral (Jones et al., 2016; Han et al., 2013; Green, 2012), the complexity of current wood building standards and regulations, combined with the lack of experience and limited research, cause resistance and low ambition from the construction sector to adopt wood construction methods (VTT, 2017; Jones et al., 2016). As a result, increased risks for wood construction without a corresponding return on investments can be perceived as inefficient in terms of cost (Darner, 2009). This can become a barrier, especially when a commercial opportunity is imperative in construction project implementation (Jones et al., 2016; Goverse et al., 2001).

Despite a number of well-known and frequently cited wood buildings around the world, as well as a high interest for wood construction due to its sustainability credentials and versatility, there is not enough sufficient information on the financial performance of wood buildings to generalize its economic potential (Gosselin et al., 2017; Cazemier, 2017). There is an identified knowledge gap regarding the economic efficiency of wood buildings, which indicates the need for research to study a larger number of wood buildings. This would produce an awareness of the economic aspects of wood construction development (Gosselin et al., 2017; Cazemier, 2017). Moreover, it has been noted that an evaluation of wood buildings' whole life cycle costs, including production, operation, and end-of-life stages, can be crucial in demonstrating integral economic efficiency and identifying economic potential for each of the life cycle phase (Gustavsson, 2015; Kuzman & Standberg, 2015; Werner, 2007). Also, to produce more competitive price policy, provide high quality, and guarantee long-term benefits of wood buildings, key stakeholders need to be informed of the building's whole life cycle costs (Ahmad & Thaheem, 2017; Bartlett & Howard, 2000). However, literature studying the life cycle costs of wood buildings is extremely limited, resulting in inconsistency in the representation of those viewpoints for the construction industry (Wang et al., 2013 Atmaca, 2016; Morrissey & Horne, 2010; Bowyer et al., 2016).

For these reasons, the question of cost-efficiency of wood buildings is at the forefront of construction development, as wood is the main alternative to traditional material in combatting climate change (Hynynen, 2015). Implementation of LCC methods can play an important role in developing objective information on likely costs and benefits of proposed wood building projects (Ahmad & Thaheem, 2017). Comprehensive economic assessments enable the examination of profitability and cost competitiveness of wood buildings covering economic performance aspects. This means, that LCC is prerequisite for an assessment of buildings economic sustainability and may ensure satisfaction of demands for sustainable development (European Standard EN 16627:2015; Bartlett & Howard, 2000).

A key contribution of the current thesis arises from the assessment of wood building economic efficiency based on LCC assessment method and adds to the literature related to the economic performance of modern wood construction. The empirical study and representation of final results contribute to the wider goal which is to create further knowledge of wood construction economic optimization strategy and support involved stakeholders decision-making process.

As LCC is an integrated part of building's economic performance assessment, its relevance to demonstrate the most optimal solution based on investment effectiveness can assists developers decision making (European Standard EN 16627:2015). Further, materials supply chain can benefit from the study on the life cycle costs by investigating end-of-life potential of building materials and introducing to the circular business development. Also, LCC can provide the detailed estimation of operational costs for different building solutions and inform on the most energy and cost-efficient option for the end-users.

Moreover, use of LCC method reveals its benefits for the construction industry key stakeholders through their engagement along the assessment process. Indeed, change towards more environmental responsibility in the construction industry requires more focus on understanding interrelated building systems and the industry stakeholders' involvement is one important part of it. In order to make holistic study contribution and generate verified research data, this thesis considers the construction industry attitude and provide an overview of key stakeholders perspective regarding wood construction. More precisely, the study intends to understand what wood construction aspects including cost-efficiency are perceived as benefits and obstacles and impact the industry decision-making to implement wood construction practices. The focus group is key players involved in the development of wood building projects, including contractors, property developers, engineers, and architects.

With this background, the study investigates two main topics: Life Cycle Costs (LCC) and Stakeholders' Decision-Making. First, it will provide a comprehensive economic assessment of modern wood building to contribute to the factoring of life cycle costs in building analysis. The goal is to analyze the costs of a wood building throughout its lifecycle and indicate what cost factors impact the overall economic efficiency of the building the most. It follows by investigating the question of how LCC assessment can be integrated as a tool to increase wood construction competitive development. Second, to contribute to the modern wood construction further development, it is essential to look at key stakeholders' perspectives as the bottom line for decision-making, affecting construction and market development.

## 1.2 Thesis Aim, Research Questions and Objectives

The main aim of this thesis is to assess economic efficiency of a wood building based on LCC assessment method. In this study, the expression "economic efficiency" represents building's cost-efficiency during a defined period of time (Ristimäki et al., 2013) and shows the allocation of costs throughout a wood building's life cycle. The study intends to identify which of life cycle costs have the most impact on the economic efficiency of a wood building. Also, to demonstrate the economic performance potential and economic competitiveness of wood buildings, LCC of a wood building is compared with LCC of alternative building.

In this study, the alternative building referrers to traditional buildings, which are products of a well-established construction system, where commonly used materials such as reinforced concrete and structural steel are transported to the site and cast-in-situ (Jester, 2014; Cao et al., 2015). Heavy materials like concrete, steel, and brick, also known as 'conventional,' represent traditional buildings because of their strong position, wide use and development expertise gained over the last couple of decades. Additionally, the fact that traditional buildings are the most common and well-known building types makes market entry for other materials like wood difficult (Riala & Ilala, 2014; Thomas & Ding, 2017).

The main quantitative part of this thesis is done with respect to European standardization (SFS-EN 16627) which demonstrates an economic performance calculation method utilizing LCC assessment. In order to provide a holistic approach to the research subject, the study also considers human factors along with the quantitative assessment and examines key stakeholders' perspective on wood construction through an online survey and individual interviews. This additional qualitative approach sets the balance, enabling a view into the research through a wider lens and search for patterns of a relationship between stakeholders' decision-making factors and other unspecified sets of concepts.

Thus, the study is divided into two parts. Therefore, the following set of research questions have been developed:

- ***What is the economic efficiency of a wood building based on LCC assessment?***
- ***What wood building benefits and obstacles determine stakeholders' decisions to implement wood construction practices?***

In order to answer the research questions, the thesis sets the following objectives:

*First*, Analyse the economic efficiency of a wood building utilizing a comprehensive LCC assessment method

*Second*, Identify which life cycle costs impact on a wood building's economic efficiency

*Third*, Compare the economic performance of a wood building with alternative concrete building

*Forth*, Understand what wood construction aspects impact on key stakeholders' decisions to build with wood, by conducting an online survey and individual interviews.

## 1.3 Thesis Scope and Limitations

To evaluate the economic efficiency of a wood building, the current study adopts the LCC calculation method described in European Standard EN 16627:2015 "Sustainability of construction works. Assessment of economic performance of buildings. Calculation methods" (shortly SFS-EN 16627). To implement the LCC assessment framework in practice, the research is further scoped down to one specific case of a wood building. The short introductory list of facts for the case building are:

- Project: Bridport House

- Geography: United Kingdom, London
- Sector: Residential
- Type of occupancy: Rental
- Main construction material: CLT

Further, to produce the building's economic assessment in compliance with the European Standard, the research identifies specific economic indicators within system boundaries of the object of assessment. Figure 1 expresses the system boundary for the existing building, which shall include all costs during three main phases of building's life cycle, namely "*Before Use*", "*Use*" and "*After Use*" (SFS-EN 16627).

The actual study is limited not to include all the costs in LCC assessment due to a data shortage and probabilities of insufficient specification. The LCC analysis of the study DOES NOT include costs for: Land purchase/ rent; Taxes; Water use; Refurbishment; Transportation; Demolition Fees and Taxes. Economic indicators of the case building included in the assessment are highlighted with ***Bold Italic*** font as shown in Figure 1.

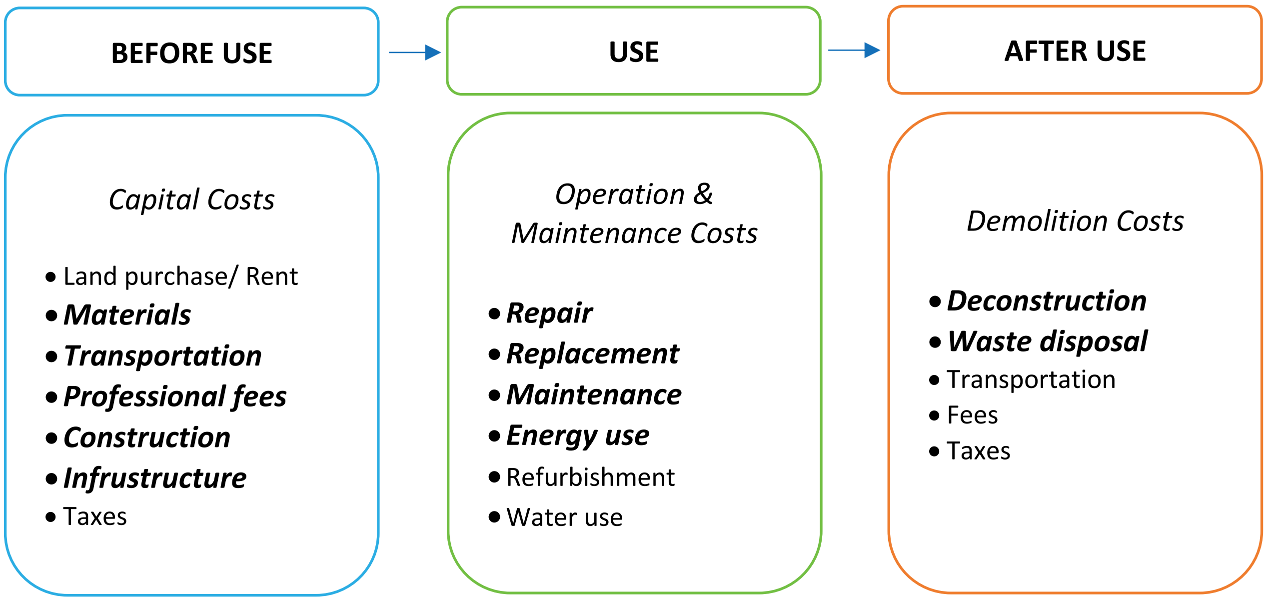



**Figure 1** Building life cycle phases including proposed life cycle costs (adopted from SFS-EN 16627)

In the present study, the LCC assessment is performed for a defined period of time of 30 years. This is not an end of the life period for the case building, but it captures the time period for which future costs assumption are relevant enough. Further, the study does not apply sensitivity analysis, but instead a short overview of lifetime cost variables, which can possibly make changes in wood building's economic performance calculations.

For an adequate evaluation of the economic performance of wood buildings, cost competitiveness and investments potential, this research compares LCC of wood building with LCC of alternative building. To make the comparison as close as possible, alternative concrete building should possess similar physical and technical features as the case wood building. Thus, specifically for this study, alternative concrete building will be theoretically constructed utilizing existing data of the case building and adapting additional data from available open sources to complete its LCC.

## 1.4 Structure of the Thesis

The thesis is organized as follows:

Chapter 1, being the *Introduction*, presents the background of the study, elaborating on sustainability benefits of modern wood construction. It also defines the research problem, states the research aim, identifies the research questions and objectives, outlines the research scope and limitations, and mentions the target audience.

Chapter 2, *Theoretical background*, gives the reader a short overview of the modern wood building market situation in Europe and describes cost indicators for wood building throughout its life cycle. It then briefly introduces economic assessment methods and includes theory on stakeholders' perception and decision-making based on existing knowledge from the literature of the field.

Chapter 3, *Methodology*, comprises the description of the two main research approaches and data collection methods. The first part of the chapter gives a short theory on Life Cycle Costs and shows the exact data required for the LCC assessment. It also introduces the case study and demonstrates the application of LCC assessment method in practice. The second part describes relevant information needed to obtain from key stakeholders, including the process of data collection through an online survey and individual interviews.

Chapter 4, *Findings and Results*, collects LCC assessment results for the case building, and then presents the outcome of comparative economic assessment between the case and alternative buildings. This chapter also reveals the results and findings of the online survey and interviews to highlight insights from the practical perspective.

Chapter 5, *Discussion*, draws the outcome based on LCC results, the online survey, and interviews findings. It elaborates on the assessment of the economic efficiency of a wood building in comparison with concrete building and reviews current drivers for key stakeholders' decision-making.

Chapter 6, *Conclusion and Further Research*, summarizes three key outcomes of the thesis research including relevant scopes for further studies.

# 2 THEORETICAL BACKGROUND

The following chapter begins with a quick overview of the wood buildings market share in the construction industry, including barriers and existing research demands for wood building development. The economic efficiency and different costs occurring during the life cycle of wood buildings are presented thereafter. This is followed by general description of the main economic assessment methods and specific focus on the LCC assessment method for wood buildings. Finally, vital factors in regard to key stakeholders' decision-making are presented.

## 2.1 Wood Buildings Market

In recent years, wood buildings as part of a diverse sustainable development and climate policy strategies gained a lot of attention, showing a positive trend for multi-story wood construction (Toppinen et al., 2017; Gosselin et al., 2017; Ministry of Foreign Affairs of Finland, 2010; Bowyer et al., 2016; Mahapatra, 2012). Multi-story wood construction often refers to modern timber construction with massive wood elements as the core structure of the building (Bowyer, 2016; Reynolds et al., 2015; Smith et al., 2017). In this thesis, research emphasis is on multi-story construction wood (shortly wood construction), owing to the high potential of tall buildings to drive sustainable building development, address carbon emission reduction objectives and support local forestry industries (Bowyer et al., 2016; Kuzman & Sandberg, 2015; Wang et al. 2014).

In Europe, conditions for wood buildings market growth with big potential to new business opportunities is most favorable in Nordic countries, the Alpine region and the British Isles (Hurmekoski, 2016; Mahapatra et. al., 2012; Jochem et al., 2016; Klussel, 2008). A number of studies explain this predisposition is based on consumer preferences, culture and traditions, demographics and environmental policy initiatives (e.g. Hurmekoski, 2016, Toivonen, 2011). In countries like Sweden, Norway, Finland, Germany, Austria and UK, wood construction development follows by increased wood promotion campaigns, technology advances in construction products and changes in institutional environment, allowing more flexible building regulations (Hurmekoski, 2016; Holopainen et al., 2015; Kuzman and Sandberg, 2015). In addition, local origin of wood materials has been associated with environmental quality and as consumers gain knowledge about the environmental impacts of different materials, it affects their preference pattern (Toivonen, 2011). For example, the market share of multi-story wood buildings increased in Sweden by 15% from 2000 to 2012 (Kuzman & Sandberg, 2015; Gustavsson, 2015), while in Finland, the market share has grown by more than 9% since 2010. This can be partially explained by changes in building regulations in 2011, allowing erect wood buildings up to 8 stories high (Toppinen et al., 2017; Karjalainen, 2017; Sun, 2016). Also, Mahapatra et al. (2012) as part of their study investigated the wood buildings market in the UK. They showed that in ten years by 2008 the market for wood multi-story buildings grew by 25%. Due to less availability and high prices of land, cities consider promoting wood construction tendency even more and stimulate an overall increase in the wood construction market. This shows the ability of wood buildings to demonstrate similar structural properties as other alternative buildings, while showing competitive cost levels and, most importantly, complying with environmental goals set by the government.

Nevertheless, the amount of tall wood buildings in the EU is insignificant in relation to the whole building stock (Hurmekoski, 2016; Karjalainen, 2017; Gustavsson, 2015). According to Hemström (2016), more than 90% of apartment buildings in Sweden continue to be constructed with conventional materials. In Germany, annual statistics show a constant number in amount of multi-family wood houses built, which is about only 2% each year (Mahapatra et al., 2012; Jochem et al., 2016). Further, due to data inconsistency on the use of wood in multi-story construction, there is a limited representation of the average market share which is seen to be less than 1% as a whole (Jonsson, 2009 cited by Hurmekoski, 2016). While there are plenty of possibilities that considerably increase the number of wood buildings and growing consumers' interest, what is keeping wood construction from increasing further?

The following section overlooks the main reasons of resistance to implement wood materials in the construction industry. The section after indicates the existing knowledge gap and explains the need for further research related to the economic competitiveness of wood buildings.

### 2.1.1 Development Barriers

Several prior studies show that implementation of wood construction methods is often met with some resistance from the construction industry (e.g. Mahapatra et al., 2012; Jones et al., 2016; Hemström et al., 2011; O'Connor et al., 2004). Particularly, Gosselin et al. (2017) investigated and recognized main barriers for using wood in multi-story buildings by saturating data from an intensive literature review of 53 scientific articles. The research gathered and prioritized six main barriers with encompassing elements based on repetitions' frequency within relevant articles. Accordingly, limitations of building codes with 40% frequency are determined to be the main obstacle in wood implementation, followed by a lack of expertise with 18% frequency, costs (16%), material durability and technical aspects of wood materials (8%), culture of the industry (6%) and finally, material availability with 4% frequency.

Corresponding analysis was done in 2015 by Espinoza et al. (2015). The study identified CLT adoption barriers in the European context and showed that compatibility with building codes was considered the "main" barrier. Also, limited availability of technical information, misperception about wood materials and costs are among other barriers considered by industry experts.

The most recent report about buildings with timber in Europe from VTT Technical Research Centre of Finland (2017) provides interesting Strength Weaknesses Opportunities Threats (SWOT) analysis of timber construction, based on surveys and assessing knowledge gained from practice by researchers, architects and industry representatives. According to the study, the main weakness is the complexity of current timber building standards and regulations, which resembles the main barrier in the study by Gosselin et al. (2008). The indicated threat is low ambition from large construction companies to implement new methods of wood construction. This is explained as a lack of qualified and experienced professionals in the industry and a preference for traditional construction methods.

Hurmekoski et al. (2015) and Espinoza et al. (2015) describe perception as a strong influence in the wood buildings market development. The authors maintain that negative perception related to the credibility of wood construction throughout the value chain can be sensitive to even small setbacks, leading to low adoption rates. However, it is mentioned further in the study that when experience increases, the perception tends to grow more positive. This also supports previously reviewed research by Gosselin et al. (2017), which states these barriers are perception outcomes that could gradually evolve and change as the actors gain experience. Therefore, as Hurmekoski et al. (2015) summarized, one of the key drivers to successfully increase uptake of wood construction is to overcome negative perceptions and prejudices formed on path-dependency.

Path-dependency can simply be described as previous events affecting present decision-making to implement radically new innovative systems. In construction, path-dependency appears to be one of the main reasons behind the dominance of concrete and steel materials (Mahapatra et al., 2012; Jones et al., 2016). Therefore, to explain the slow adoption of wood construction, Hemström's (2016) in his study focuses on sociotechnical regime, indicating decision-making as being dependent on established concrete practices influencing selection of structural materials. He provides a deeper understanding of why construction managers are key influencers in maintaining concrete path-dependency and how prior experience favoring concrete solutions can imply risk for implementing new types of construction methods.

Another interesting study produced by Jones et al. (2016) investigates limiting factors to adopt new approaches in construction with focus on CLT materials. The study also finds path-dependency to the use of dominant technologies being one of the main barriers to adopt unconventional materials. However, one important lesson of the study shows that contractors and quantity surveyors have a higher capability to introduce new solutions to the projects, but a lack of commercial opportunities due to perceived risk in a costs-competitive environment reducing the motivation to do so.

According to the literature review, it is possible to conclude that development barriers have common ground as poor economic perception of construction companies towards wood construction. This perception is related to uncertainties and risks emerging as a consequence of a lack of experience (Mahapatra et al., 2012; Hemstrom et al., 2010; Roos et al., 2011). Therefore, the importance of exploration of commercial opportunity through value generation is recognized as key stimulation to adopting CLT materials. Further elaboration on the topic of factors that influence the decision-making process of key stakeholders is presented in sub-chapter 2.4.

### 2.1.2 Research Demand for Wood Construction Development

Despite all the barriers, wood construction seems to have great potential to become innovative and an environmentally conscious construction solution to satisfy growing housing demand (Kuzman & Sandberg, 2015; Wang et al. 2014). To take steps towards that direction, more research and knowledge are required as it plays a big role in determining pro-environmental actions (Darner, 2009; Keith, 2011; Hines et al., 1987 cited by Høibø et al., 2015). This section reviews literature and explores the most common demand for knowledge to enhance wood construction development.

Espinoza et al. (2015) dedicated his study to identify research needs for the CLT growth and development in Europe. According to the authors, the most important research needs were related to the structural performance of CLT, like connections, joints, manufacturing issues, durability, moisture performance, and customer research. However, this can't be generalized since the survey method adopted non-probability sampling strategy; thus, results and conclusions are relevant only for the study respondents (Rea & Parker, 2014).

A large part of the literature argues that there is a general need for more knowledge, research and development to facilitate understanding of how to optimize wood buildings through each of their lifecycles (e.g. Gustavsson, 2015; Kuzman & Standberg, 2015; Werner, 2007). Kuzman and Standberg (2015) state that further research and more experience will lead to an increase in the knowledge on buildings' life cycle costs, physical performance and technical aspects.

Goverse et al. (2001) discuss opportunities and constraints in the wood construction sector and recognize the importance of whole life cycle knowledge, specifically directing research programs at selective demolition, waste separation, and opportunities for wood reuse, improving end of life rates. Also, similarly to Goverse et al. (2001) study by Jones et al. (2016) mentions that construction development is mainly based on construction costs and not on life cycle costs.

Furthermore, Bartlett & Howard (2000) maintain that correct consideration of life cycle costs can deliver true long-term value for the end-users. Additionally, better informed construction professionals can encourage key stakeholders to make choices to improve sustainable development in built environment. Klussel (2008) likewise emphasizes that the main prerequisites for wood as material to thrive is to focus research on knowledge development around calculability of wood construction. This view is shared by Wang et al. (2013) in the study about the use of wood in green buildings, where it was found that experts see environmental sustainability and affordability to be mutual aspects and the cost concern continues to be one of the key issues left to resolve before wood buildings can dominate in the construction market.

While research knowledge is limited specifically from the economic perspective, the market seems to be evolving with respect to environmental issues and people are growing more and more concerned about alternatives to maintain sustainable living (Darner, 2009; Bartlett & Howard, 2000). In accordance, Høibø et al. (2015) studied Norwegian consumer building material preferences in the housing sector and found that people in general have very limited knowledge about wood materials and their environmental impact (Keith, 2011). At the same time, the study also noted that the younger generation have stronger environmental concerns and therefore are found to be the best target for developing wood-based built environment.

Along with the environmental aspect, consumers are thinking of price as a key economic aspect of sustainability. In alignment with the conclusion provided by Høibø et al. (2015) that wood market will have positive growth in the future, Wang et al. (2013) found that wood industry players also think interest in sustainable construction is increasing. However, they emphasized that price has now become one of the strongest aspects to based decision on.

In conclusion, it is fair to note that despite many well-known and frequently cited studies of wood buildings all around the world, there is indicated a great need for research to explore the economic potential more and provide a comparative financial performance of wood buildings (Gosselin et al., 2017; Cazemier, 2017). Moreover, there is a need to evaluate wood buildings with regard to their whole life cycle, which includes the production and end-of life stages, and not only based on the energy demand during the use stage (Peterson & Solberg, 2005; Green, 2012). Research-based knowledge and increased experience can increase competition in the industry bringing down the costs for wood construction and provide credibility due to the market interest. Hence, the next subchapter describes Life Cycle Cost phases of wood buildings and points out main cost factors which may impact on building's economic efficiency. Also, it will bring discussion on differences between life cycle costs for wood and concrete buildings as it is part of the empirical study.

## 2.2 Wood Buildings' Economic Efficiency and Costs

According to Hurmekoski et al. (2015) the concept for multi-story wood construction seems to have passed the peak of its innovative value, which tends to be far greater than the economic potential of the product (Lindenn and Fenn, 2003 cite by Hurmekoski, 2015). Similar perception is described in the study by Koppelhuber at al. (2017), where it states that after wood construction has been developed considerably as a modern building system, it is logical and necessary to concentrate on its economic aspects and constant optimization of construction management. That is, large scale of commercial application for wood multi-storey construction should start taking place in the market.

However, even if wood as a solid construction product experienced great interest, the practice of multi-story wood construction is still identified as experimental (Loss and Davison, 2016; VTT report, 2017; Asdrubali et al., 2016). Therefore, a lack of sufficient data on technical regulations for the wood construction can cause uncertainty towards costs. In turn, costs fluctuations from case to case make it difficult to assign total cost factors for wood construction, leading to possible cost overruns (Winter, 2010; Hossaini, 2014; Han, 2013; Mahlum Arch., 2014). Eventually, to avoid unexpected risks and additional costs, the construction industry prefers to play it safe and choose well established building methods instead of modern wood construction.

Also, often the construction industry emphasizes the initial phase of building's costs rather than life-time costs. Thus, not all long-term benefits can be factored into the proposal (Arif et al., 2017; Sinha et al., 2013, Milaj et al., 2017). In fact, there are numerous independent life cycle studies available on wood-frame buildings covering their environmental performance (e.g. John et al., Atmaca, 2016; Puettmann & Wilson, 2005) and with very limited understanding of economic efficiency in the assessment (Petersen & Solberg, 2005).

Meanwhile, with rising living standards and increasing environmental attitudes in society, a greater proportion of end-users are growing concerned about the selection of environmentally friendly material alternatives and the lifetime cost of their buildings (Jones et al., 2016; Bartlett & Howard, 2000; Høibø et al., 2015). Accordingly, building owners and investors have started showing long-term interest for built assets and require that they be informed on the building's life cycle costs to ensure satisfaction of demands for sustainable development (Bartlett & Howard, 2000).

Thus, economic analysis early at the construction development stage can make the assessment method policy relevant, bringing cost-effective actions against global warming. Also, investigation on costs during the building's whole life cycle might reveal its potential economic efficiency. It refers to maximizing the building's net benefits during the life period as a result of decision-making (Ruegg & Marshall, 2013).

Therefore, estimation of wood building's initial costs and the time-adjusted future costs creates an opportunity to access new markets and act as an impetus for the construction industry to gain confidence (Heralova, 2014; Koppelhuber et al., 2017). Indeed, to analyze overall value of wood building, it is important to acknowledge its whole life cycle costs (Peterson & Solberg, 2005; Green, 2012). Sections below disclose Life Cycle Costs in the context of wood buildings and reveal which cost factors impact the most on building's economic efficiency.

### 2.2.1 "*Before Use*" Phase Costs

Life cycle of the building consists of 3 main phases: *Before Use, Use* and *After Use* (European Standard SFS-EN 16627, 2015; Gustavsson, 2015). First phase ***Before Use*** also referred as pre-use phase including all the processes related to *pre-construction, product manufacture*, as well as *construction* of the building envelope (Blengini, 2009).

During each process, there are activities forming certain costs before the building is being erected. In general, there are the following cost categories (European Standard SFS-EN 16627, 2015):

***Pre-Construction Costs***

- prior land acquisition
- related taxes and fees

***Product Manufacture Costs***

- raw material supply
- transportation and manufacturing

***Construction Costs***

- ground works and landscaping
- direct costs of equipment
- transportation to and from site
- construction-installation process
- waste management
- professional fees and handover costs etc.

It is fair to note that every cost category is adapted for each specific project and linked to decisions about the building. In other words, every building construction is a different product concept, not only in terms of materials, but also involving technical changes, knowledge, skills, and economic aspects (Goverse et al., 2001). The decision on building development is usually highly dependent upon initial cost factors like construction cost, competition fairness, interest rate and time pressure (Oberndorfer & Haring, 2014; Milaj et al., 2017). One of the primary concerns about building's *Before Use* cost could be that it makes a large share of whole Life Cycle Costs.

Scientific literature investigating economic performance and practical implementation of LCC assessment for modern wood buildings seems to be very limited. Thus, to demonstrate general *Before Use* cost share in building's Life Cycle Cost, the thesis viewed several LCC-oriented articles. In a study by Kaming (2017), construction cost comprises 41% of total costs, during 25 years of residential building life cycle. However, the study did not use discounting method for future costs and did not include demolition costs in LCC assessment. Han et al. (2013) broke down and showed the share of costs during the different office building life cycle phases. Results showed that *Before Use* cost for 40 years period comprised about 44% of total costs. Ahmed and Thaheem (2018) demonstrated the general structure of building's economic sustainability indicators and specified that capital costs can make up 40% of LCC.

The only study found by Hossaini et al. (2014) viewed specifically six-story wood building and concluded that manufacturing and construction costs take only 5% of LCC in 60 years of life cycle. Another study by Heralova et al. (2014) estimated that the construction cost for public building within 30 years of analysis period make 68% of total costs, where 89% of it is building costs. Similarly, Huang et al. (2017) maintain that the building materials correspond to 91% of cost at construction stage.

Considering the results of previous studies, it is clear that *Before Use* makes a significant contribution to the Life Cycle Cost. Thus, it is interesting to look at the features of wood construction which may impact *Before Use* costs and building's economic efficiency.

Today's modern wood construction is characterized by its ability to easily process for prefabrication, which enables it to develop industrialized building methods with wood materials (Koppelhuber et al., 2017). Thomas and Ding (2017) as part of their study analyzed wood construction time and established that it requires less detailed formwork, as the plumbing system doesn't depend as much on footing installation. This serves to hasten the construction process. Gosselin (2017) noted that speed of wood construction can bring additional advantages, especially in high density areas, with the possibility of reducing the duration of traffic interruption and minimize disruptions to neighborhoods.

Hurmekoski et al., 2015, concluded industrial prefabrication provides the opportunity to decrease construction time on site almost by two times. Prefabrication process can provide several great advantages for wood buildings. Most importantly, shifting to the factories can result in shorter delivery times with quick assembly and less transportation cost again affecting on the formation of the final building costs (Gasparri et al., 2015). Another great benefit of prefabrication is related to quality and ease of production systems. In addition to an accurate, faster manufacturing and a reduction of defects, building industrialization can provide safer working environments. Independent from the weather conditions, indoor production helps to monitor levels of emissions and provide more environmentally friendly modes of building with respect to dust, noise and waste (McGraw-Hill, 2011 cited by Arif et at., 2017; Švajlenka et al., 2017).

Therefore, it is reasonable to consider the high prefabrication aspect of wood buildings as a *Before Use* cost saving feature due to reduced building programme times. Fast construction periods may considerably drive down initial construction (capital) costs, making wood buildings cost-neutral compared to other buildings from concrete and steel (Koppelhuber, J. et al., 2017; Jones et al., 2016; Han et al., 2013; Green, 2012; Arif et al., 2017; Klussel, 2008; Gasparri et al., 2015).

Cazemier (2017) analyzed the financial performance of CLT building in comparison with concrete & steel building, covering main initial costs like land costs, construction costs and potential revenue as the primary variables of a new development. As a result, CLT building appeared to have 30-40% shorter construction program reducing time-related costs and increasing period of revenue inflow. However, debt facilities like banks perceive CLT buildings as riskier due to pre-payment for the off-site manufacturing and therefore establish higher contingency rates which cause an increase in total development cost. Moreover, total construction costs are 3% higher for wood building due to high material and installation costs. Indeed, it has been mentioned that high prices for wood-based building materials can be a decrease point for the wood construction development (e.g. Hynynen, 2015, Jones et al., 2016).

Another area to indicate potential impact on Life Cycle Costs using wood materials in the structure is foundation, ground works and landscaping costs. Few studies showed that light weight of wood structure enables the reduction of building load and therefore requires less reinforcement for the foundation works, contributing to overall construction cost reduction (Karakusevic Carson Architects, 2011; Cazemier, 2017; Burback & Pei, 2017; Švajlenka et al., 2017). On the contrary, a study by Thomas and Ding (2017) elaborates that even if wood building design may have less ground works cost, it requires significant material and labour cost for foundation works. For instance, the installation process of concrete pad footings and cement sheeting may cause greater cost for wood substructure work, which in turn increases *Before Use* cost.

Therefore, according to the reviewed literature the costs occurring in *Before Use* phase are considered an integral part of the building's life cycle and can demonstrate the potential for economic efficiency improvement in the initial LCC phase of the building. However, due to limited literature and a lack of studies covering the topic of Life Cycle Costs for modern wood buildings, the challenge to demonstrate relative or absolute *Before Use* phase costs compared to other life cycle phases remains (Atmaca, 2016; Morrissey & Horne, 2010; Bowyer et al., 2016). Thus, there is indicated strong need for more research of the topic.

### 2.2.2 "*Use*" Phase Costs

The ***Use*** phase firmly remains the longest stage in a building's life cycle and it covers the period from official completion until the time when building is ready to be demolished (European Standard SFS-EN 16627, 2015). Therefore, the Use phase includes the costs related to maintaining a building's proper functioning: *operational* costs, *maintenance and management* costs, *repair and refurbishment* costs.

Accordingly, each of the cost categories has a boundary of processes which form lifetime costs, and which could be included in a building's economic assessment. Some of those are (European Standard SFS-EN 16627, 2015):

***Operational Costs***

- energy use
- water use

***Maintenance and Management* Costs**

- ancillary products
- cleaning processes
- maintenance of functional and technical systems
- aesthetics qualities of the building etc.

***Repair and Refurbishment Costs***

- repaired, replaced and new building components
- waste management of removed parts
- process of removal, repair, refurbishment and installation
- management and design fees

*Use* phase of the building is usually preconceived as not highly dependent on a building's structural materials, but more on the physical properties of the building, such as absolute architectural design (Jafari & Valentin, 2017). Theoretical considerations suggest that an appropriate building design and the choice of applied technologies has great importance for the energy performance in a manner that significantly decreases primary energy use, while the choice of frame material is of marginal importance (Gustavsson, 2015).

Today, there is a relatively small amount of existing modern wood buildings in the market with life cycle duration longer than 6-8 years (M. Viljakainen [PuuInfo] pers. comm., 18 September 2017; Finnish statistics, Puupäiva). That results in a restricted number of studies being available on operational, maintenance and refurbishment costs for wood buildings. However, there are a few studies that looked at wood building life cycles within the comparative economic assessment. For example, Dodoo et al. (2011) analyzed wood-frame building primary energy balance in comparison with concrete building and concluded that the demand for wood space heating is slightly higher due to thermal mass properties in the concrete-based system. Also, several prior studies agree that wood-frame buildings almost always had similar or higher lifetime energy use costs than buildings associated with concrete systems (e.g. Marceau & VanGeem, 2002; Gadja, 2001, Hossaini et al. 2014; Thomas & Ding, 2017).

Nevertheless, the number of reports and studies on already built wood projects demonstrate that wood materials in the structure can provide energy savings during the life cycle through better results in air tightness (Arif et al., 2017; Karakusevic Carson Architects, 2011; Alinea, 2017). For example, architects and engineers in the study by Karakusevic Carson Architects (2011) mention how the CLT building system ensures to provide the best results in air tightness because of the precise wood frame elements production using computer modelling combined with high installation tolerances.

A similar conclusion can be found in the report on the cost model of a specific CLT building by independent construction cost consulting company Alinea (2017) from the UK. It states that a prefabricated CLT structure allows for higher levels of air tightness. Indeed, prefabrication can address not only environmental concerns by minimizing waste production and provide quick building erection period, but it also can reduce lifecycle energy usage by improved insulation and a tighter building enclosure (Arif et al., 2017).

Residential primary energy consumption also associated with embodied energy, maintenance, renovation, recycling of used materials can come out as a large portion of life cycle costs. Heralova (2014) showed, in 30 years of life cycle public building will gain 43% of maintenance and operation costs from total costs excluding disposal expenses. Hossaini et al. (2014) calculated wood building's operational phase including operation and maintenance costs would be 93% of total life cycle costs in a 60-year period. Gustavsson et al. (2009) found that operational phase has the largest share of energy use, becoming dominant with the longer life span of the building. Han et al. (2013) also found that energy consumption becomes the primary cost if building life cycle is longer than 30 years. The study also revealed that wood frame can be more economically optimal for a building with up to a 60-year life span. This claim is based on wood conductance and maintenance costs, which can influence energy consumption and accordingly result in lower costs.

Maintenance and repair processes have also been one of the factors to have an impact on a building's life cycle costs by increasing materials effective service life. Wood is often perceived as a material lacking durability, associated with decay and susceptible to termite attacks (Hynynen, 2015; J. Haapio [Settle] pers. comm., 25 November 2017). Foliente et al. (2002) explained the situation with existing general perceptions that wood buildings are less durable come from the past experiences. Today, additionally to make use of naturally durable wood species such as larch, physical and chemical treatments can improve the durability of wood building products before they are permitted for the construction (Ramage et al., 2015). Additionally, appropriate maintenance and management are integral parts of the life-cycle analysis supporting a building's overall performance and durability (Foliente et al., 2002; Winistorfer et al., 2005).

A building's structure maintenance is largely related to roof and façade maintenance including shingles replacement and exterior paint (Winistorfer et al., 2005). Usually wooden external surfaces may need ongoing painting every 10-15 years and other treatment requirements which can be taken as disadvantage of wood products (Thomas & Ding, 2017; Gold & Rubik, 2008). Nevertheless, it is important to note that higher maintenance and replacement costs can be caused by a lack of knowledge regarding physical properties of wood building materials and design deficiency (Ishak et al., 2007).

Therefore, it is possible to hypothesize that the *Use* phase may become the major part with longer wood building's life cycle and comprise most of the costs which can impact its economic efficiency. However, a building's total energy consumption costs are often neglected when making economic decisions, including embodied energy (Syal et al., 2014). To provide a full picture on a building's energy efficiency and maintenance costs, it is important to analyze its entire life cycle. At this point, the choice of building material becomes relevant (Dodoo et al., 2011).

### 2.2.3 "*After Use*" Phase Costs

The ***After Use,*** also known as the end-of-life phase, refers to the processes that occur after the building exceeds its service life and is intended to be demolished. According to the European Standard of sustainability of construction works (2015), demolition of the building is a multi-output process, which includes costs for *deconstruction*, *transportation* of discarded materials and *waste disposal*.

The costs during building's demolition can be presented as separate modules with specific costs boundaries that form each process. They are as follows:

***Deconstruction Costs***

- site operations
- building's dismantling/ demolition

***Transportation Costs***

- transportation from the site and to the end-of-waste place, e.g. recycling site or final disposal

***Waste disposal Costs***

- waste processing, e.g. recycling, reuse, recovery
- disposal

With an increasing awareness of sustainability and a circular economy, great attention has paid to buildings' whole life cycles, including the end-of-life stage (Chau et al., 2016; Howard & Bartlett, 2000). Yet it appears that the *After Use* phase costs are still the least to be taken into account when it comes to the economic decision-making, composing the smallest share of life cycle costs. For instance, demolition costs for an office building including transportation will take about 7% of total costs at the 60 years of the building's life cycle (Han et al., 2013). A study by Hossaini et al. (2014) assessed LCC for six-story wood building; results showed that in 60 years, end-of-life cost including demolition, recycling and reuse costs will take about 2.1% of total cost.

Property developers are one of the main building construction decision-makers and they may not consider a modern wood building's end-of-life costs as part of the investments formation (Roos et al., 2010). It is common that after a building has been constructed and released into the market, property rights usually transfer to another owner or to building residents. Therefore, the most relevant costs for developers and investors are early in the building development and construction stages (Bartlett & Howard, 2000; Goverse et al., 2001; Jones et al., 2016), whereas building decommissioning process and related costs may not play significant role in overall decision-making (Goverse et al., 2001).

However, previous research shows that there is technical potential to lower demolition costs and innovation characteristics to increase wood recycling. A recent study on wood building performance by Thomas & Ding (2017) shows that end-of-life costs with timber material are less than for concrete and brick-designed building. The reason for this difference in costs is associated with the light weight of wood materials for disposal. Lighter wood loads require less transportation and landfill fees. Also, less use of special heavy machinery to demolish wood frame can decrease *After Use* phase costs (Winistorfer et al., 2005).

Another study by Blengini (2008) analyzed building demolition and recycling potential. The study concludes that a building's materials selection and choice of proper end-of-life management process could lower the life cycle impacts in terms of contribution to the total energy use. Also, recycling opportunities can save costs for not paying to the landfill and obtain income for selling recycled materials with that decrease *After Use* costs.

Indeed, as the use of wood in construction industry grows, opportunities for wood materials reuse and recycle are also increasing, thereby offering possibilities to enhance wood resource efficiency. Ormondroyd et al. (2015) studied opportunities and challenges for recycling wood materials and found that there is great potential for reclaimed wood in different markets. The most dominant market for recycled wood waste is production of particleboards like oriented strand board (OBS) and medium-density fiberboards (MDF). As a result, wood building material can maintain its value after the primary use (Wang et al., 2016, Franklin Associates, 1998 cited by Winistorfer, 2005).

As briefly touched on in the *Use* phase, another primary industry to utilize waste wood is for energy and heat recovery (Goverse et at., 2001). Wood buildings can provide carbon dioxide storage, and biomass from wood building materials can be integrated as biofuel for primary energy consumption to substitute fuel-energy and to lower CO2 emissions during building's life period (Gustavsson, 2015; Gustavsson, 2009). For example, the renewable energy generation in the UK is increasing and wood as biomass is expected to make a significant contribution in energy production (Kutnar & Muthu, 2016).

Therefore, it is shown that *After Use* phase of wood buildings has the potential to reduce costs in the form of recovered and reused wood products as well as energy production from bio-waste and general waste minimization. That is, with further research and wider spread of results, key stakeholders should acknowledge *After Use* phase costs and take into consideration potential end-of-life savings at the beginning of building development (Heralova, 2014; Cyert & March, 1963 cited by Miner, 2006).

## 2.3 Economic Assessment Methods: LCC

The subchapter introduces and briefly defines different assessment methods to evaluate economic performance of buildings. Afterwards the focus shifts to the Life Cycle Cost method as a main quantitative research approach used for the study. Detailed applications of LCC to assess the economic efficiency of wood buildings is presented with a description of required data and its sources and potential impact of LCC into stakeholders' decision-making.

The main purpose of the economic assessment is to examine economic performance of a building as part of an integrated holistic sustainability assessment. It is mainly performed to provide assistance in decision-making including (European Standard SFS-EN 16627, 2015; Ruegg & Marshall, 2013; Gluch & Baumann, 2004):

- financial analysis, investment attractiveness and profitability
- determination of all costs associated with building project
- economic comparison of different design options
- determination of the most cost-efficient design option
- comparison of replacement, refurbishment and/or new construction
- identification of the potential for improved performance
- determination of ownership costs reduction etc.

The scope, goals and intended use of the economic assessment will define the economic method that should be applied. Thus, in last two decades, many different economic methodologies and assessments tools have been developed. The most common methods among those would be (Hoogmartens et al., 2014; Haapio and Viitaniemi, 2008):

- LCC (Life Cycle Costs)
- LCCB (Life-Cycle Cost-Benefit)
- CBA/ BCA (Cost Benefit Analysis/ Benefit Cost Analysis)
- NB (Net Benefit)
- Payback period

Listed methods mainly originate from the LCC analysis and are modified economic assessment tools adapted for and applied to different contexts (Gluch and Baumann, 2004; Finkbeiner et al., 2010). These methods are closely related to each other, even though there are some differences in formulation, in assessment scope, in unit of measure, interpretation, etc.

*LCC* is a rational life-cycle approach considering all the costs incurred over a defined life time with regard to all relevant material and energy flows. This economic analysis estimates costs ranging from initial construction, maintenance, and repair, to demolition costs with failure costs included and work as an explicit part of the decision-making process (Padgett et al., 2009; Thoft-Christensen, 2014; Carter & Keeler, 2007). Including further performance parameters, LCC can be utilized in a broader sense, like investment appraisal, estimation of waste streams and application of specific economic analyses

(European Standard SFS-EN 16627).

*LCCB* analysis used to appraise project proposal by making expected assumptions on costs and future benefits (Thoft-Christensen, 2010). It is explained by Thoft-Christensen (2014) as LCC with expected social and environmental benefits included in the assessment. Also, Carter and Keeler (2007) pointed out that LCCB is a conventional cost–benefit analysis applied over the life cycle, in their study case, of the green roof system.

*CBA (BCA)* was introduced to assess the attractiveness of investments of projects based on Net Present Value (NPV) method (Hoogmartens et al., 2014). It has been widely recognized as a useful framework for comparing alternatives over time and considering positive and negative aspects of relevant actions using discounting method to formulate findings (Carter & Keeler, 2007). The test of NPV is a standard method for assessing the present value of competing projects over time.

*NB* method is described in the book of Building Economics by Ruegg & Marshall (2013) as a straightforward and reliable tool. It is estimated as the difference between a building's time-adjusted benefits and time-adjusted costs of investments and mainly applied when there is the possibility for significant reduction in building's future costs.

*Payback period* measures the length of time required to recover the additional investment (increment cost) on efficiency improvement (Hesser et al., 2017). The concept of payback period is also found to be useful as part of the Life cycle analysis to determine environmental impacts of applied products enabling the analyzing of investment attractiveness and the evaluation of environmental technologies early at the development stage (Hesser et al., 2017; Mahlia et al., 2010).

However, preliminary investigation shows that LCC is most used as standalone methodology to assess cumulative cost of the building because it is simple to formulate and used in scenario driven applications to choose the best option based on economic consequences (Ruegg & Marshall, 2013). Indeed, LCC analysis reflects the economic part of sustainability development in the construction industry and its relatively simple method to perform considering the use of discounting technique to count the time value of money (Giuseppe et al., 2016). Therefore, economic assessment for the quantitative research has been computed using general LCC method and is discussed in further details in the next sections.

## 2.3.1 Life Cycle Costs (LCC) Method

Life Cycle Costs (LCC) is a method used to produce a detailed assessment of total costs occurring during a building's life time to provide comprehensive economic impacts conception to achieve the lowest long-term cost of ownership (Mahlia et al., 2010). Therefore, the LCC is chosen as an assessment method for the current study, since it has further potential to perform the whole economic sustainability evaluation for modern wood buildings. The idea of economic sustainability is to minimize costs during a building's life cycle, which produces more competitive price policy (Ahmad & Thaheem, 2018; Koppelhuber et al., 2017; Bartlett & Howard, 2000).

LCC makes up the quantitative part of the current study and its calculation approach is based on the European Standard EN 16627:2015 "Sustainability of construction works. Assessment of economic performance of buildings. Calculation methods". There are several reasons why the study chose European Standard SFS-EN 16627, 2015 as an assessment framework for quantitative research study:

- Straight forward specification of calculation methodology
- Easy implementation
- Reliable origin of the document
- Relatively up-to date standard
- Sustainability assessment under the European context

According to the European Standard SFS-EN 16627 (2015), every LCC assessment should be carried out based on the object of assessment life time called reference study period. For a building, the reference study period is the required service life of the building. A number of studies define a building's service life as a period during which the structure performs based on the intended purpose to meet users' needs and finally exceed the minimum acceptable values (with necessary maintenance) (Nireki, 1995; Kelly, 2007; Sistonen & Al-Neshawy, 2016; Blok et al., 2000).

However, depending on the initial goal of assessment, the reference study period to analyze a building's LCC can vary in length, but it needs to include all the phases through which each building passes during their life cycles (Heralova, 2014). As discussed in the previous sub-chapter, a building's life cycle consists of different costs during three main phases, namely "*Before Use*", "*Use*" and "*After Use*". These phases consist of allocated costs, which define a building's economic performance during a specific life cycle study period. Figure 1 is an outcome of LCC assessment framework described in European Standard EN 16627:2015 and shows the building's three phases with economic aspects, which are specified according to a building data.

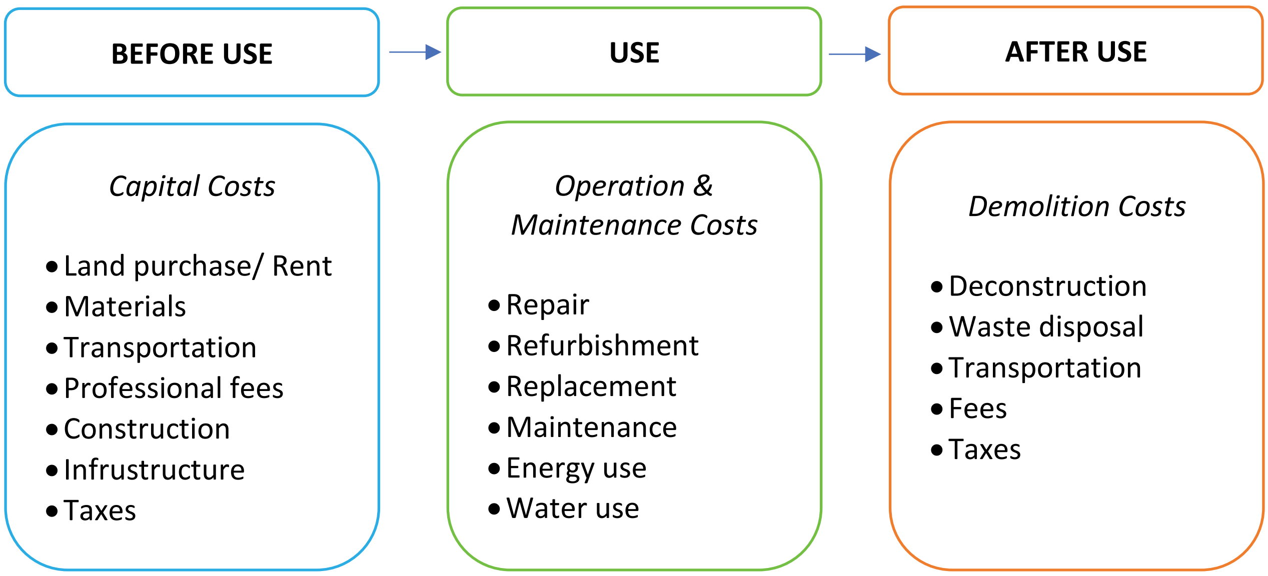



**Figure 1** Building life cycle phases including proposed life cycle costs (adopted from European Standard SFS-EN 16627, 2015)

Building life cycle phases expressed in the Figure 1 are not restricted to mentioned costs. LCC method also considers essential the fourth category which is "Income" to assess the economic performance of a building. Often, income category is considered to assess comparative financial performance of the building and to determine its financial advantages. It includes any income to the building owner from reuse, recycling and energy recovery resulting from flows of materials and components as potential resources of future use (European Standard SFS-EN 16627, 2015).

The costs and incomes assigned to the relevant phases are meant to support the decision-making process for key stakeholders. However, due to limited availability of the data, the quantitative part of the study will not include all the economic impacts in LCC assessment for the case wood building.

To capture and to compare present and future costs of a building, LCC is commonly measured in Net Present Value (NPV) method (Kishk et al., 2003; Schade, 2007; Reyck et al., 2004). NPV is the most sophisticated economic technique that takes into consideration the time value of money (Heralova, 2014). It applies across the full range of a building's economic flows, discounting them to the present value with a given discount rate (Maurer, 2008; Žižlavský, 2014).

Discount rate can vary based on a country's specific economic situation, inflation rate, capital cost, investment opportunities, and increases with the estimated riskiness of project opportunity (Žižlavský, 2014; Gulch & Baumann, 2004; Heralova, 2014; Doctor et al., 2001). In general, NPV presents a project's future annual income and outcome as a lump-sum throughout the analyzed period (see Formula 1). Usually, among mutually exclusive solutions option with the greatest NPV is the economically favorable one and decides on the worth of investing (Maurer, 2008; Smullen & Hand, 2005).

As noted by Schade (2007), however, LCC focuses on costs rather than on income; that is, life time costs are treated as positive and income as negative. Consequently, the most cost-efficient choice between two competing alternatives would be the one with minimum NPV (Kishk et al., 2003; Heralova, 2014).

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+d)^t} - IC \tag{1}$$

Net present value (adopted from Ruegg & Marshall, 2013),

where

NPV – net present value for all cash flows;

C – net cash flow in year t;

n – number of years, life cycle;

d – discount rate to adjust cash flows to the present value;

IC – total initial investment costs

Therefore, there are several advantages of LCC as a common assessment method to compare different building alternatives with the use of NPV technique. These are presented in Table 1 (Flanagan et al., 1989; Gaily, 2011 cited by Žižlavský, 2014). However, LCC has been criticized for having certain limitations that could be critical for the practical usability of the method, which is important to note (Kishk et al., 2003; Kester, 1984; Hodder and Riggs, 1985; Chapman and Cooper, 1987; Brealey and Myers, 1996, Gluch, 2004). Thus, Table 1 also shows potential drawback of the method's framework along with the advantages.

**Table 1** Advantages and drawbacks of LCC as an economic assessment method

| Advantages | Drawbacks |
|---|---|
| + cash value seen as an opportunity, rather than a time period | - difficult to cope with the potential flexibility that comes with investment projects |
| + time value of money is taken into account | - over-simplification in interpretation of environmental costs |
| + considers projects with different risk profiles | - not suitable for comparison of alternatives with different life length |
| + does not involve setting an explicit arbitrary threshold such as a minimum rate of return or a maximum pay-back time | - difficulty to define right discounted rate<br>- availability and reliability of data |

As LCC is an important decision-making tool to select the most economically efficient building project, data should be presented in a way that it enables an appropriate comparison of alternatives based on real values. The next section looks into LCC application processes and also reveals data sources required for the economic assessment and its collection.

### 2.3.2 LCC Application

According to Ruegg and Marshall (2013), LCC can be applied to evaluate comparative building alternatives based not only on the costs. The following cases reveal opportunity for LCC assessment to be applied as a decision-making tool for various reasons (Goh & Sun, 2015):

- Accept or Reject
- Lease or Buy
- Build new or refurbish/ reconstruct
- Design & Size Decision
- Location Decision
- Replacement Decision
- Combined interdependent system
- Assigning cash flows to individual actors
- Estimating waste streams
- Tendering, budgeting, estimation of future maintenance and energy costs
- Encouraging green buildings by growing recognition etc.

Generally, the study focuses on the application of LCC as a method assessment to examine economic performance of existing wood buildings and compare it to alternative buildings to analyze whether wood construction has marketing potential based on the profitability of investment. And prior to the LCC assessment, there are certain data on the building that need collecting; these must be reported to provide the most reliable cost model (European Standard SFS-EN 16627, 2015):

a. *Specification of assessment building*

To produce a cost model for wood buildings, a full description of its physical and time-depending characteristics is required. Data should be reorganized into fundamental and coordinated description by different technical processes and functionalities of the building.

For the comparative assessment, it is essential to make clear the basis of comparison. That is, two buildings should have a common reference unit corresponding to their functional characteristics. Therefore, it is necessary to include common functional information for both buildings which are linked to their economic aspects.

According to SFS-EN 16627, there are several descriptive aspects of the building that should be consistent throughout the assessment to assist in performing candid cost evaluation:

- building type (e.g. apartment, detached building)
- constituent parts (all building elements, building's components, products, materials)
- relevant technical and functional requirements (e.g. the regulatory specific requirements)
- pattern of use (e.g. for rent, sale, social housing)
- data on relevant building cost

The choice of the level of detail depends on the goal and scope of the assessment. A large part of it depends on the availability of data at the time the assessment is carried out (e.g. sketch plans, blueprints, information on capital cost, procurement, handover etc.).

b. *Determination of system boundary that applies to the building*

Setting the system boundaries is taking into account processes in each life cycle phase, which influences the building's economic performance. For instance, this study examines existing modern wood buildings. Therefore, system boundaries should include all the costs associated with the acquisition of the site and all the remaining stages of the building during its life period (European Standard SFS-EN 16627, 2015; Heralova, 2014).

Additionally, to determine the system boundaries, it is important to outline specific scenarios to represent a building's different life cycle stages. For each stage, realistic and representative scenarios in accordance with functional, technical, physical aspects of the building must be drawn.

**Table 2** System boundaries for the building life cycle

| ***System boundaries*** | *Cost item* |
|---|---|
| Boundary of the *Before Use* Phase | Investment costs: pre-construction, including design fees, product manufacture, delivery to site, equipment, inventory, preliminaries and construction costs |
| Boundary of the *Use* phase | Operation costs: maintenance, management, inspection, repair, replacement and refurbishment. All costs to operate the building: power and water supply, cleaning, lifts and escalators |
| Boundary of the *After Use* phase | Demolition costs: liquidation costs, like dismantling, demolition, site sorting, transportation and waste management |

c. *Life cycle period and procedures for the calculations*

For wood buildings, selection of an appropriate period for the economic assessment is necessary to determine the effect of building service life on life cycle costs associated with the specific structural material (Rauf & Crawford, 2014). Yet depending on study goals, it is possible to produce an assessment for a different period of time than required service life, however it is important to estimate the whole life cycle and include discounted end of life costs to the assessment.

Kneifel (2009) states that life-cycle cost assessment can be conducted over four different study periods: one year, 10 years, 25 years, and 40 years. The author also mentions that with a longer study period, energy-efficient building design alternatives become more cost-effective to adopt, showing the greatest change between 10 and 25 years of the study period. Sarma and Adeli (2002) also suggest that the economic study period of most structures is often in the range 30to 40 years, while the actual lifespan can be 60 to 85 years if not more. Heralova (2014) agrees that for public buildings the length of the study period should be as 25 to 30 years, and that private investors could use a shorter period with a maximum of 10 to 12 years.

Thus, a longer study period can be more effective at capturing all relevant costs of owning and operating a building. But at the same time, a longer study period increases uncertainty because of the assumptions surrounding future activities, such as operational costs and energy consumption. Overall, the main principle that applies to the study period is that it has to be the same for all alternatives considered. (Fuller, 2006)

Procedures for the LCC calculations include conversion of costs spent in the course of the life cycle to the present value considering inflation rate and length of analyzed period. In order to add and compare cash flows that are incurred at different times during a building's life cycle, future cash flows have to be presented in the time value of money. It also reflects an investment opportunity by taking into account the interest rate of the minimum acceptable rate of return (Gluch & Baumann, 2003; Sarma & Adeli, 2002; Fuller, 2006).

## 2.3.3 LCC Data Sources

Performing an LCC analysis is a data intensive method due to the complexity of the building processes and a large number of building components need to be taken into account. Therefore, to balance LCC performance against numerous costs data, it is important to have accessible sources. The final result, then, is dependent on the availability and reliability of the input data. (Gluch & Baumann, 2003)

As captured by Flanagan et al. (2005) in their book called *Whole Life Appraisal for Construction*, it will require a great deal of time to look for accurate cost information from numerous sources. The process of data collection is time consuming and shows the gap in data availability to create a sufficient costs model for a building assessment. Nevertheless, the author also mentions that with the use of electronic systems, it became possible to gather necessary data.

Schade (2007) allocated three of the most common sources for a building's costs data collection, which are also used in the current study:

- Main stakeholders: contractors, architects, facility and property manager
- Historical data based on existing buildings and statistics
- Data from modelling techniques

For existing buildings, the most reliable and accurate data can be achieved from key stakeholders like manufacturers, suppliers, contractors, testing specialists etc. For example, contractors may have an initial construction cost model with detailed allocations of all costs occurring in the *Before Use* phase. In the same logic, it is assumed that architects may have detailed knowledge on the design processes and fees, while suppliers can share characteristics of delivered materials and components to compare and approve all the expenses. For the building's performance data during *Use* phase, building owners or occupiers could source out data for operational and maintenance costs based on actual consumption estimations (Schade, 2007; Flanagan et al., 2005).

However, if the required data is not available, historical data and modelling techniques can be used. There are available databases to estimate maintenance and renovation costs and make comparisons with similar building projects to establish *Use* phase costs (Heralova, 2014). Thus, it is important to select comparable alternatives based on building requirements and indicators that have an impact on its economic performance. Moreover, extensive knowledge and experience of experts and specialists could be a valuable source for life cycle information. Thus, to improve building measurements and validate costs assumptions, engaging professionals can contribute to more accurate information on a building's costs optimization (Cazemier, 2017).

Another data source is modelling techniques like mathematical models which are developed for analyzing costs. Those techniques are usually based on statistics and can be incorporated to address the uncertainties (Flanagan and Jewell, 2005 cited by Schade 2007). Data from existing buildings can be gathered and processed digitally to simulate the life cycle pattern for a required building model and evaluate its performance based on identifying a building's characteristics and its specific surroundings (Goh & Sun, 2015). There are programs like BCIS Online and Building running costs meant to provide sound basis for life cycle costs advice and further optimization of economic plans (RICS.org, 2018).

As LCC is dealing with a great amount of present and future costs data, it can be applied with some level of embodied uncertainty. Therefore, irrespective to LCC recognized benefits, the uncertainty may have an effect on the motivation to adopt the method for decision-making (Goh & Sun, 2015; Cole & Sterner, 2000). The following section elaborates on the current interest and limitations to implement LCC method in decision-making.

## 2.3.4 LCC in Decision-Making

It is often stated that LCC initiatives should be integrated in decision-making process early at the development stage based on the theory that firms are looking to maximize profits by operating with full knowledge (Heralova, 2014; Cyert & March, 1963 cited by Miner, 2006). Implemented at the design and construction procurement stages, LCC has the most potential to impact effective selection of building material (Heralova, 2014 ADD). To give priority and preferences, decision makers must have access to complete information about the consequences of selected alternatives and ensure that the decision balances feasibility, desirability and sustainability (Gluch & Baumann, 2003; Langston, 2012).

For example, in the context of wood construction, LCC can be included in decision-making to show cost aspects and primary feasibility variables of alternating construction materials like Cross Laminated Timber (CLT) and Laminated Veneer Lumber (LVL) (Cazemier, 2017).

However, it is evident that there has been continuous low motivation from practitioners to implement LCC in decision-making (Larsson & Clark, 2010 ; Cole & Sterner, 2000; Lindholm & Suomala, 2004). Main hesitant factors seem to be the uncertainty level involved in the LCC, unreliability and poor availability of data, and the overall difficulty to understand and present concept of sustainability (Gluch & Baumann, 2003; Lozano, 2008 cited by Langston, 2012).

Lindholm and Suomala (2004) from Tampere University of Technology conducted intensive research on LCC and its application for decision-making. Interviews with Finnish industries confirmed that lack of availability of the input data and uncertainty of LCC calculations are among the main challenges to implement the method. Gluch and Baumann (2003) also mentioned that lack of data and a poor quality of existing information makes LCC unappealing to support decision-making.

In his master's thesis, Guoguo (2009) mentioned that LCC implementation involves comprehensive building design along with quality materials and construction practices with environmental considerations. When the decision should consider sustainability goals and investments for environmental solutions, detailed level of LCC calculations may be perceived as overcomplicated. In contrary, Gluch & Baumann (2003) pointed out that LCC method can improve the structure of processing large amounts of complex information and helps to translate environmental concerns into familiar monetary dimension. However, this thesis does not translate building's environmental impacts and there is no further elaboration on the subject.

To date, it is shown that sustainability strategies and frameworks have too wide of objectives, which are noticeably difficult to integrate in the built environment decision-making (Fiala, 2008; de Meester et al., 2009 cited by Langston, 2012). Therefore, the existing gap between theoretical and practical understandings of LCC merits and the monetization approach of the economic sustainability constrains decision-makers to consider life cycle perspectives (Lozano, 2008; Flanagan et. al., 1987; Gluch & Baumann, 2003; Cole & Sternere, 2000).

Additionally, there is an extended number of cost efficiency-oriented tools and neither an agreed-upon definition nor an approach for assessment (Hong et al., 2011). This lack of uniformity in methods and concepts and multidimensional information required can cause confusion and subjective choices throughout the assessment process. This can make decision-making difficult and hinder the adoption of LCC method during the conceptual and development phases (Gluch & Baumann, 2003; Lindholm & Sumoala, 2004; Kiesse et at., 2017).

## 2.4 Key Stakeholders in Wood Construction Industry

LCC is an assessment methodology which can indicate economic performance differences between alternative buildings and determine the optimum solution with minimal life cycle costs. However, it is the decision-maker who, depending on considered economic objectives and requirements, selects the most suitable of options. This thesis is investigating economic performance of wood building. To obtain a wider perspective on the topic, theory should be compared and verified with professionals from the industry.

Collecting construction industry professional perceptions on different aspects of the wood construction market can be a very effective tool, especially when it is almost the only source of information (Blind et al., 2001 cited by Toppinen et al., 2016). This subchapter provides information on construction key stakeholders, their economic interests and their perception on wood buildings' economic efficiency as well as decision-making factors for wood construction.

### 2.4.1 Main Stakeholders: Who Are They?

In any project, there are different stakeholders' interests that need to be considered. A stakeholder is an individual or a group that can affect or can be affected by a process and without whose participation, a project cannot survive (Donaldson and Preston, 1995 cited by Roos et al., 2010; Hillman and Keim, 2001). There are many actors in the wood construction business and different professionals, technicians, representatives of all enterprises can be involved in the construction project.

In the literature, main construction players are usually presented as experts and information contributors to the research field. Like so, experts from different disciplines were involved in the study survey by Koppelhuber et al. (2017), mainly being architects, engineers, contractors, public and private investors. The study by Wang et al. (2013) examined potential of wood use in green buildings focusing on timber and construction sector experts like manufacturers and suppliers, contractors and timber expert organizations. While Thomas and Ding (2017) mentioned developers, design consultants and occupants to the primary stakeholders for materially specific buildings.

Toppinen et al. (2015) investigated future growth prospects for wooden multi-story construction and used qualitative analysis for experts' interviews to study their experience and preferences for wood as sustainable building material. They specifically highlighted a sector of wood construction value chain including forest industry, wood products industry and building industry. Thus, the study excluded consultants and architects from the analysis. In contrast, Jones et al. (2016) studied conditions for the adoption of CLT materials in the construction industry by targeting mainly designers and contractors, stating that these are primary decision makers on the selection of construction materials. Interestingly, the study found that quantity surveyors perceive innovative wood materials riskier in terms of costs and therefore might influence the decision-making.

Gosselin et al. (2017) and Schmidt and Griffin (2013) mentioned that architects and structural engineers are early stage influencers, have experience in specifying materials for multifamily houses, reflecting on client's requirements and taking on decisions. Roos et al. (2010) also pointed out architects and structural engineers as central technical professionals called "system integrators", who are involved in material selection during the design stage. Their attitude is considered as the key factor to diffusing timber construction.

Hemström et al. (2016) find main contractors to be influential in the selection of the building frame and therefore have a significant role in decision making. In addition, manufacturers and product suppliers are recognized to have a huge influence on the decision making and that it is in their interest to demonstrate sustainability and whole life costs of offered products (Bartlett & Howard, 2000; Roos et al., 2010). Meanwhile, Cazemier (2017) conducted research on the CLT financial performance from the real estate developers' perspective, considering them to be main actors to promote the adoption of new structural materials.

Considering previous studies and connecting different stakeholders in the wood construction industry who are most frequently mentioned as main decision-makers, this study mapped out building construction stakeholders (Figure 2). As seen below, Figure 2 represents the building project process, where each phase has its main stakeholders who have the ability to make decisions and affect the whole building system.

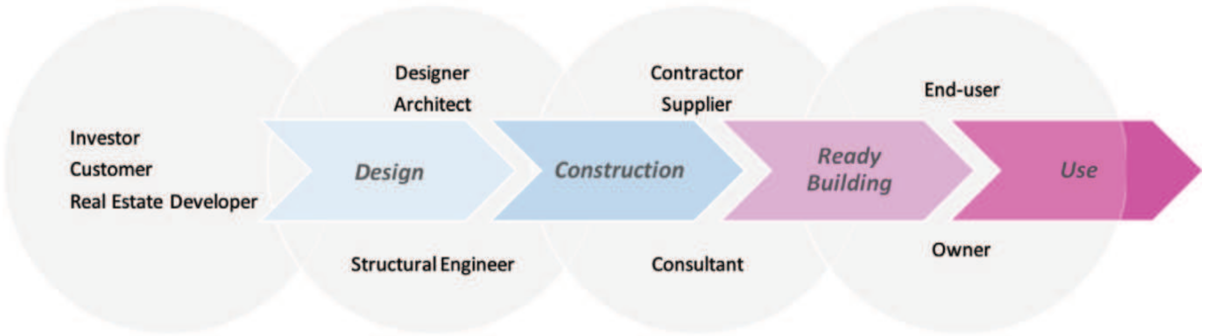



**Figure 2** Building construction process and main stakeholders

Bartlett and Howard (2000) give detailed explanation of different actors to deliver sustainable building projects and what economic driving values they pursue. In the same way, a study from the Philippines on the business ecosystem for green buildings (Ma et al., 2017) presented a detailed list of stakeholders in a building's life cycle including building owners, real estate developers, contractors, material and energy suppliers, and end-users. Both studies maintain that each stakeholder has different needs, interests and abilities to impact a building's sustainable life cycle.

Jafari and Valentin (2017) observed that most of a building's financial decisions occur early =, considering mainly initial construction costs instead of a building's life-cycle costs. Therefore, it is common that the developers, investors and contractors might be the main decision-makers based on their economic interest. As confirmation, Høibø et al. (2015) mention in their study that owners or end-users today often have little influence on material selection. At the same time, information about consumer preferences on new building materials can be very important and valuable for those who take on decisions.

Project stakeholders and the goals they pursue affect building development and management processes. It is therefore important to recognize stakeholders' interest towards life cycle costs in order to understand the main economic decision-making factors to implement new construction methods. Previous studies show that different stakeholders have different needs, interests and concerns (e.g. Martinez & Olander, 2015; Olander, 2007; Newcombe, 2003; Bartlett & Howard, 2000). Figure 3 represents a general picture of main external (white cells) and internal (blue cells) stakeholders involved in a building's life cycle and their interests. External stakeholders have indirect influence on direction and decisions for building project development (Olander, 2007). Those can be municipalities, local authorities, financial institutions like banks and insurance companies, as well as administrative boards and government (Newcombe, 2003).

This study focuses in particular on the internal stakeholders, also known as primary stakeholders, who have financial interest over building's life cycle and expectations on its performance (Jawahar & McLaughlin, 2001). Thus, Figure 3 shows that developer's interest at the Before Use stage when receiving revenue from selling new building and the site. In addition, architect and contractor have economic interest before building's completion. Usually for investor and owner, all monetary flows during a building's life cycle are relevant with the exception of operational costs. Energy efficiency and running costs are end-users' (tenants) main responsibilities and interests (Bartlett & Howard, 2000).

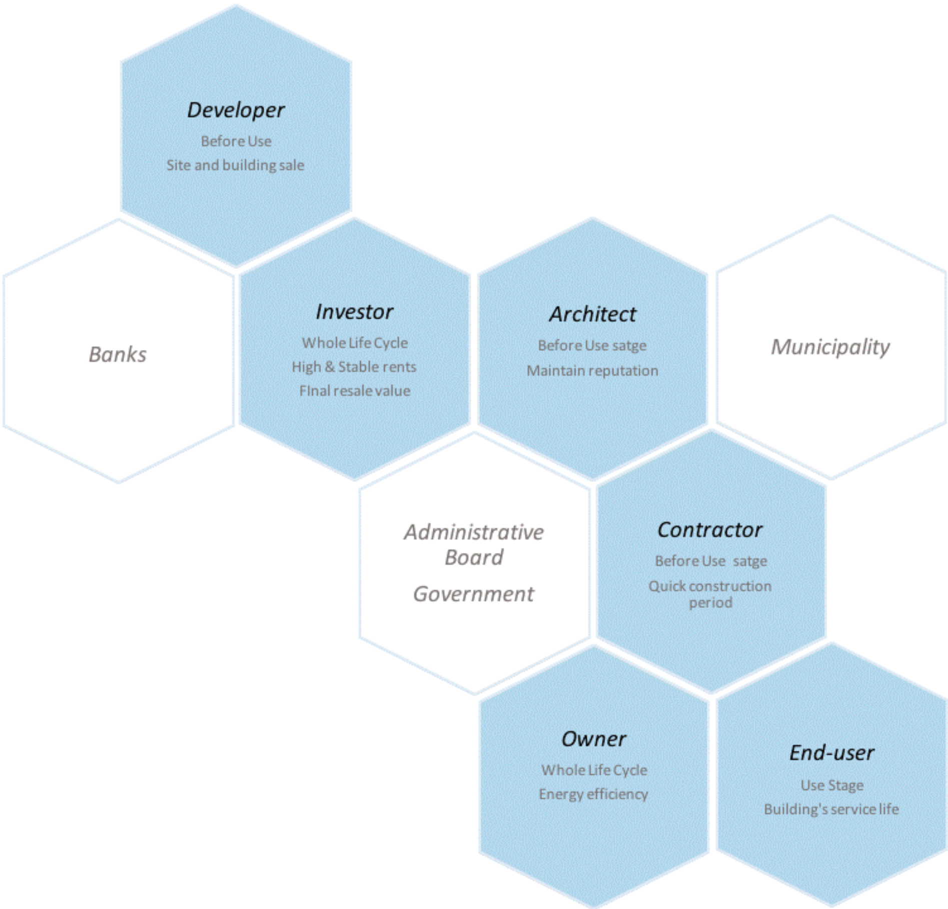



**Figure 3** Stakeholders mapping with their economic interests

Therefore, key stakeholders will have different priorities throughout a building's life cycle and at any given time, some of them would be more important, granting a higher level of decision-making power (Newcombe, 2003; Olander, 2007; Jawahar & McLaughlin, 2001). In order to make an impact and provide successful building performance, it is important to acknowledge all various parties involved and consider close orientation on their needs and interests.

## 2.4.2 Perception on Wood Buildings' Economic Efficiency

Today's perception towards the economic aspect of wood buildings is considered as one of the main barriers for extended wood implementation in the construction industry (Hemström et al., 2011; O'Connor et al., 2004). Lack of economic knowledge among stakeholders can contribute to perception that wood building projects are more unpredictable in terms of costs.

According to Cazemier (2017), investors and banks who act as a debt facility to fund the completion of building projects are still quite unfamiliar with all the risks involved in modern wood construction and thus may set a higher contingency rate on development finance, which in turn will increase the total price of a wood project. Also, the trade-off between perceived project risk and return is a primary factor for developers to evaluate economic efficiency of the project (Jones et al., 2016; Cazemier 2017). At the same time, developers appreciate inherent properties of wood like its light weight, which can speed up the construction process and save money (Roos et al., 2010). Thus, there is a clear extent of uncertainty towards economic performance and risks of wood construction, which may impact on developers' determination.

A VTT (2017) report indicated an opinion among construction developers that wood buildings will yield no compensation for reduced lifecycle costs in the local market-driven demand. Therefore, to avoid unexpected costs and uncertainties, construction companies prefer other building materials to wood. Jones et al. (2016) claim that construction actors are likely to stick with the same materials they have been working with for a longer period of time. Contractors also have an impression that domestic wood producers prioritize export markets (Roos et. al., 2010). Thus, a limited number of producers with wider target customers may increase their rates for wood construction products.

Moreover, two studies (Bartlett & Howard, 2000; Jones et al., 2016) acknowledged that quantity surveyors or costs consultants can be conservative when it comes to the innovative development costs estimation. There is a general misconception that environmentally friendly construction methods like building with CLT materials can be between 5% to 15% more expensive to construct from the outset compared to traditional construction (Jones et al., 2016).

Therefore, it appears the overall stakeholders' perception on wood construction economic efficiency is vague and sceptical, which may evoke negative communication. Table 3 summarizes main reasons why stakeholders have a likely negative perception on wood construction economic efficiency. It includes results of interviews and surveys presented in a number of studies, where stakeholders' attitudes and perceptions towards wood construction cost is analysed as the research topic (Hemstrom et al., 2010; Roos et al., 2010; Jones et al., 2016; VTT, 2017; Thomas & Ding, 2017).

Still, perception and reasons shown in Table 3 are not applicable, nor are they generalizable, for a bigger population of construction stakeholders. However, it is important to understand the root causes for the existence of such perceptions and how they formed during this time. Also, a larger study is required to verify and confirm stakeholders' poor perception about cost aspect of wood construction. In continuation, Roos et al. (2010) argue that there is no exceptional perception that wood construction costs is a barrier.

**Table 3** Stakeholders perception on wood construction costs

| Perception | Reason |
|---|---|
| ***Investors, Real Estate Developers, Contractors, Engineers*** | |
| **High construction costs due to risk** | • new construction method/ limited knowledge<br>• failure by the subcontractor to perform<br>• off-site manufacturing & on-site fabrication processes<br>• payment of CLT prior to delivery on site |
| ***Cost Consultants, Surveyors*** | |
| **More expensive than conventional construction** | • limited understanding of innovative technologies involved<br>• limited wood material production processes<br>• no full attention to the client's financial view point and long-term interests<br>• incompatible comparison of high-profile buildings with conventional cases<br>• simple substitution of conventional materials capital costs with modern materials<br>• limited presentation of relative economic impacts for innovative alternatives etc. |
| ***Architects, Designers, Structural Engineers*** | |
| **Ambiguous about economic aspects and associated risks** | • limited knowledge<br>• insufficient education, lack of experience |

It is fair to note that end-users were not included in the table because of the existing idea that consumers seem relatively uninformed about the economic efficiency of wood buildings (Keith, 2011). It appears that ultimate decision-making criteria for users is location, price/rent, including aesthetics, and architectural design (Roos et al., 2010). Accordingly, in several studies, market participants of the residential building sector showed that the choice for construction materials and buying decisions are based on non-quantifiable variables like perceived product quality, value and personal tradition rather than just price (Jochem et al., 2016; Toivonen, 2011; Høibø et al., 2015; Roos et al., 2010). The next section explores in more details what factors actually play role in stakeholders' decision-making.

### 2.4.3 Decision-Making Factors to Implement Wood Construction

From previous sections, it is clear that economic factors play an important role in decision-making and can be used as an argument to select construction material (Hemstrom et al., 2010; Roos et al., 2010). In fact, material choice can be a very rational and economically-led process, especially for developers who are risk-averse and procure deals with cost-constrains (Gold et al., 2007 cited by Jochem et al., 2016). Though, Jochem et al. (2016) also recognized that economic factors are more significant in commercial, non-residential projects rather than in residential, where price plays a minor role.

Sustainability credentials are considered to be one of the main factors in deciding on wood materials for projects (Jones et al., 2016; Jochem et al., 2016). It is also confirmed in other studies (e.g. Gosselin et al., 2015; Schmidt & Griffin, 2013; Gold & Rubik, 2008; Werner & Richter, 2007) that the environmental performance of wood buildings is highly valued, as renewable material in multi-story buildings. Toppinen et al. (2017) remarked brought general attention to the climate-related regulations as one of the driving forces for the development of modern wood construction. The environmental quality of wooden products can be identified and seen as logical (Toivonen, 2012); however, the practical meaning of environmental benefits can still be vague for the majority of consumers.

The sustainability benefits of wood building are more known as ''soft'' factors (Gold & Rubik, 2008) such as aesthetics, well-being and environmental friendliness. In this case, architects were seen as the primary group to value sustainability more as a decision-making factor, emphasizing social engagement and aesthetics of wood buildings (Jones et al., 2016). Therefore, sustainability was revealed as "lucky adjunct" (Jones et al., 2016), rather than the primary driving factor. Indeed, Jochem et al. (2016) investigated that environmental benefit does not increase customer willingness to pay more for the product and it is only a decisive factor when prices for two products are the same. Therefore, developers are interested in emphasizing environmental benefits during marketing as it helps to promote sales (Bartlett & Howard, 2000).

Apart from the costs and sustainability, another key factor in influencing stakeholders' decisions is technical performance of construction material (Jones et al., 2016; Høibø et al., 2015). In the survey by Jones et al. (2016) about 96% of respondents pointed out this factor as ranging from important to very important. Stakeholders are unlikely to adopt a material which cannot meet technical requirements. Espinoza et al. (2015) chose CLT technical performance as the main subject of the study and showed that this building material can have great lifespans and could be used as a load bearing structure. Moreover, they pointed out advantages of CLT regarding fire performance and excellent seismic behavior. Also, for the flexibility of wood construction, its low weight, as well as industrialization methods along with environmental benefits are considered to be convincing points which can impact the material selection (Roos et al., 2010; Gosselin et al., 2015).

From the survey among a large amount of apartment block dwellers on material preferences, Høibø et al. (2015) found that respondents preferred wood materials if they had previous experience with wood buildings and considered environmental issues to be important. However, when it comes to the structural product, the majority will prefer to choose other material than wood for building construction. This could be also related to the limited knowledge people have towards wood construction materials. This supports the findings of Schmidt and Griffin (2013): that if stakeholders are to be provided with information necessary for understanding the product and its capabilities (in addition to their own professional knowledge), then wood materials like CLT are seen to be capable of fulfilling a building's structural needs. Thus, it is suggested (e.g. Høibø et al., 2015; Schmidt & Griffin 2013) that if the knowledge about wood will be more present in society, the difference between the preferences for other heavy materials versus wood can decrease. Once the capabilities of wood construction are known, stakeholders could agree that wood is a viable alternative building material.

Therefore, the general perception of the benefit of using wood products has to be increased at the various stages of decision-making through raising an adequate awareness on material values and knowledge about its technical quality, economic competitiveness and environmental performance (Werner & Richter, 2007). Another necessary step is to integrate 'life-cycle thinking' and consider costs and environmental benefits in conjunction to deliver true long-term value for the client/owner and end-users, and thus, more interest from stakeholders towards sustainable building development practices (Bartlett & Howard, 2000).

# 3 METHODOLOGY

This chapter represents a connection between the research questions and the findings. It is also leads to the discussion and conclusion part. The nature of the thesis is based on two research methods: qualitative assessment and quantitative exploration. Thus, the research approach is describing two methodological choices in the relation to the topic.

## 3.1 Research Approach

The thesis has set two main research questions and each of them requires a different research method: quantitative and qualitative. The quantitative research method is used to quantify data through numerical measurement and is presented as LCC assessment for the specific case study. This method is primary in the research because it enables the combined answer to the first research question and presents main idea of the thesis topic looking into the study through a certain lens with a specified set of variables.

On the other hand, qualitative methods set the balance that provides a look into the research through a wider lens. From this, the search for a pattern of a relationship between decision-making factors and other unspecified set of concepts can be conducted. The qualitative research method was commenced with a critical literature review on the subject to identify relevant stakeholders in wood construction and further relies on individual views of participants through an online survey and interviews. As a result, this method helps to answer the second research question of the thesis.

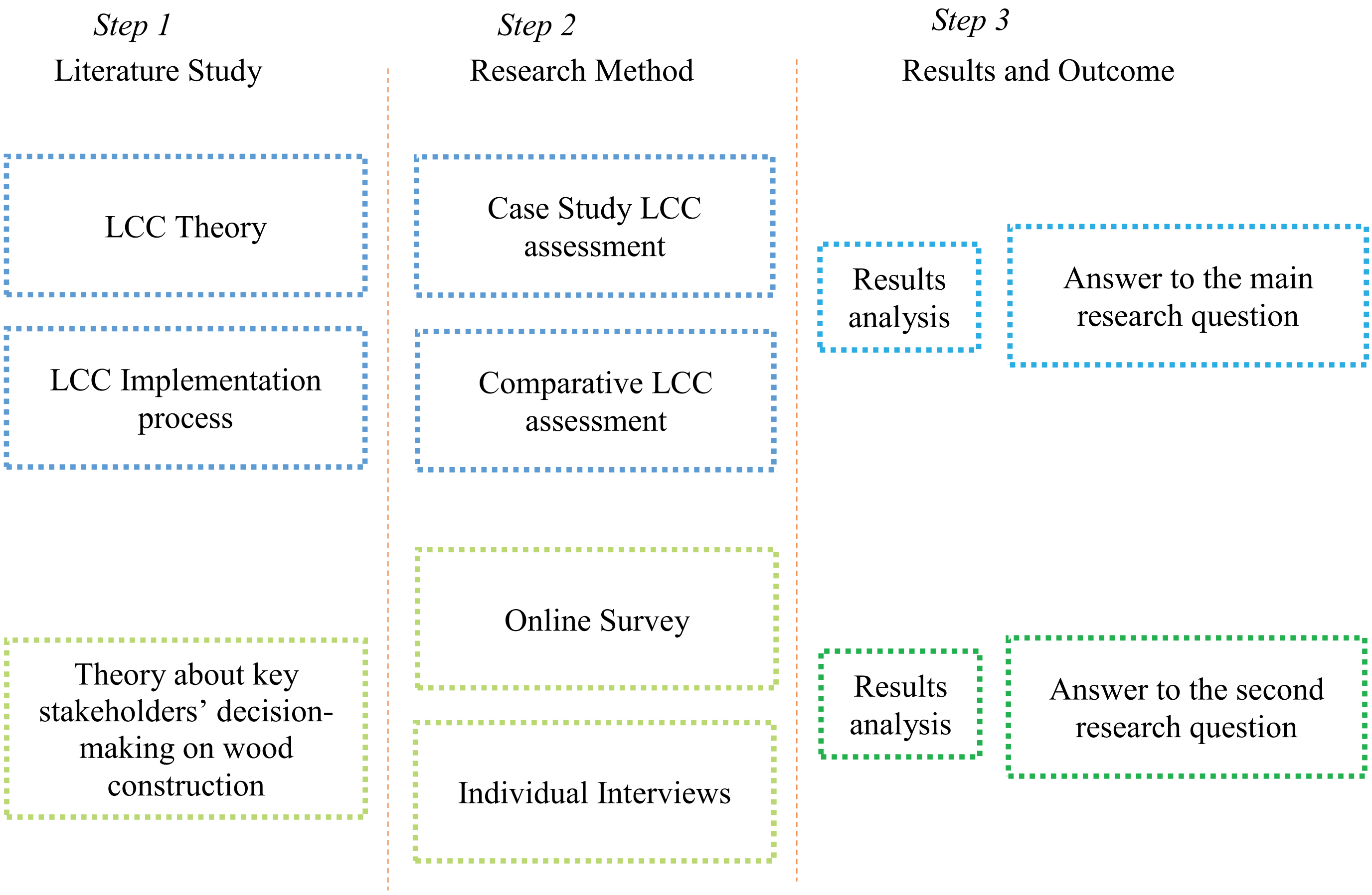



**Figure 4** Research framework with 3 steps

Figure 4 explains how the research was conducted and provide schematic overview of how different research methods are used to answer the two main questions. Thus, each research approach follows 3 common steps: Literature Study, Research Method, Results and Outcome. The research framework shows that the literature study serve as an input to conduct the research by different methodologies and then it leads to resulting the research outcomes.

Therefore, subsection 3.1.1 starts with a brief description of the main research method LCC and its analysis as the most suitable methodology to assess the economic efficiency of wood buildings. After, subsection 3.1.2 continues with the frame for the online survey and interview questions as research methods based on previous studies and experiences placing an emphasis on the economic aspects of wood construction.

### 3.1.1 Life Cycle Costs

Life Cycle Costs (LCC) is the economic efficiency assessment tool and is explored as a quantitative research methodology with regards to the specific case study. LCC is one of the economic assessment tools which is relatively simple to perform, and it corresponds with the thesis scope and set goals. Also, there are three main advantages to implement LCC assessment to determine the economic efficiency of wood building.

*First*, LCC enables the examination of the economic efficiency of wood buildings as part of an integrated sustainability assessment. As previously mentioned, the study employs Life Cycle Costs assessment framework described in the European Standard on sustainability of construction works (European Standard EN 16627:2015 "Sustainability of construction works. Assessment of economic performance of buildings. Calculation methods"). LCC covers the economic aspect of sustainability and helps to demonstrate maximum value for all costs that occur during a building's life cycle. It also supports a complete sustainability assessment of a building's project development including environmental and social aspects.

*Second*, LCC is based on realistic cash flow analysis and allows one to translate sustainable building applications into the monetary unit, which is a more familiar and comprehensive dimension for decision-makers (Gluch & Baumann, 2004). The calculation method for LCC includes determination of all costs, which might occur over the life cycle as result of implemented project. Additionally, it can add to the value generation by providing data for (European Standard EN 16627:2015):

- Budgeting and optimization project's future costs
- Estimation of end of life costs and waste streams
- Identification of circular economy development opportunities
- Specific economic analyses (e.g. cost benefit analysis, payback period, internal rate of return)
- Assigning cash flows to individual stakeholders (e.g. landlord, owner, tenant)

*Third*, LCC allows for the consideration of long-term view on sustainable responsibility and therefore assists as a tool in decision-making. The tool can provide a comprehensive comparison of alternative building structures and select the most cost-efficient option based on economic performance over a long period of time (Ristimäki et al., 2013; Goh & Sun, 2015). Essentially, LCC performed early at the design stage can bring economic feasibility study for the project complementing the overall sustainability goal.

The key incentive to apply LCC assessment in this thesis is to demonstrate the possibility of cost reductions during the whole life cycle of wood building, even if an additional increase in the initial investment is necessary. Results of the study have potential to support the overall economic sustainability assessment of wood construction and lead to well-reasoned decision-making for contractors and other main stakeholders. LCC assessment could be important due to practical and experience-based view on improving sustainable construction development and offering better built environment.

For the current study the implementation of LCC was organized in following way:

*Specifying case buildings for the economic assessment*

- Confirm case wood building
- Identify building parameters and analysis requirements

*Collection of costs data for the economic assessment*

- Assembly of costs and performance data for the case building

*Life cycle cost assessment*

- Calculations
- Economic analysis and results

*Communication*

- Verification
- Results interpretation and reporting

*Wood building's economic efficiency*

*Comparison LCC of wood building with LCC of concrete building*

*Wood building economic sustainability conclusion*

However, the actual LCC implementation process deviates from the plan and does not follow it completely due to unpredictable behavior of external information providers related to the real case building taken for the assessment.

Moreover, the current study doesn't claim to promote LCC analysis as the only and integral approach in making environmentally responsible decisions, but rather concludes that it is an important financial factor in a decision-supporting analysis (Gluch & Baumann, 2004).

### 3.1.2 Online Survey and Individual Interviews

The research methodology also includes the Online Survey and Individual Interviews among wood construction industry representatives. The quantitative research method considers key stakeholders' perspectives on wood construction, affecting the overall conclusion of the research. This is of particular importance, as stakeholders' interests towards economic efficiency and overall performance of wood buildings are aligned and taken into account as a step to achieve further effective stakeholders participation.

***Online survey*** as a quantitative research tool is capable of reaching a larger number of participants simultaneously and can be managed in a time-efficient and flexible manner (Wright, 2005; Evans & Mathur, 2005). It is a method to collect highly structured results that are easy to present. The aim of the current online survey is to bring statistical patterns from the participants' answers about their perspectives on wood construction.

The initial and primary aim of the online survey was to identify differences in construction costs between wood and traditional buildings and find out what indicators are the most considerable during the construction development phase. The study and organization of the online survey started with a relevant literature review focusing on construction costs and wood construction market. The key words the search have started with were construction costs allocation and main economic aspects to consider in construction process. To be able to maintain focus on the wood construction, all words have been combined with wood, timber building, or CLT. This helps to narrow the view.

The literature review was meant to form a theoretical framework which has served as the basis for the practical study. Eventually, a survey with the title "Economic aspect of modern wood construction and their impact on decision-making" was developed and was mainly directed to the construction industry representatives. A sample of the online survey with all the questions attached can be found in Appendix

1.

Nevertheless, the online survey can also be limiting in regard to the variety of questions, its adaptability, and the approachability to respondents. Additionally, it cannot show deviation or clarification, but it can have probabilistic sampling and may introduce "systematic bias" etc. (Wright, 2005; Andrews et al., 2003; Evans & Mathur, 2005). To improve response quality and obtain a deeper perspective into the subject, it was decided the qualitative research methodology would include Individual Interviews for focus groups.

***Individual Interviews*** more accurately capture key stakeholders' past experiences and allow them to be responsive to relevant issues raised during the sessions (Legard et al., 2003). Semi-structured interview questions were also organized in advance to ensure the validity of the research findings but remained flexible to give the interviewee the freedom to express important points related to the interview topic.

In addition to the Finnish market, individual interviews were conducted in several other European countries to achieve deeper knowledge on the wood construction industry. Specifically, wood construction and real estate representatives from Austria, Sweden, UK, Norway and France were invited to the interviews. The country focus group is defined based on the wood building market overview (Chapter 2, Section 2.1), and also on the professional cooperation contacts from Stora Enso.

To overcome geographic boundaries due to the thesis scope, additional individual interviews were conducted over the phone. This enabled the collection of data from different countries with the set timeline. In both cases, the structure of interviews remained more or less the same, and questions were formed based on the previous studies related to stakeholders' perception on wood construction. The aim was to find out to what extent economic efficiency was taken into account in existing buildings based on stakeholders' experience and how the wood construction market could be improved. Afterwards, the interview results were compared to find common ground between the theory and the practice. Overall, each individual and phone interview is unique and allowed for the gathering of more information, adding value to the research findings. The list of semi-structured interview questions can be found in Appendix 2.

## 3.2 Research Process

This section aims to present a practical approach of the research work. It presents the process of implementing the research methods to collect the data required to answer the research questions. First, this section starts with the introduction of the case study for the comparative life cycle costs assessment. It then continues with a description of each research method analysis.

### 3.2.1 Case Study Introduction: Bridport House

To demonstrate LCC analysis in practice, the study provides an economic assessment of a specific case building. The case building is a residential wood building located in London, UK called Bridport House. It is one of the first modern multi-story buildings to have an entirely CLT structure including the ground floor. The building's main CLT supplier is Stora Enso, which acted as a partner for the present research work.

Stora Enso is a renewable materials company and has a wide range of products and services available including a wood products division. The study had a direct connection with the Building Solutions department within the wood product division which provides innovative wood-based solutions for the construction industry. They mainly operate in European countries like: Finland, Germany, Austria, Sweden, UK, and France with deliveries all over the world (e.g. China, Australia, Brazil etc.) (StoraEnso.com, 2018).

The UK has a relatively long history in building multi-story CLT residential buildings and Bridport

House is great example where CLT is adopted as the main structure. Except having the wood structure, the building fits well for the Life Cycle Cost assessment because of the relevant period it has been in use. Also, it was important to take the case study from country other than Finland to potentially promote a more independent assessment. Therefore, Bridport House was initially introduced by Stora Enso and was eventually selected for the economic assessment as the thesis's case study.

The design of Bridport House successfully combines solid timber and other building materials such as brick, aluminum and copper, which are used in the architectural details for the façade. The building's total CLT volume is 1,576 cubic meters and all CLT boards were prefabricated and delivered in 30 sequences from Austria. Just on time delivery benefitted, resulting in a significant reduction in construction time and man hours required on the site (Willmott Dixon, 2011; Stora Enso, 2011).

**Table 4** General information on Bridport House

***BRIDPORT HOUSE (CLT)***

| | |
|---|---|
| *Location* | Bridport Place, Hackney, London, UK |
| *Date of completion* | August 2011 |
| *Occupancy* | Residential/ social housing |
| *Main construction material* | Cross Laminated Timber |
| *CLT volume* | 1576 m3 |
| *Gross Area* | 4153,7 m2 |
| *Storeys* | 8 and 5 |
| *Height* | 25,6 m |
| *Units* | 41 |

Bridport House is a building with two main entrances and eight front doors to the family sized 4-bedroom maisonettes at the ground and first floor. The upper floors consist of 33 apartments in the range of 1-3 bedrooms. All apartments are well lit with natural daylight thanks to large windows, balconies and terraces. The foundation level has piling and shotcrete to retain the excavated area. From the reinforced concrete ground, there are transfer concrete slabs that create the foundation structure (Picture 1). The CLT structure is then erected to the $8^{th}$ floor above ground and has non-visual grade. The party walls dividing apartments are also made of CLT with insulation and plasterboard and the internal walls in the apartments are made from steel studs, also with insulation and gypsum board. The external façade is brickwork wall up to the top floor. The internal fit-out is a standard design and it remains the same between the case study building and alternative building. Floor plans including detailed specification on building structural elements are provided by the architects – Karakusevic Carson and the main contractor – Willmot Dixon and the sample can be found in Appendix 3.

A large Victorian storm sewer under the site predetermined the use of CLT in the structure because of its lighter weight. However, there are other additional advantages apart from its light weight like air-tightness, acoustics, minimal assembly time, safety and healthy indoor climate. Also, CLT's structure is long-lasting and due to its strength and dimensional stability, it can form to the lift shaft instead of steel or concrete (Stora Enso, 2011).

**Picture 1** Bridport House CLT frame (Mannevitz, S. Karacusevic Carson Architects, Design with Cross Laminated Timber Design and Construction, 2015)

To assess the economic performance potential and marketing competitiveness of Bridport House (CLT), LCC analysis employs a comparison of the case wood building with an alternative concrete building. The goal of the comparison is to find out what differences in life cycle costs two buildings with the same physical characteristics have, but with alternative structural materials.

In this study, the alternative building (RC) is based on the case study building structure, but hypothetically constructed from reinforced concrete. Thus, the RC building has many of the same construction features as the CLT building, where instead of CLT load bearing walls, reinforced concrete walls along with columns and slabs are put in place. This structural methodology continues up to the top floor. The external façade remains the same with brickwork until the 8$^{th}$ floor. Internal finishes are something considered to be different for the RC building. With verification from Stora Enso engineers, it was agreed that the RC building doesn't require an extensive plasterboard covering for internal walls.

**Table 5** General information for Alternative building

| ***Alternative Building (RC)*** | |
|---|---|
| *Location* | Bridport Place, Hackney, London, UK |
| *Date of completion* | October 2011 |
| *Occupancy* | Residential/ social housing |
| *Main construction material* | Reinforced Concrete |
| *Concrete volume* | 1529,4 m3 |
| *Gross Area* | 4250 m2 |
| *Storeys* | 8 and 5 |
| *Height* | 25,6 m |
| *Units* | 41 |

### 3.2.2 Life Cycle Costs Analysis

The LCC analysis refers to the collection of quantitative cost data occurring during the building's life cycle. As mentioned earlier in the previous chapter, there are 3 main LCC data sources including "main stakeholders", "historical data" and "data from modelling techniques" (Schade, 2007). However, it was impractical to collect empirical data from all the sources at the same time. Therefore, "main stakeholders" was selected as the first choice source to obtain the most accurate data on the case building's costs.

First, it is important to define the main stakeholders who are involved in each phase of the case building life cycle and further acquire necessary data through cooperation with them. In this context, cooperation means emailing and phone calling the involved parties with the introduction of the researcher, the thesis subject and following with enquiry to obtain the data.

For the case building's *Before Use* phase, five main stakeholders were indicated:

- Main Contractor *Willmott Dixon*
- Architect *Karakusevic Carson Architects*
- Timber subcontractor *Eurban*
- Structural Engineer *Peter Brett Associates*
- Timber Supplier *Stora Enso*

For the *Use* phase one main stakeholder identified:

- Client *Hackney Council*.

The owner of the building is a governmental authority representing London Borough of Hackney with official power and duties in accordance with the law and functions related to country planning and development control. Construction processes in the London Borough of Hackney is based on the regeneration program for social rent and shared ownership (Hackney.gov.uk, 2018).

For the *After Use* phase, the study had to use an assumption to suggest a possible building's end-of-life version. According to common sense and together with a Stora Enso representative, it was agreed that by the end of its life cycle, the building will be demolished/deconstructed. In this case, the main stakeholder is to be a demolition and waste management company operating in the UK market. A number of demolition companies were contacted in London to get professional estimations of end-of-life costs. Eventually, one company agreed to provide consultancy services to estimate demolition and waste management costs specifically for the case building.

- Demolition company *McGee*

However, to verify and compare the costs for demolition works, local companies were contacted as well. Therefore, the company "*Delete*" which operates mainly in Finland and several other Nordic countries provided short estimations for the Bridport House demolition process mainly based on Finnish market figures. This provided credibility to support assumptions made on demolition costs.

Due to the study location limitations, where the case building is situated in the UK and the researcher in Finland, each stakeholder was contacted mainly through phone calls. The researcher used personal judgement on a number of contact times until a sufficient amount of data was collected. Because of the different response rate from stakeholders, the overall process of data collection took 6 months starting from August 2017 until January 2018.

Additionally, a number of further data sources were contacted during the same period to collect extra and missing data, to verify, adjust, and cross-check data to reach more accurate, comprehensive and objective results.

- 2 Architect companies
  *DRMM, AHMM*
- 5 Construction cost consultants

*Alinea Group, Gardiner&TheObald, Egenuiti, Fortem*, *Mace*

- 2 LCC consultants
  *Gardiner&TheObald, BSRIA*
- 12 Demolition company
  *Hughes and Salvidge, Brown and Mason, Erith, EuroDemolition, NorthBank Demolition, NFDC, John F Hunt, Keltbray, Deconstruct UK, General Demolition, Squibb Group, Sydbishop*
- 4 Steel construction companies
  *Metsec, MTJ Builders, M&M Contracts Ltd, Turick Ltd*
- 3 University Professors
  Dr. Jack Goulding (Northumbria University, UK), Dr. Alan Richardson (Northumbria University, UK), Dr. Alireza Tatari (Portsmouth University, UK)

The LCC analysis employed all the acquired cost data and origin of data presented in Table 6. The study utilizes the building construction cost model as initial data for *Before Use* phase, gas and electricity costs, maintenance, replacement and repair costs as data for *Use* phase assessment, plus demolition and waste management costs data for *After Use* phase. The chosen assessment period is 30 years.

**Table 6** Providers of cost data for LCC assessment

| *Cost Data* | *Provider* |
|---|---|
| CONSTRUCTION COST MODEL | Hackney Council, Willmott Dixon Re-thinking |
| ASSEMBLY, INSTALLATION | Eurban |
| CLT MATERIALS | Stora Enso |
| GAS AND ELECTRICITY | Hackney Council |
| REPAIR AND REPLACEMENT | Hackney Council |
| DEMOLITION | McGee, Delete |
| WASTE MANAGEMENT | McGee |

When all the relevant cost data for the assessment was received, it cumulated into the life cycle cost assessment framework. However, it was necessary before that to verify that given data from different data sources matched the reality and was reliable to use for the assessment. Specifically, there was some discrepancy in construction costs data derived from different stakeholders, which created ambiguity. Thus, it was decided to recalculate Bridport House building material costs, which is one of the main categories forming construction costs, based on architectural plans and blueprints.

The next step is the production of an economic efficiency analysis for the case wood building including the calculation of Net Present Value (NPV) of costs. NPV of costs calculation is done by discounting all costs to the present value in order to juxtapose them (Ristimäki et al., 2013). A discount rate of 3.5% was chosen in accordance with the real terms UK government appraisal system (Green Book, 2018). This rate is applied to all costs for all three LCC phases, including construction costs, energy costs, maintenance costs, replacement costs and demolition costs.

After, to identify wood building's economic performance potential and assess its economic competitiveness wood building's LCC compared to the alternative concrete building's LCC. For this purpose, LCC for the alternative concrete building was formed based on the case building parameters. Further, conducted economic assessment is enabling to see which of the building cases is the most cost-efficient in 30 years of study period.

### 3.2.3 Key Stakeholders' Online Survey and Individual Interviews

The qualitative research process performed in spiral progression following four basic steps: plan, act, observe, and reflect (Kemmis & McTaggart, 1988). And in the context of the current study, the action process is shown in Figure 4 with the specified activity plan (Berg, 2004):

- Identifying the research question and executing literature review
- Gathering data through online survey and individual interviews
- Analyzing, examining and interpreting the data
- Reflecting, communicating and sharing the results

From there, the online survey was created in September 2017 and developed in two steps. First, the literature review and previous studies on the subject led to an initial draft of the questionnaire according to the research goals. Second, the questionnaire was modified to be more industry focused based on a list of key stakeholders, which was then reviewed by experts from academia and the industry. The feedback obtained shaped the final version of the questionnaire and the Google Forms survey tool enabled it to be online (Espinoza et al., 2015).

In total, thirteen questions were developed for the Online Survey. Most of the questions used a rating answering system, requiring compulsory responses from respondents. The questions have a structured nature and mainly provided a "Hard to tell/No answer" option if the respondent struggled to provide an answer or doesn't agree with the given options. The intention to have restrictive questions was to encourage participants to make more conscious choices and to be able to retrieve more distinct results.

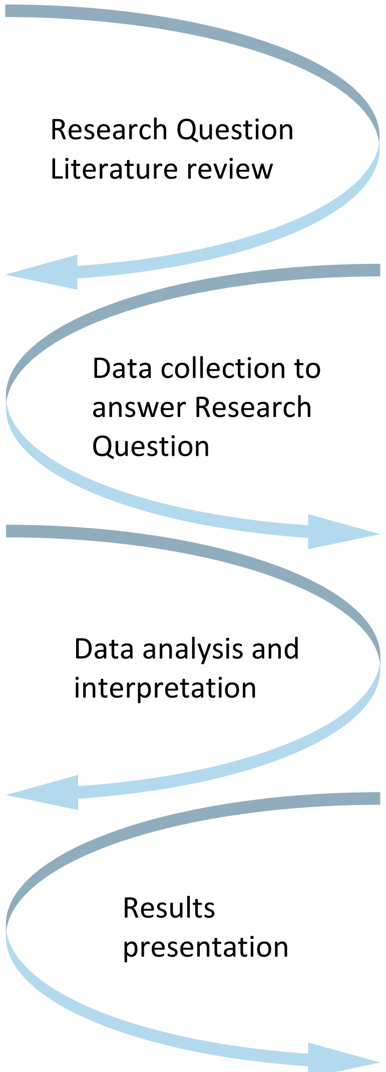



**Figure 5** The research spiral process (adopted from Berg, 2004)

The population of interest for the online survey includes experts in timber engineering, which are classified as key stakeholders in this study. The survey used a purposive sampling method, where respondents purposively selected based on their profession. Industries were contacted through a Stora Enso professional and partner channel, through Aalto University channel, and personal connections etc. Industry experts included in the distribution list assembled worked in wood construction firms, manufacturing entities, timber engineering firms, private industry, industry associations, design and engineering firms, research and educational institutions and real estate development companies. The final distribution list contained over fifty contacts and *twenty-one* of them responded.

The *Online survey* was implemented in two ways. First, an email message was sent to a potential list of key stakeholders with an introduction and explanation of the survey goals, as well as containing a link to the survey. Then, a reminder was sent to non-respondents after one week, and after two weeks, second reminder.

Surprisingly, the online survey collected less responses than anticipated. According to the literature (e.g. Wright, 2005; Evans & Mathur, 2005; Nulty, 2008; Sax et al., 2003), it is assumed that online surveys are a convenient, time- and cost-saving form to reach the largest sample of people and simplifies evaluation system. However, the target audience was reluctant to participate in it in practice and showed a lower response rate in comparison to individual interviews (Nulty, 2008). This generally can be explained by different factors like time commitments to complete survey which may not bring any particular value to the participant (Fenton-O'Creevy, 2001; Baruch & Holtom, 2008). Another reason to neglect responding is related to the situation when recipients are overwhelmed with the number of questionnaires they receive. Over-surveying leads to the automatic tendency to think that an online survey shared through the common work channel might be considered as unessential and end up incomplete (Weinner & Delassion, 2006 cited by Baruch & Holtom, 2008).

Therefore, the second way to implement the online survey was invitation to individual interviews. At the end of August 2017, an initial email message was sent to the distribution list introducing the researcher of the thesis and inviting them for the interview session. If the contacted person agreed to the interview, a suitable date and time for the meeting was set between parties. In the same way, a specific date and time was agreed upon for the phone interviews. After each interview, respondents were additionally asked to complete the online survey. With their agreement, a second email containing the link was sent. The survey was closed by the end of December 2017 and answers were collected for analysis.

Therefore, *Individual Interviews* were geared toward the same focus group as the online survey. Contacts for Finnish wood industry representatives were selected based on the construction market rates and the company's position in the market. Other EU companies were reached through Stora Enso partnership relations. Interview questions were more personalized depending on the interviewee background and aimed to obtain a deeper understanding of their decision-making experiences.

In five months, twenty-nine individual stakeholders' were interviewed for the current study. The interviews were designed to be personal and have a "face-to-face" approach; therefore, sixteen interviews (the majority) were conducted in Finland (Espoo, Helsinki, Tampere, Seinäjoki) and two in Trondheim, Norway. However, as mentioned previously, the study intends to investigate not only the Finnish market, but also to overlook other wood construction practices in different European countries including Norway, Sweden, Austria, France and the UK. To overcome distance and time limitations, the other eleven out of twenty-nine interviews were conducted through phone call sessions.

During the interview sessions, participants were verbally asked if they agree to be recorded and that the answers will be submitted for the thesis analysis. One interviewee preferred to stay anonymous and asked not to mention the company's name in the analysis. All in all, each personal interview was audio recorded, while phone interviews were typed by the author using Microsoft Word 2016 program during the sessions.

Altogether, each interview had about ten core questions plus an additional number of sub-questions adapted in accordance with interviewee answers and depending on general interview's dynamic. To provide a basis for discussion, the core questions were well catered and based on three themes that focused on relevant topic: *Benefits, Obstacles* and *Solutions* for wood construction. Within each of the three themes, the most relevant questions linked to sustainability concepts were formulated. Table 7 shows how the themes map onto the research analysis.

**Table 7** Connection of thematic questions and theoretical sustainability concepts

| ***Themes*** | ***Questions corresponding to sustainability concepts*** |
|---|---|
| **Benefits** | Wood construction: main advantages for different players from the economic, technical, social and environmental perspectives. |
| **Obstacles** | Social, economic, technical and environmental limitations of wood construction affecting it development. |
| **Solutions** | Knowledge, information and actions required to increase wood construction development from different perspectives. |

Interviews used a semi-structured method where questions were flexible and unrestricted in formulation from interview to interview. The number of questions, different orders of questions and varying degrees of questions' adaptation was utilized to create a fruitful dialogue and to accommodate interviewees (Rowley, 2012). Conversation during interviews encouraged participants to speak more freely around the topic.

In relation to time, the interviews varied from twenty-six to one hour and twenty-seven minutes long, with an average of forty-five minutes per interview; nearly 22 hours of recording. After all interviews were conducted, the data was organized, acquainted and classified into a number of categories to represent similar patterns in the research topic. Thereafter, two main categories for Benefits and Obstacles were formed for further analysis and interpretation. These categories are introduced and discussed in greater detail in Chapter 5: Discussion.

# 4 FINDINGS & RESULTS

The results of the study are presented in three sections. The primary results of the LCC analysis are introduced first. Secondly, the main results of the Online Survey are presented including diagrams and tables. Finally, the more detailed results of Individual Interviews are portrayed in the third section of the Chapter.

## 4.1 LCC Assessment: Bridport House Cost Data

According to the subchapter 2.3, for the LCC assessment, the study determined LCC calculation framework for the Bridport House with three main cost modules, namely *Before Use, Use, After Use* (Figure 1). However, due to certain reasons and limitations outgoing from the stakeholder's side, the research process deviated from the initial planned direction (Table 8). The fluctuating presence of information and often its unavailability led the study to limit the input cost data. This resulted in the outlining of certain system boundaries for each life cycle phase and consideration of modified cost categories for LCC calculation (Figure 6). Thus, each life cycle phase comprises different cost information based on the project stakeholders' response level and cost categories which are taken into LCC calculation are reflected in Figure 6 with Bold Italic highlight.

**Table 8** Common reasons and limitations for the case study cost data unavailability

| ***Reasons and limitations*** |
|---|
| No possibility to share the information |
| Not available/ time constraints |
| Confidential/ sensitive data |
| No interest in the research objectives and goals |
| No adequate benefits for the stakeholder |
| The case study is long overpass |

As mentioned in the previous chapter, the Bridport House cost model was obtained through the client and was further used as a base to represent *Before Use* costs. The original cost model for the Bridport House can be found in Appendix 4 and it reflects the system boundary for the *Before Use* phase describing all the costs occurring prior the *Use* phase. Therefore, the framework for *Before Use* cost categories was slightly modified based on the original cost model. Like so, "Transportation" and "Construction" costs are merged and referenced as **Building** cost, "Professional fees" is presented in two categories like **Design fees** and **Overhead and profit**, whereas the "Infrastructure" category was replaced with **Preliminaries**.

The study avoided the inclusion of LCC assessment costs that repeat for both buildings, have the same value, and would not influence on the final figures. Thus, as shown in Figure 6, *Before Use* phase costs for "Land purchase/ Rent" and "Taxes" were eliminated from the assessment assuming equal economic weight for the two buildings.

In *Use* phase, costs categories like "Refurbishment" and "Water use" were excluded from the LCC assessment due to a data shortage for the case building. According to the previous chapter, the case building's *Use* phase costs were provided by the client (Hackney Council) and represent **Replacement, Maintenance, Repair** and **Energy** use costs which is the *Use* phase system boundary. Further in this study, "Repair" costs are merged with "Maintenance" costs, due to the specification of the provided data.

*After Use* phase was subjected to alterations in the same manner. "Transportation", "Fees" and "Taxes" cost categories were removed because of the impossibility of making long term predictions and time constraints of the study required to establish mentioned costs. However, the study had the opportunity to engage professionals from the demolition sector to set **Deconstruction** and **Waste management** costs for both of the buildings. This forms the system boundary for the *After Use* phase costs.

Figure 6 also provides information on an additional fourth life cycle cost module: *Income*. It is essential to include any cash inflows during a building's life cycle to analyze the economic efficiency in terms of financial return, in addition to carrying out the decision on investments. *Income* includes cash inflow from the **Rent, Reuse** and **Recycling** design of a building's components and **Energy recovery**, which makes the life cycle and materials flow circular. All income elements should be based on current available technologies and calculated with current price points.

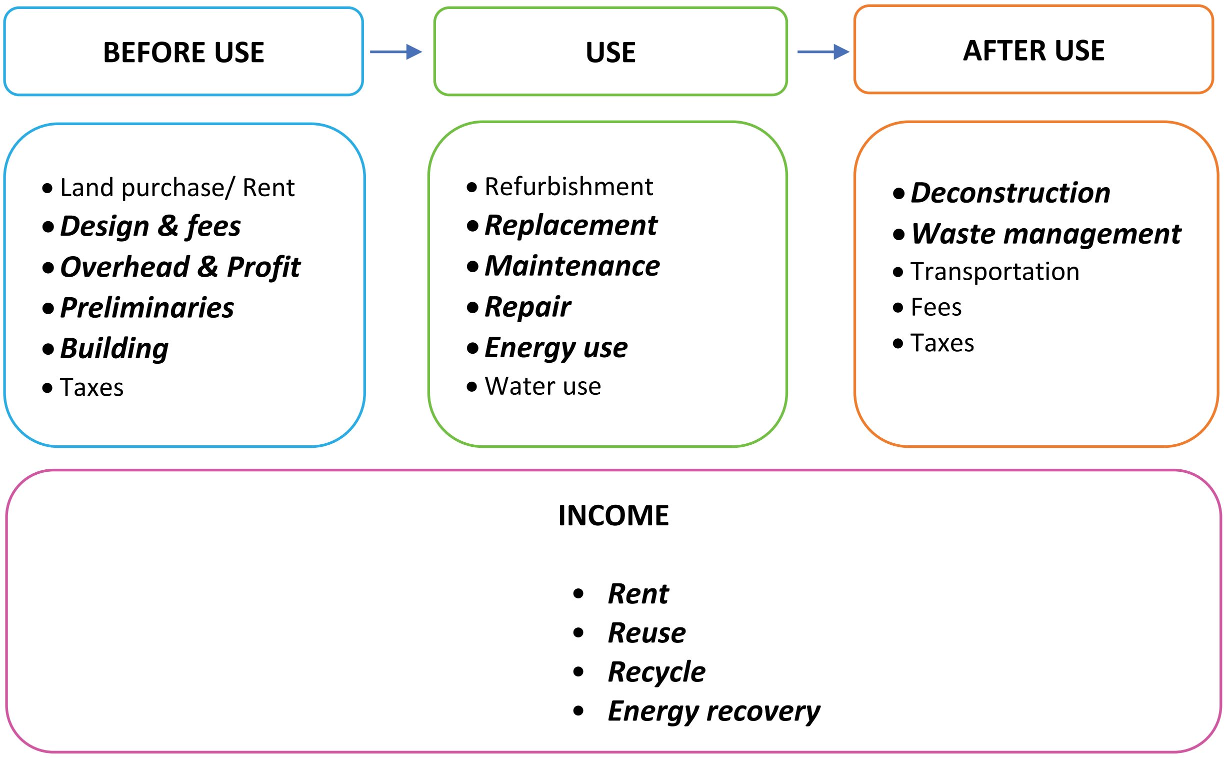



**Figure 6** Building life cycle cost/ income used for LCC calculation (adopted from European Standard SFS-EN 16627, 2015)

To allow for a comparative assessment for the case building, the alternative building should have similar cost and income categories. It implies that the same life cycle phase costs/income were assessed to identify LCC of reinforced concrete building.

Another important aspect before the actual LCC calculation takes place is the determination of life cycle periods or the study period for the assessment. As discussed in previous chapters, it is possible that the assessment study period may be based on the study goals.

The thesis has the goal to assess LCC of wood building to define its economic efficiency. Also, LCC is the method that shows at the point in the life cycle wood building that can indicate the costs peak and at what point it can start recovering invested capital. Thus, considering the goal of the study, the LCC assessment for wood building has 30 years of life cycle study. This study period is assumed to provide the balance between effective capture of all the building's cash flows during its life cycle and an increased level of uncertainty.

The Bridport House was built in 2011 and have been in Use phase already for 7 years until 2018. Thus, having the study period of 30 years allows LCC assessment to be used up to the year 2042. Also, the study period is the same for the alternative concrete building.

### 4.1.1 LCC for Wood Building

*Before Use* costs assessment

While collecting *Before Use* costs in addition to **Design and fees, Preliminaries, Overhead & Profit** and **Building** costs, it appeared that the building development period can include extra costs like **Interest charges**. This cost is related to the amount of funds drawn from debt facilities (e.g. bank) to pay for the construction costs and is repaid once the building project is completed (Cazemier, 2017). Thus, Interest charges costs were included in *Before Use* phase as shown on the Table 8.

*Use* costs assessment

Cost data for **Replacement** was included in the cost model provided by the client (Hackney Council) and had estimations of future performance costs for 100 years onward. Data for **Maintenance and Repair** costs was also given by the Hackney Council after the separate request. **Energy use** cost data was provided for the last 3 years of the building's operation period. Thus, to estimate Energy use cost for 30 years of life cycle period, this study evaluated future costs based on current consumption patterns and energy rates progress relevant for the area where the case wood building is situated.

*After Use* costs assessment

A demolition company operating in central London (McGee) provided current rates for deconstruction and waste management works. **Demolition** and **Waste management** costs were estimated specifically for the case wood building using these rates.

*Income assessment*

Revenue from materials **Reuse** and **Recycle** were calculated using rates provided by the demolition company (McGee). **Energy recovery** revenue estimated based on average electricity production from one dry tone of wood waste and average energy prices for the area. While **Rental income** was estimated based on average rent prices in specific the city area adding annually overhead percentage of 7% until the year 2027 and 3% until the end of the study period. The overhead percentage is applied according to the Land registry statistics for the London city and potential increases in property value for the next two decades. The fast grow in rents and house prices in London Borough of Hackney are due to the area regeneration and improved transportation links and it is expected prices will grow further.

All the assumptions, additional rates and figures used for LCC assessment are presented in Uncertainties section in the Discussion and Conclusion chapter of the thesis.

After all the entry data were collected, sufficient assumptions on each value was made and when the case building had a cost profile, Net Present Value (NPV) of costs was calculated (Formula 2). Deterministic calculation of NPV of costs is rather simple in terms of computation, yet it involves conversion of all costs in course of the life cycle to the present values. Formula 2 shows how NPV of costs is calculated for this study as the sum of construction costs, discounted annual operating costs, other future cash flows (assumed to be spent) and demolition cost of the product subtracting potential revenue inflows generated during the period, like resale value, interest charges, income related to renewable energy etc. (Mahlia et al., 2010; Schade, 2007; European Standard SFS-EN 16627, 2015; Heralova, 2014).

$$NPV = C + O + M + R + D - I \tag{2}$$

Net present value of costs (adopted from Schade, 2007),

where

C – construction cost (investment costs)
O – annually recurring discounted operating costs
M – annually recurring discounted maintenance costs
R – discounted replacement costs
D – demolition and waste management cots
I – any discounted cash inflows

Table 9 presents Life cycle costs for the case wood building (Bridport House) considering the study period of 30 years. First, each life cycle phase's costs and incomes are in column "*Total*" and display total cash flows without any discount. Column "*Present value*" portrays calculated and discounted to the present value cash flows occurred during buildings life cycle. Thus, representation of *Total* and *Present Value* cash flows demonstrate the difference between the figures revealing the importance of costs timing and consideration of investments required to create economic value. Also, it is possible to observe which cost/income category make the most of the difference during life cycle phases in Table 9. Finally, the table also demonstrates NPV of costs for the case wood building. The currency is United Kingdom pounds (£) and all the figures were rounded up to 100 pounds.

**Table 9** LCC for case wood building with 30 years of study period

| Cost/ Income | Total, £ | Present Value, £ |
|---|---|---|
| | ***Before USE*** | |
| **Design and fees** | 221 600 | 221 600 |
| **Overhead and Profit** | 368 700 | 368 700 |
| **Preliminaries** | 637 800 | 637 800 |
| **Building** | 4 708 900 | 4 708 900 |
| **Interest charges** | 195 500 | 195 500 |
| ***Total*** | ***6 132 500*** | ***6 132 500*** |
| | ***USE*** | |
| **Maintenance costs** | 2 340 000 | 1 512 600 |
| **Energy use costs** | 823 550 | 546 800 |
| **Replacement costs** | 2 507 000 | 1 185 100 |
| ***Total*** | ***5 670 550*** | ***3 244 500*** |
| | ***After USE*** | |
| **Demolition and waste management costs** | ***1 417 700*** | ***599 900*** |
| **LCC** | ***13 220 700*** | ***9 976 900*** |
| | ***INCOME*** | |
| **Materials recycling revenue** | 65 900 | 27 900 |
| **Materials reuse revenue** | 303 800 | 128 500 |
| **Energy recovery revenue** | 32 600 | 13 800 |
| **Rental income** | 42 101 700 | 28 159 200 |
| ***TOTAL INFLOWS*** | ***42 504 000*** | ***28 329 400*** |
| **NPV of costs** | ***- 29 283 300*** | ***- 18 352 500*** |

Overall, LCC provides an assessment of the long-term cost-effectiveness of a wood building with focus on total costs. During the calculation process the most time-consuming obstacle was the process of costs data collection. Stakeholders behavior confirmed the theory on separated responsibilities and that each stakeholder involved in the project for the limited period of time (Gluch & Baumann, 2004). Thus, stakeholders sense of engagement with the building was very low which lead to reluctance to share the information.

### 4.1.2 LCC for Wood and Concrete Buildings: Comparison

In order to further produce comparative economic analysis, this study theoretically produced a reinforced concrete (RC) building. At this point, calculated building frame volume and the configuration of an original building structure enabled the production of a technical estimation for the reinforced concrete frame building taking case wood building (CLT) as a baseline.

After using estimated technical parameters of CLT case, the construction cost for RC case was formed. The RC building is hypothetical and many of the structural features are similar to the CLT case. The main difference is from the first floor and above, all the load bearing external and internal walls, floor slabs are replaced with reinforced concrete. According to Stora Enso's building manager, internal fire rated layers like plasterboard can be removed in RC case, explaining that concrete walls tend not to require additional fire-resistant finish, rather than just simple smoothening and surface grinding. The quality of other internals elements like stairs, internal partitions, floor finish, doors and windows, fittings and furnishing are identical to CLT building. Thus, those costs are the same for the RC building as well. The façade remains the same as well, with brick cladding up to the eighth floor. This similarity is important in order to achieve the same sales figures as the CLT building.

Construction rates for the concrete building were set out in accordance with the British cost data program Building Cost Information Service (BCIS) Online from Royal Institution of Chartered Surveyors (RICS). The program has an extensive database for construction projects all over the UK and it also allows for the adjustment of estimating prices based on a preferable location, contract value and construction date (Rics.org, 2018). Therefore, it was possible to acquire the most feasible rates for the reinforced concrete building if it was built at the same time and location as the Bridport House. Using rates from 2011 and for London Borough of Hackney region allowed for a credible comparison between the two buildings.

The total LCC for the RC building, including all the costs and inflows over a 30-year study period, is presented in Table 10. However, LCC for the RC building doesn't include the materials **Reuse** and **Energy recovery** revenue because they are assumed to be irrelevant for a reinforced concrete building.

**Table 10** LCC for reinforced concrete building with 30 years of study period

| Cost/ Income | Total, £ | Present Value, £ |
|---|---|---|
| | ***Before USE*** | |
| **Design and fees** | 221 600 | 221 600 |
| **Overhead and Profit** | 322 200 | 322 200 |
| **Preliminaries** | 707 800 | 707 800 |
| **Building** | 4 441 200 | 4 441 200 |
| **Interest charges** | 233 200 | 233 200 |
| ***Total*** | ***5 926 000*** | ***5 926 000*** |
| | ***USE*** | |
| **Maintenance costs** | 2 340 000 | 1 512 600 |
| **Energy Use costs** | 1 109 800 | 715 900 |
| **Replacement costs** | 2 507 000 | 1 185 100 |

| | | |
|---|---|---|
| ***Total*** | ***5 956 800*** | ***3 413 600*** |
| | ***After USE*** | |
| **Demolition and waste management costs** | ***811 400*** | ***343 300*** |
| **LCC** | ***12 694 200*** | ***9 682 900*** |
| | ***INCOME*** | |
| **Materials recycling revenue** | 64 600 | 27 300 |
| **Rental income** | 41 995 600 | 28 053 100 |
| ***TOTAL INFLOWS*** | ***42 060 200*** | ***28 080 400*** |
| **NPV of costs** | ***- 29 366 000*** | ***- 18 397 500*** |

With the knowledge of LCC for both buildings, a comparative analysis is performed. Table 11 shows the comparison between Present values for each life cycle phase and their variation. It also identifies the difference between Net present values of wood and concrete buildings. The most cost-efficient alternative is the one with minimum NPV of costs.

Table 11 shows the comparison of cumulative Life cycle cost phases costs and final NPVs of costs. It is important to note that due to the similar structural parameters and location, Rental income for CLT and RC building estimated to be the same. Nevertheless, there is two months' difference in favor of the CLT building caused by a faster construction period and an earlier settlement date of the wood building.

**Table 11** Comparison of NPVs for CLT and RC buildings with 30 years of study period

| Cost/ Income | CLT, Present value (£) | RC, present value (£) | Variation (£) | % |
|---|---|---|---|---|
| **Before USE costs** | 5 937 000 | 5 692 800 | 244 200 | 4% |
| **Interest charges** | 195 500 | 233 200 | -37 700 | -19% |
| **USE costs** | 3 244 500 | 3 413 600 | -169 100 | -5% |
| **After USE costs** | 599 900 | 343 300 | 256 600 | 43% |
| **LCC** | *9 976 900* | *9 682 900* | *293 900* | *3%* |
| **Income** | *28 329 400* | *28 080 400* | *249 000* | *1%* |
| **NPV of costs** | ***- 18 352 400*** | ***- 18 397 500*** | ***45 100*** | ***0,2%*** |

As can be seen from the Table 11, ***Before Use*** cost is **higher for the CLT** case by **4%**. This is mainly due to the higher cost of the CLT building structure. The cost for the CLT frame is approximately 401 £/m3 plus additional construction layers like plasterboard, insulation and finish, bringing the total frame costs to 608 £/m3. Meanwhile, the cost for the RC frame structure is about 531 £/m3, which results to be 12.7% cheaper than the CLT frame.

For CLT construction, development funds were drawn from June 2010 until June 2011, whereas RC construction continued from June 2010 until August 2011. As a result, **Interest charges for the CLT** case are **reduced** by **19%,** making a difference of £37,740 with the RC case (Table 11). Meanwhile, the ***Use*** cost also shows a **5%** difference **in favour of the CLT** case, where energy use cost was the main variable.

***After Use*** was estimated to be **higher for the CLT** building than for RC building, resulting in a difference **43%**. At the same time, Income category demonstrates that the CLT building has opportunities to generate value through the reuse and recycle of building materials. However, results are insignificant in correlation to the entire life cycle period and ***Income*** **for the CLT** case is **1% higher** than for RC case. Finally, overall economic performance comparison showed that ***NPV*** **of costs for** the **CLT building is 0,2% higher than for the RC case**. A detailed analysis of Life Cycle Costs for case wood building, as well as an interpretation of its economic efficiency potential and economic competitiveness in comparison with an alternative concrete building, are presented in the next Chapter: Discussion.

## 4.2 Online Survey Response Rate

In total 21 usable responses were received out of 50 invitations sent and resulted in response rate of 42%. All answers were included in the analysis, where each answer was analyzed and presented in graphical way based on the Google Forms tool.

Table 12 shows demographics of all the participants, comprising information on age group, country of work location and self-reported position. As for the geographic distribution, the survey was distributed to over 7 European countries, from which 52.4% of respondents from Finland, following by Sweden and Norway (each 14.3 %), Austria (4.8%), France (4.8%), Germany (4.8%), and UK (4.8%).

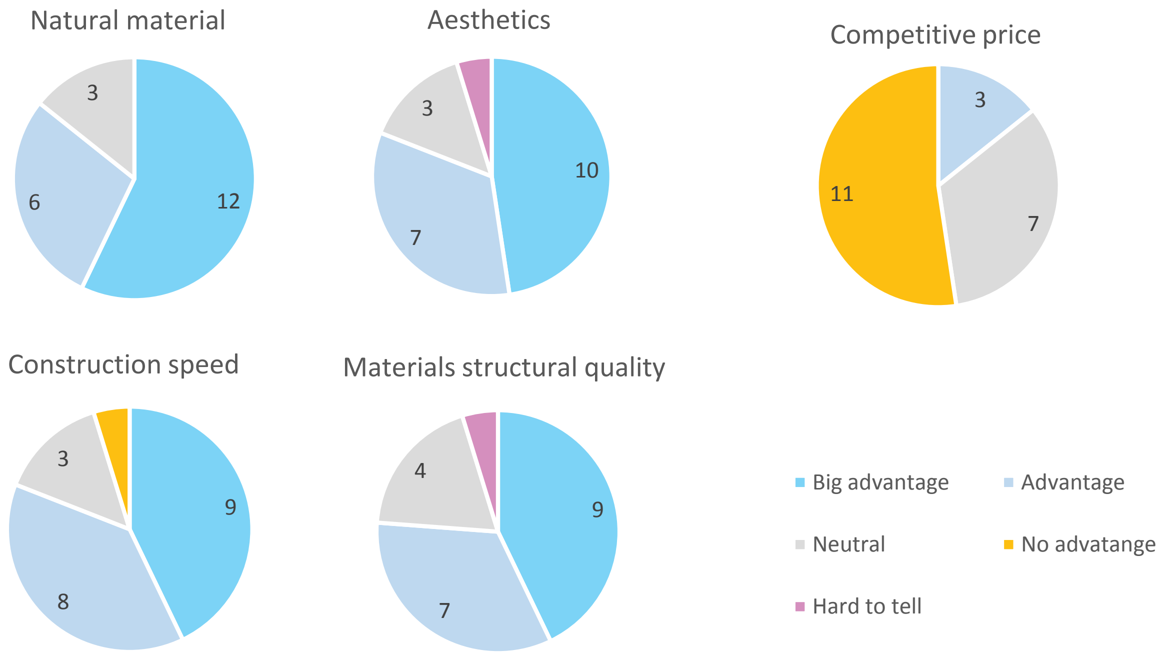
**Table 12** Online survey respondents' demographics information

| ***GEOGRAPHY of WORK*** | **COUNT** | **PERCENTAGE** |
|---|---|---|
| FINLAND | 11 | 52 |
| SWEDEN | 3 | 14 |
| NORWAY | 3 | 14 |
| AUSTRIA | 1 | 5 |
| GERMANY | 1 | 5 |
| FRANCE | 1 | 5 |
| UK | 1 | 5 |
| ***AGE GROUP*** | | |
| 20-25 | - | - |
| 26-35 | 4 | 19 |
| 36-45 | 7 | 33 |
| 46-60 | 9 | 43 |
| 61 < | 1 | 5 |
| ***POSITION/ FIELD of WORK*** | | |
| CONSTRUCTION | 5 | 24 |
| CONSTRUCTION CONSULTANCY | 6 | 29 |
| ENGINEERING | 3 | 14 |
| DESIGN and ARCHITECTURE | 2 | 10 |
| ENERGY EFFICIENCY, ENVIRONMENT | 1 | 5 |
| ACADEMIA | 1 | 5 |
| REAL ESTATE DEVELOPMENT | 3 | 14 |

### 4.2.1 Online Survey Results

The online survey started with a question to define the main advantages of wood construction. Results summarized in Graph 1. The Graph 1 is composed of five smaller graphs, which represent the *four* most rated advantages and the *single* least rated advantage.

As can be seen from Graph 1, the four most rated advantages include *Natural material, Aesthetics, Construction speed* and *Materials structural quality* and the single least rated advantage is defined to be *Competitive price* of wood construction.

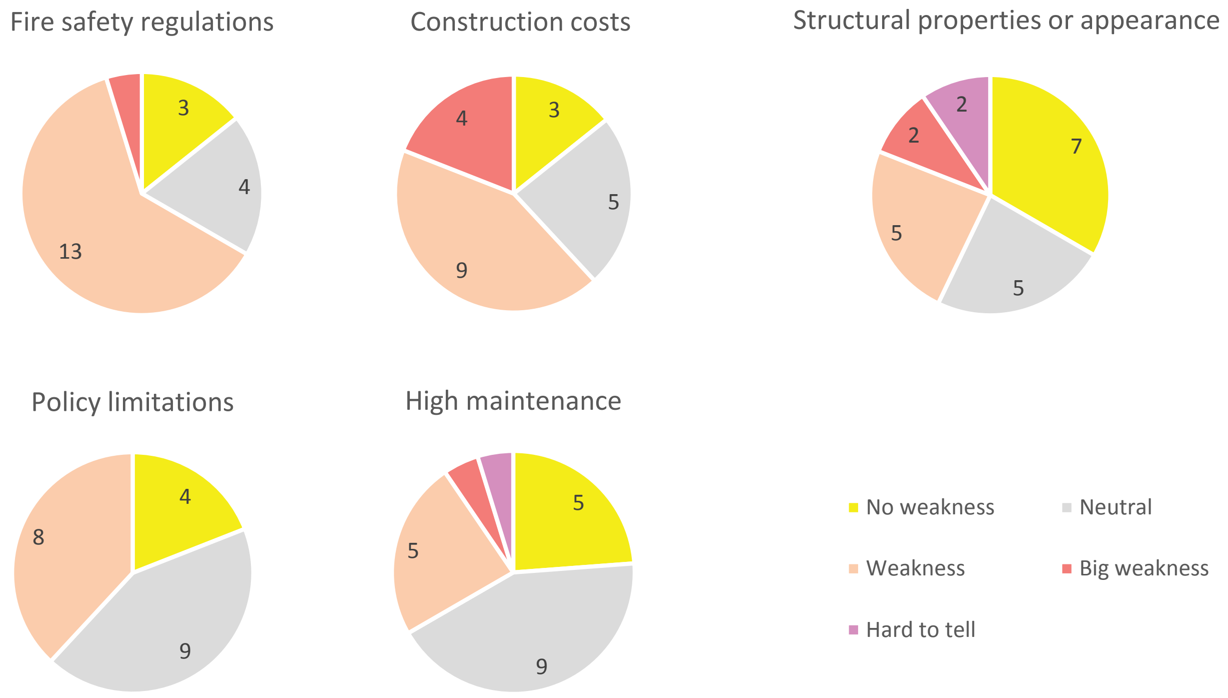



**Graph 1** Main advantages of wood construction according to survey

In the survey, *Natural material* is presented as a specific building material feature which has relation to health benefits and is a safe, nontoxic material to work with. Twelve respondents rated this option as a "big advantage" and six people considered it as simply an "advantage". *Aesthetics* is wood appearance as the building material and in some cases, wood can cut costs on the finish if left as is. Thus, ten people put this option as a "big advantage", seven rate it as an "Advantage" and one respondent marked it as "hard to tell". Meanwhile, *Construction Speed* implies reduced wood construction time and resulted in nine people noting it as a "big advantage", eight people noted is as an "advantage" and one person rated it as "no advantage". A material's structural quality includes properties of wood construction like light weight, durability and strength. Also, nine people considered it as a "big advantage", seven people as an "advantage" and one person didn't rate it, choosing the "hard to tell" option instead.

Competitive price was attributed as the least rated advantage of wood construction. Eleven people marked it as "no advantage", seven people rated it as a "neutral" aspect and only three people rated is an "advantage".

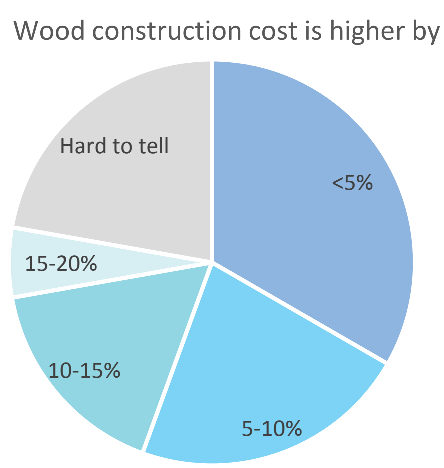
According to the weaknesses of wood construction, participants rated the options more or less equally as shown in Graph 2. *Fire safety regulations* counted as one of the main weaknesses of wood construction and it was mentioned thirteen times as a "weakness" against three respondents who rated it as "no weakness". Another main weakness is *Construction costs*; nine people note it as a "weakness", while four people recognize it as a "big weakness". Next, *Policy limitations* meant that wood construction might take longer time to get building permits because of an unfamiliarity with the wood building system. Additionally, *High maintenance* referred to maintenance during the construction process, including re-arrangement and the storage of wood building materials. These two aspects were considered mainly as "neutral" rather than categorizing them as a weakness or non-weakness. Finally, *Structural properties or appearance* referred to sound susceptibility and rotting properties of wood buildings and was rated by most of the participants as "no weakness" with seven votes in total.




**Graph 2** Main weaknesses of wood construction according to survey

The survey continued with the question to choose which of the Use phase indicators respondents consider as the most important to take into account during the initial planning and construction phases. This question intended to find out what indicators key stakeholders would base their decision-making on to provide the most optimal utilization period. Among the top 3, participants included *Environmental impact* (reduction of CO2), *End-users satisfaction* with fourteen people indicating those as highly important indicators and *Investments profitability* scored eleven votes as a highly important indicator. The other three indicators, *Building Energy performance*, *Building's life span* and *Building operation and functionality* (e.g. efficient facility management), were also considered as important in decision-making.

The next question was to identify how much higher or lower wood building construction costs were than traditional building construction costs. Results showed that the majority of respondents chose wood building to have higher construction costs, reflected in Graph 3.




**Graph 3** Range of high wood construction costs

Graph 3 shows that many stakeholders, ***18*** people recognized ***wood building*** to ***have higher construction cost*** than traditional building. Six respondents selected that wood construction costs are 5% higher than traditional construction costs. Another four respondents chose that the cost difference is in the range of 5-10% and three persons think that wood construction is 10-15% higher in costs than traditional construction. Also, four other people decided that construction costs for wood buildings are higher than for traditional buildings even though they did not choose any specific cost range.

Interestingly, ***three*** respondents chose that ***wood building construction costs are lower*** than traditional building construction by less than 5%. Additionally, eight people selected that there is no significant difference in construction cost between the two buildings.

The results of another question asking to allocate wood building's construction costs came out to be ambiguous. The task was to assign to each given construction cost component a percentage that would indicate what portion of the total construction costs it represented. Table 13 indicates the distribution of construction costs for wood buildings according to the survey respondents.

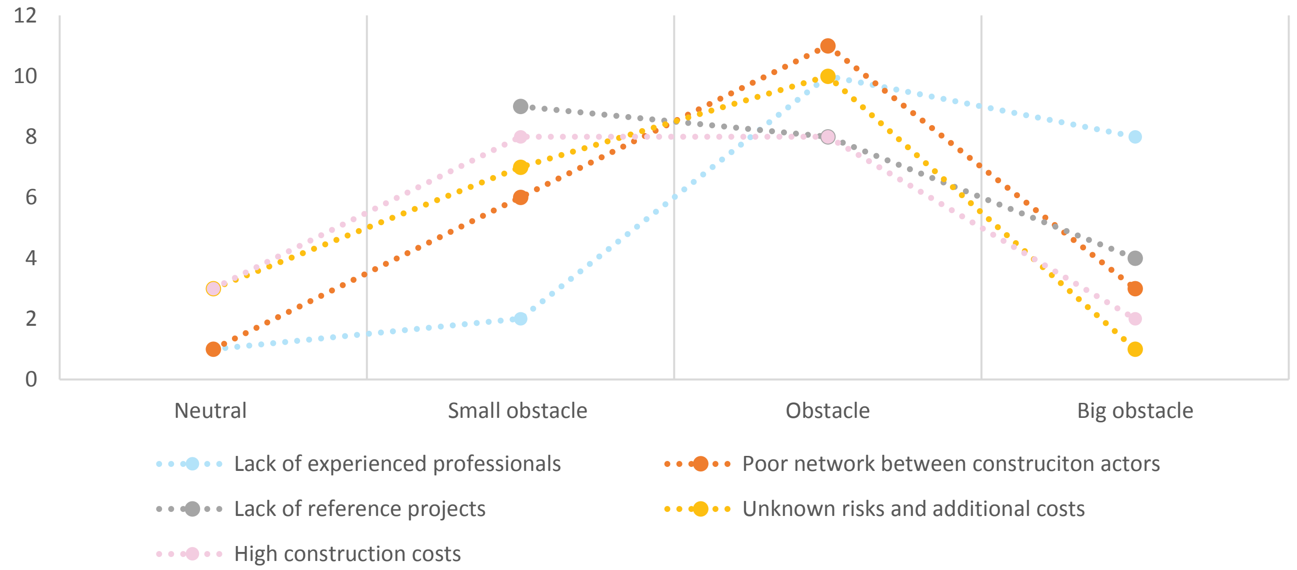
**Table 13** Distribution of construction cost for wood building

| **CONSTRUCTION COST SHARES** | Allocation of total wood construction costs, 100% | | | | | | |
|---|---|---|---|---|---|---|---|
| | **0-5%** | **5-10%** | **10-20%** | **20-40%** | **30-40%** | **40-50%** | **>50%** |
| **Design and planning** cost (i.e. upfront and rigorous planning process, experts: fire, acoustics etc.) | 6 | 8 | | | | | |
| **Building elements** (i.e. foundations, ground floor, frame, internal space elements, façade, | 3 | 3 | 3 | | | 2 | 3 |
| **Site elements** (i.e. ground works, site equipment, site construction etc.) | 7 | 5 | 1 | | 1 | | |
| **Building service elements** (plumbing, air conditioning, electrical elements, mechanical elements: lifts, escalators; laundry, kitchen equipment) | 4 | 5 | 5 | 2 | | | |
| **Property management** (i.e. land acquisition, rent, taxes, property development, planning etc.) | 9 | 3 | 1 | 1 | | | |
| **Construction site services** (i.e. energy supply, heating, ventilation, materials storage, cleaning, site transports etc.) | 10 | 3 | 2 | | | | |
| **Professional tasks/** costs (i.e. project management: construction preparation, supervision etc.; construction management: quantity and cost surveying) | 7 | 7 | 1 | | | | |
| **Waste management** (i.e. transportation from building site; final disposal fees etc.) | 14 | 2 | | | | | |
| **Transportation** (i.e. to the site and from site: materials, products and equipment) | 11 | 4 | 1 | | | | |
| **Risks and price level changes** (i.e. design, construction changes etc.) | 9 | 5 | | | | | |

From Table 13, it is possible to see that one of the main construction cost components is *Building elements* with five people giving it more than 40% share of all costs. The component with the next highest cost share would be *Building service elements,* where two people measured it to be 20-40% of all costs; ten people recognize that this component has from 5 to 20% of total costs. It follows by labour fee costs like *Design and planning* and *Professional tasks* with many votes indicating those to have from 5 to 10% of total construction costs. The rest of the components seem to have an equal amount of costs allocation, either below or a little bit over 5%.

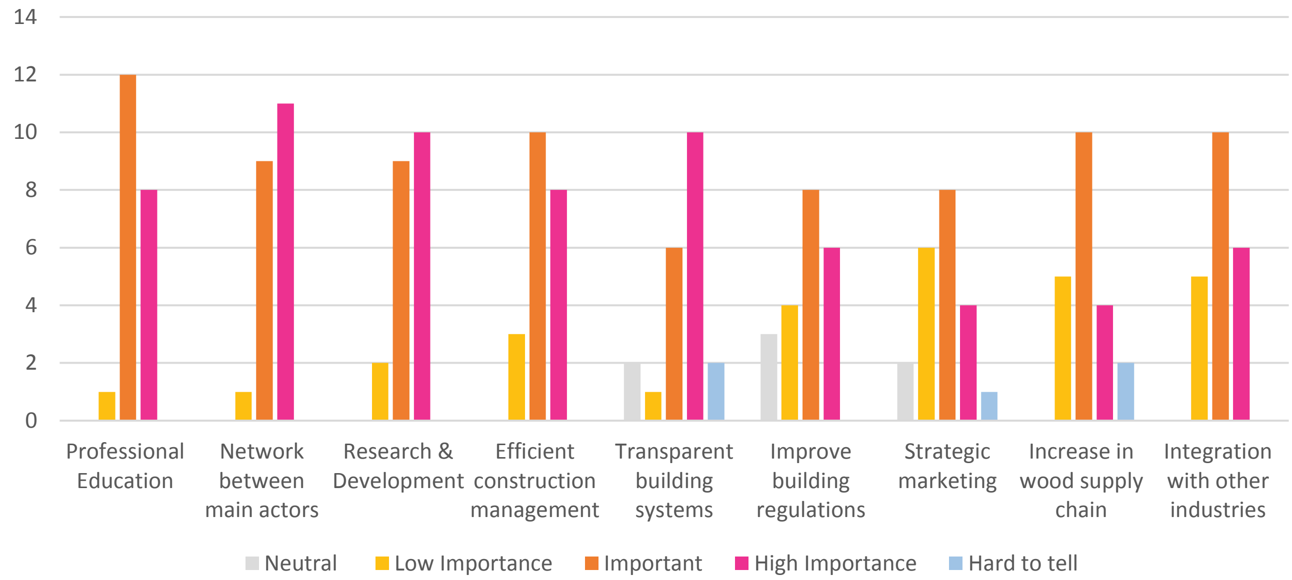
Further questions were dedicated to the topic of the wood construction building system and its practice in the market. Thus, Graph 4 reflects five out of nine obstacles considered to be the most troublesome in preventing the wood construction system from becoming more widely practiced in the market.

From Graph 4, we can observe that a lack of experienced professionals and limited knowledge is one of the biggest obstacles with eight points. Also, *Poor network between construction actors* with no early engagement and *Unknown risks and additional costs* become the main obstacles for wood building systems to become wider practice. Then it follows by *Lack of reference projects* and respondents mentioned *High construction costs,* which implies a high demand for professionals in the field and quality building materials as obstacles of wood building construction practice. It is also worth mentioning that among the least considered obstacles categories were "Low market demand" and "Threat to natural resources". Respondents marked these options mainly as *small obstacles* or *neutral*.



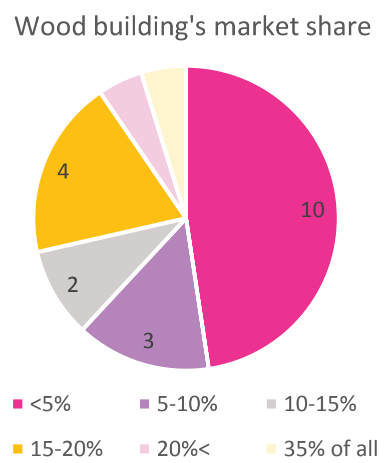

**Graph 4** Major obstacles for wood construction to become wider practice

The next question intends to find out which of the given actions are the most important to take to improve wood construction practice and are reflected in Graph 5. As shown in Graph 5, all options were rated to some extent as "important". However, improving *Network system between main actors*; *Professional Education* in wood construction, engineering and design; *Research & Development* and *Efficient construction management* are among the options to receive the most ratings of "high important" solutions to improve wood construction. Meanwhile, *Strategic marketing*; *Increase in wood supply chain* and *Integration with other* (forest) *industries*, government and knowledge share were mentioned as the least important options.




**Graph 5** Importance level of actions to improve wood construction practice

The last three questions were about the building market picture and the position of wood buildings share in it. Thus, the next question was to specify with the percentage rating the market share for wood buildings. The idea was to get the overall pattern of what is the proportion of wood buildings in the market.

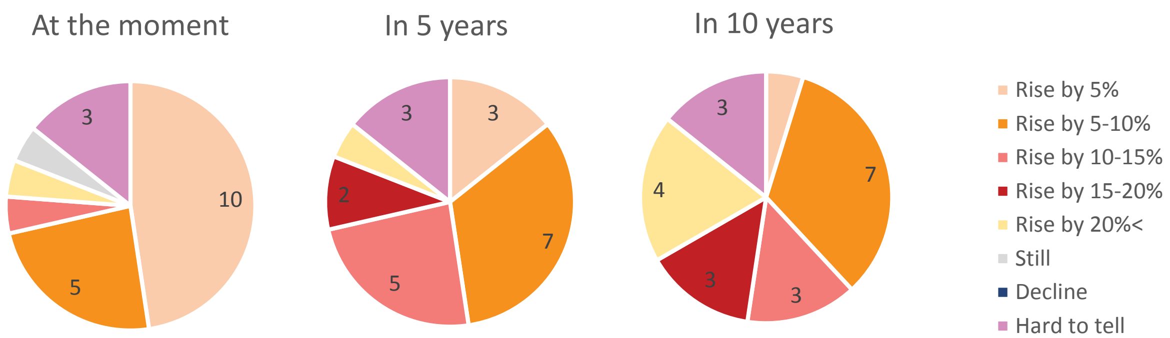



Graph 6 shows the results and what the opinion is of respondents to their local wood buildings market share. As it can be seen, the majority of answers (48%, or ten people) indicate that the wood buildings market share is quite small and is less than 5%. At the same time, four people marked that wood buildings hold from 15% to 20% of the market, while three people thought wood buildings have 5% to 10% of total market share. Two respondents think that the wood building market share is more than 10% but less than 15%. Also, there were a couple of individuals who scored 20% and 35% for wood building market share.

**Graph 6** Distribution of answers on wood buildings market share

The following question was about the market demand for wood construction. This question was designed to analyze if the demand meets supply and if the situation may change in five and ten years. Graph 7 shows the results and it can be observed that the majority (ten respondents) decided that the current wood building construction demand is rising by 5%, while another five respondents think the market demand is rising up to as high as 10%. There are also individuals who scored that wood buildings market is rising by more than 10%, while one person marked that the demand is unmoving for wood buildings.

On the second pie chart of Graph 7, we can see how respondents predict the wood construction market demand will look in the next 5 years. According to seven respondents, it will increase by 5 to 10%, while five other respondents think it will rise by 10-15%. Another three people assume that the demand will go up by 5% and two people predict that the rise can go even up to 20%.




**Graph 7** Market demand change in ten years

The third pie chart on Graph 7 shows respondents' visions for wood building market demand in 10 years. Seven people think the market will increase to 10%, while three people expect a rise of up to 15%. Interestingly, seven people predict that the demand may increase by more than 15%, where four people mentioned figures higher than 20%. Graph 7 demonstrates a clear pattern of how market demand for wood construction can change in the next 15 years from the current situation.

The last question was to determine the best estimations on the potential of wood building construction industry dynamic in coming ten years. Graph 8 provides results, which indicate a sequence of potential changes in wood construction.


**Graph 8** Change of wood building construction industry in ten years

According to Graph 8 and key stakeholders' responses, the potential for wood construction industry is rising and at the moment, it can increase up to 10%. In the next 5 years, people answered the industry can increase from 10 to 20%. Whereas for the next 10 years, a large portion of responses (six people) marked that wood building industry potential is quite high and can elevate by more than 20%.

## 4.3 Stakeholders Interviews Response Rate

In total, forty-seven contacts had been invited for the interview and *twenty-nine* individual interviews were conducted from August 2017 to January 2018. Nine personal interviews, including one phone interview were among the research and institutional field. The rest of the twenty interviews, comprising nine personal interviews and eleven of phone interviews, were conducted among the wood construction industry representatives.

The interviews were analyzed, and results portrayed in a different way than online survey results. Due to the large number of interviewees, it was decided that Interviews of stakeholders who operate in the Finnish wood construction industry would be separate from the rest of the interviews, shown as an individual group. It was meant to represent the results in more structured and comprehensive way. Also, it is important to note that the comparison of the Finnish wood construction industry and the European wood construction industry was not intentionally a part of the process; nor is it the aim of the study.

The details of the interviewees including their geographic location of work, job position, company or organization of work and the interview duration are shown in Table 14.

**Table 14** Individual interview participants' information

| ***Geographic location of work*** | ***Position*** | ***Company*** | ***Duration*** |
|---|---|---|---|
| **Finland** | Associate professor, Doctor of Science | Aalto University | 40 mins |
| **Finland** | Architect and professor, Senior Advisor, Specialist | Ministry of the Environment of Finland | 40 mins |
| **Finland** | Director, Moisture and mold program | Ministry of the Environment of Finland | 1 h |
| **Finland** | Project manager | Karelian University of applied science | 41 mins |
| **Finland** | Business development manager | VTT | 51 mins |
| **Finland** | Senior researcher | VTT | 50 mins |
| **Finland** | Associate professor, Architect | Tampere University of Technology | 1 h 7 mins |
| **Finland** | Timber council, Managing Director | Puuinfo | 52 mins |
| **Sweden** | Doctor of Science | Linnaeus university | 26 mins |
| **Finland** | Director, Vice president for commercial group | Lemminkäinen | 1h 27mins |
| **Finland** | Project manager at Business premises | SRV | 46 mins |
| **Finland** | Chief Sustainability Officer | SWECO | 34 mins |
| **Finland** | Managing director, Housing company manager, Project manager | Lakea | 44 mins |
| **Finland** | Managing director and Senior Cost Officer | FMC Laskentapalvelut | 1 h |
| **Finland** | Structural engineer | SWECO | 44 mins |
| **Norway** | Project Developer / Project Leader | Veidekke | 34 mins |
| **Finland** | Partner, architect | Settle | 44 mins |
| **Finland** | Project manager | SKANSKA | 48 mins |
| **Norway** | CEO, Sales manager | Woodcon | 42 mins |
| **Austria, Switzerland** | Area Sales Manager | EGGER | 28 mins |
| **Sweden** | Vice president | Folkhem | 38 mins |

| | | | |
|---|---|---|---|
| **France** | Director, Engineering and research | Woodeum | 35 mins |
| **UK** | Design & Engineering manager | CarbonDynamics | 45 mins |
| **Sweden** | Head of Residential Products | NCC | - |
| **Sweden** | Project manager | Midroc | 37 mins |
| **UK** | Director | EURBAN | 40 mins |
| **Austria** | CEO | Paul Heidenreich | 1 h |
| **UK** | Design director | Hadley Group | 49 mins |
| **Norway** | - | - | 30 mins |

As mentioned previously, the aim of the study is not to imply the comparison of Finnish and other European countries' wood industry stakeholders' perspectives. However, to avoid clutter and maintain order of the interviews, the results presented as two analogical graphs for the Finnish wood industry stakeholders and the European wood industry stakeholders. In this context, "European" includes those countries where interviewed wood industry stakeholders have their production and operation processes, namely Sweden, Norway, Austria, France and the UK.

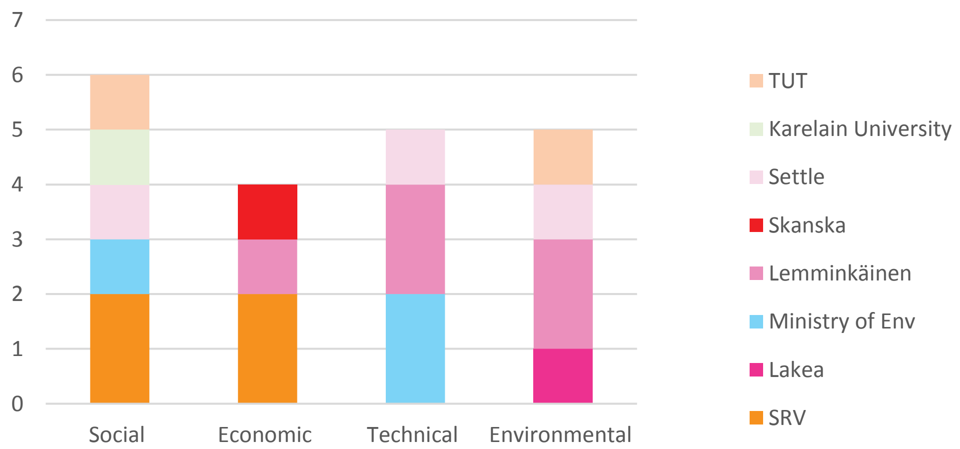
### 4.3.1 Individual Interviews Analysis

Interview material was subjected to content analysis by the three themes for wood construction: *Benefits, Obstacles* and *Solutions*.

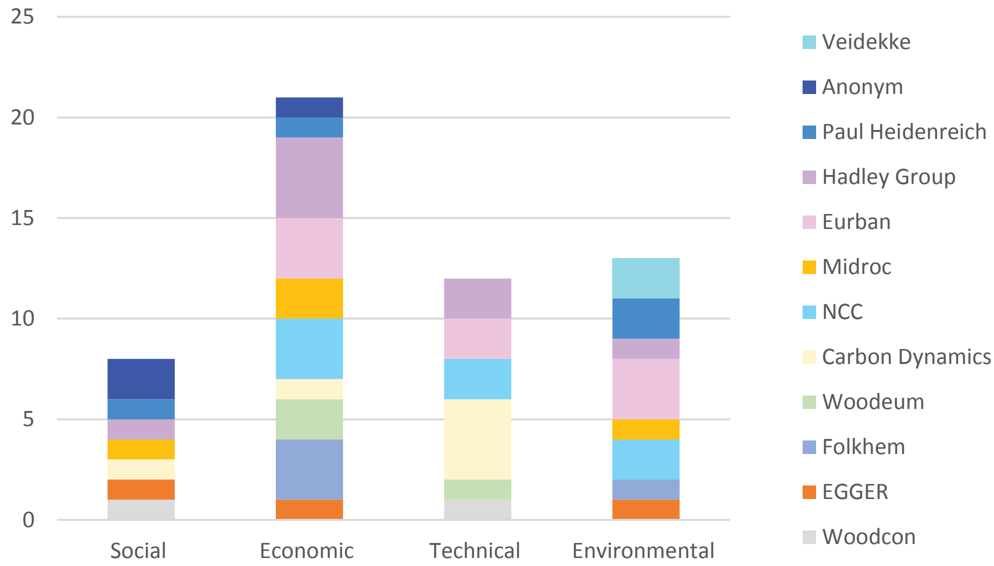
***Benefits***

The allocation of the most mentioned benefits by Finnish wood industry stakeholders (further Finnish stakeholders) is shown in four columns of Graph 9. From Graph 9, it is clear that *Social benefits* of wood construction prevail among Finnish stakeholders, while in EU *Social benefits* is the least mentioned category (Graph 10).

Graph 10 shows which benefits are considered in wood construction by EU wood industry stakeholders (EU stakeholders). According to the Graph 10, *Economic* aspect is one of the main beneficial points. This might be explained by greater experience level; therefore, there exists more awareness about the wood construction business logic among EU stakeholders.



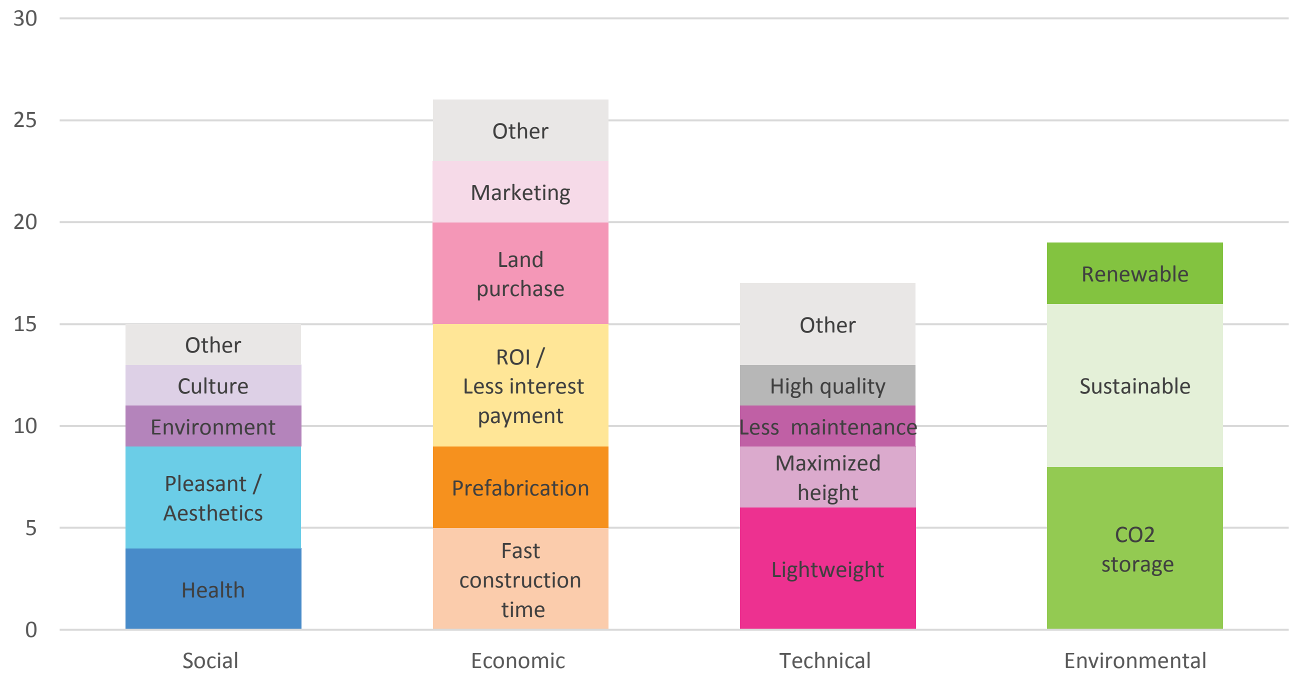

**Graph 9** Finnish wood industry stakeholders which mentioned benefits




**Graph 10** European wood industry stakeholders, which mentioned benefits

Further, detailed presentation of what social, economic, technical and environmental *Benefits* were noted the most by stakeholders are shown in Graph 11. About **17%** of respondents mentioned **Pleasant /Aesthetics** as *Social* benefit of wood buildings. Stakeholders meant that people are willing to be surrounded by pleasant natural material like wood and they take better care of wood surfaces. Also, some of them noted that wood buildings can upgrade an area image through its aesthetics.

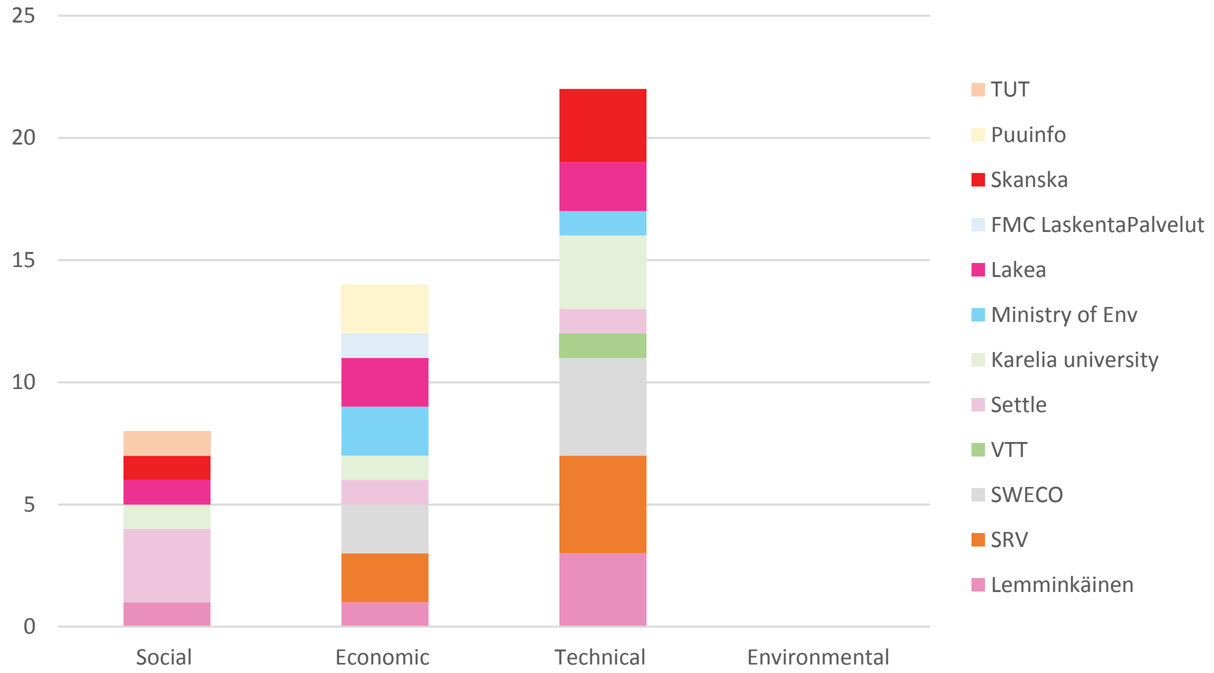
The main *Economic* benefit is (Return on Investments) **ROI/Less interest payments,** mentioned by **21%** respondents. Wood construction has a short investment time and a fast payback period with a higher annual turnover due to prefabrication and **Fast construction time** (**17%**). Another benefit is **Land purchase** where respondents reported that municipalities may prefer to provide land plots for wood building projects due to their environmental benefits. About **21%** of respondents mentioned **Lightweight** as a *Technical* benefit of wood construction. More than **37%** of respondents stated that wood construction is **Sustainable** and **Renewable**, seen as an *Environmental* benefit, meaning wood is a natural, recyclable and reusable construction material of the future.



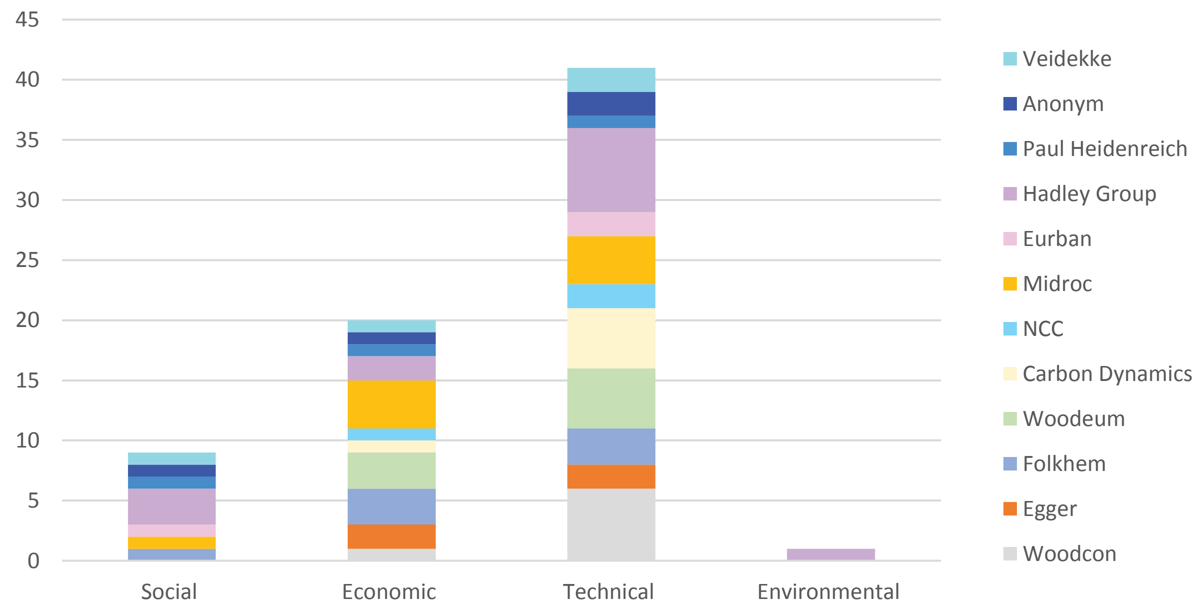

**Graph 11** Benefits by wood industry stakeholders

***Obstacles***

Answers in the theme of wood construction *Obstacles* concurred between Finnish and EU stakeholders. Thus, as shown in Graph 12 and Graph 13, technical obstacles were mentioned the most, followed by economic and social obstacles, while Environmental obstacles were barely mentioned at all.




**Graph 12** Finnish wood industry stakeholders which mentioned obstacles




**Graph 13** European wood industry stakeholders, which mentioned obstacles

Stakeholders' responses were cumulated and formulated as certain *Obstacles* within each sustainability aspect and presented in Graph 14. Among *Social* obstacles, respondents mainly mentioned that consumers are not as familiar with wood as modern construction materials and would relate wood as easily flammable and not as durable or robust as concrete. This obstacle is stated as **Wrong perception** with **34%** of the mentions. Another interesting *Social* obstacle is **Decision-making**. It means that consumers' choice of household depends on other aspects like location and rental price rather than a building's structural material.

**High cost** is considered to be one of the main *Economic* obstacles and is mentioned by **59%** respondents. This obstacle related to wood's high construction costs and the fact that wood buildings tend to be more expensive than concrete buildings. Other *Economic* obstacles were quite various and mainly projected personal/company-specific experience.

Among *Technical* obstacles, **65%** of respondents were directly related to **Lack of knowledge/experience/skills**. Generally, answers would refer to not enough practical and deep knowledge to perform efficient wood construction, as well as there being insufficient education in wood construction and no skills among professionals. Thus, it brings uncertainties into decision-making, with the fear of failure and mistakes leading to additional costs.

Interestingly, about **41%** noted **Fire & Sound** as a wood construction *Technical* obstacle. Respondents mentioned a lack of recent and relevant wood fire performance studies, issues related to wood building acoustics, and fire regulations requirements, which can add extra cost. About **31%** noted a shortage in materials supply and a small production scale. This obstacle labeled as a **Lack of supply** in Graph 15. This *Technical* obstacle reflects a lack of competition among suppliers and thus high prices for wood building products.

Only one *Environmental* obstacle was reported. **Intangible** marketing is seen as a soft value and not a very strong argument of wood construction.


**Graph 14** Obstacles by wood industry stakeholders

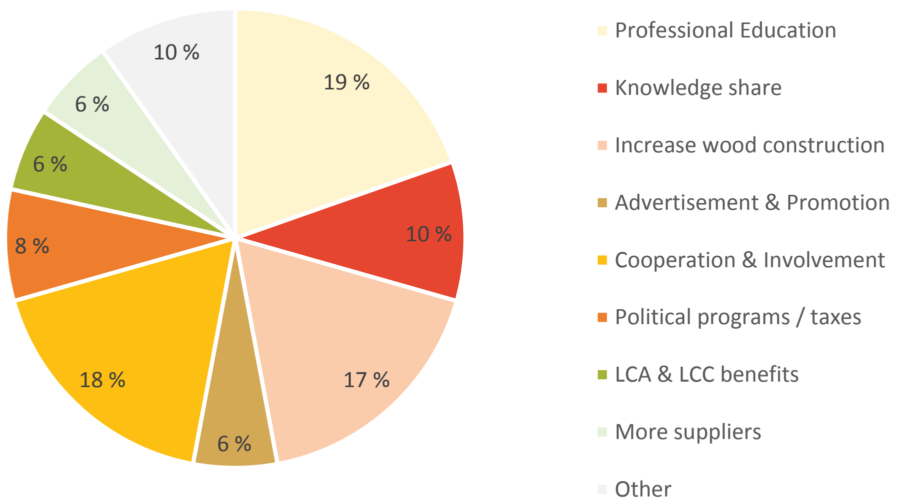
### *Solutions*

This theme is presented in Graph 15. It includes the answers of all stakeholders and consists of 51 potential *Solutions* to improve the wood construction industry and increase its market potential. As can be seen from the graph, stakeholders emphasized **Professional education** as the focus solution for wood construction improvement. "*Increase wood construction education in universities*" (construction) and "*Training programs for building partners*" (property developer). The importance of education is unrestricted only for designers, architects and engineers, but it is also essential to educate all involved partners about the potential of wood construction. "*Suppliers need to learn how business cases are built up and understand how the product can effect on customer's (developer) business*" (Property Developer).

**Cooperation and involvement** are also reported as one form of education about different wood construction stages and as a key solution for wood building industry development. "*To develop efficient building starting from the design phase, it important to build long-term relationships with suppliers*" (Construction). "*To push prices down, wood industry representatives should cooperate within the market*" (Engineer). "*Green bound – loan money for construction on the market for the lowest possible rate. To do that, you need to explain to the market what they will get from wood construction (environmentally, economically and socially)*" (Developer). Stakeholders often referred to collaborations and increasing innovating thinking to solve questions raised and to improve awareness about wood construction among end-users. "*Create extra-ordinary projects which are nice to look at and can catch customers and end-users attention*" (Property Developer). "*Cooperation with public construction and introduction of wood construction properties to other stakeholders through public projects*" (Project Manager).

While education and cooperation were also noted as long-term solutions, **Increase wood construction** is straightforward and is proposed as a more specific solution to increase wood construction rates. "*To gain more experience and more knowledge accordingly we should build more and learn from the lessons. There is no shortcut.*" (Contractor). "*We just need to build more and have more good examples of wood buildings, so the image will change, and people will accept CLT*" (Architect).

**Knowledge share** and the introduction of wood construction properties among different stakeholders are considered essential ways to improve wood construction development. "*It is important to be open for opportunities and to get more ideas on how to reduce construction costs from every perspective. New ideas can come from any competence*" (Contractor). "*Show how CLT can be used after demolition phase*" (Timber engineer). "*Life cycle proposing to end-users*" (Designer, Engineer). "*Sharing the information about different projects is the most important in wood construction development (increase the scale of the industry)*" (Project manager, Academia).




**Graph 15** Solutions by wood industry stakeholders

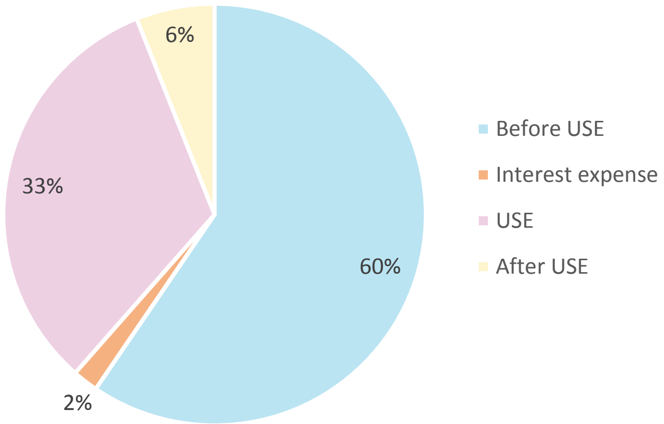
# 5 DISCUSSION

This chapter intends to communicate the results and findings from the quantitative and qualitative parts of the research with the literature review basis. The first part of the chapter discusses the economic efficiency of wood buildings and look into the results of a comparative economic assessment for the case wood building and the reinforced concrete equivalent. The following sections cover stakeholders' perspective and decision-making regarding wood construction, answering the second research question.

## 5.1 Economic Efficiency of Wood Building

The first research question was addressed through the findings from the Life Cycle Cost assessment in Section 4.1.2. According to LCC assessment results and as shown in Graph 16, over a 30-year life cycle of wood building, the present value of *Before Use* phase costs have been estimated to be 60% of total costs, while the present value of *Use* phase costs accounts for about 33% of all costs and the remaining 6% left for present value of *After Use* phase costs.

This subchapter will discuss each life cycle phase to analyse the most impactful costs for the overall cost-efficiency of wood building and answer the first research question *"What is the economic efficiency of wood building based on LCC assessment?"*




**Graph 16** LCC phases proportion for wood building

***Before USE phase***

The largest contributor to the wood building's LCC considering a 30 year study period is *Before Use* phase. According to Table 9 "LCC for case wood building with 30 years of study period", ***Building*** itself **comprises 77% of *Before Use*** phase costs and **47.2% of total cost**. This makes it the cost factor with the greatest significance in the 30 years of a wood building's life cycle which is also confirmed through the online survey results where respondents allocated 40% of all costs to Building elements. In comparison to previous studies on LCC, such a large share of *Building cost* seems to be typical for the proposed life cycle. Heralova et al. (2014) estimated 30 years of LCC and *Building* cost including mainly the materials for the building makes up 89% of the construction costs. Additionally, the study by Huang et al. (2017) maintained that the building materials can make up to 91% of construction costs in 50 years.

For the case wood building, this significant contribution of *Building* cost is mainly due to the primary frame structure costs (22%), which are Cross Laminated Timber elements. It can be assumed that the price for CLT elements is the reason for the high *Building cost*. However, a detailed breakdown of Building cost revealed that CLT frame costs include two major parts causing a high elements price:

- Transportation costs

CLT elements for the case wood building were transported from Austria. Indeed, CLT production is mainly developed in central Europe and transportation costs adds to the final market price (Passarelli & Koshihara, 2017; Mallo & Espinoza, 2015; Burback & Pei, 2017).

- Fire protection costs

Additional fire protection layers like plasterboard resulted in an additional 24% to the primary frame cost. It corresponds with the study by Hossaini et al. (2014) where it was found wood buildings require extra insurance costs on excessive fire safety applications.

At the moment, low availability in the market increases CLT costs and this becomes one of the most significant barriers to implementing modern wood materials in construction (Mallo & Espinoza, 2015; Jones et al., 2016). A study by Alinea (2017) mentioned that with the current CLT supply chain growth, it is possible to increase the pricing levels, meaning a higher degree of price variation. Thus, it is possible to say there is potential for total cost reduction through *Building* cost consideration.

Another factor increasing the *Before Use* phase costs is the mortgage ***Interest expenses***. For the case building **Interest expenses** made **2% of total costs**, which dependent on the construction time, loan amount and repayments agreement with the debt facility (e.g. bank).

***USE phase***

During the 30-year study period for the case wood building, discounted *Use* phase cost makes up 33% of total costs (Graph 16). Huang et al. (2017) also found that the operation contribution to the LCC is nearly identical to the construction cost with 35%. Major parts in the *Use* phase for the case wood building are ***Maintenance*** costs with **47%** and ***Replacement*** costs with **37%,** while Energy Use costs makes the rest at 16% of Use phase cost. In a comparison study by Islam et al. (2015), a timber frame three-story residence was assessed. It was concluded that Maintenance costs including replacement and repair over a 50-year lifetime contributes 25.9% to the LCC and Operational energy costs, 9.74% respectively.

The cost data for Maintenance costs was derived from the case wood building client and indicates a responsive maintenance including cleaning processes, repair and fixing any defects. It is important to note that the structural wood frame of the building is not exposed to the weather and is covered with a building envelope. Additionally, the inner walls, ceiling and floor were covered a type of finish covering the structural wood material. Thus, maintenance is not required for wood structural elements and Maintenance cost did not depend on the wood frame. The same results were concluded from the study by Tam et al. (2017), confirming the fact that no maintenance is required for timber structural components and corresponding replacement costs can be associated with the building structure.

Replacement costs with consideration of a 30-year life cycle, similar to the Maintenance costs, did not relate to the building wood frame. Assumptions on Replacement costs included the changing of floor finishes, internal doors, typical electrical and mechanical components, lift installation etc. Therefore, it is possible to conclude that Replacement cost as well as Maintenance cost doesn't depend or refer to the structural material and not considered as cost factors coming from the wood as building material. However, the high cost of the *Use* phase can be improved by introducing mutual agreement between the building owner and the tenants to engage with and share capital assets benefits. Zuo et al. (2017) mentioned Green lease as a novel approach to overcome split incentives, to encourage the saving of energy and create a more plausible environment for life cycle costing techniques.

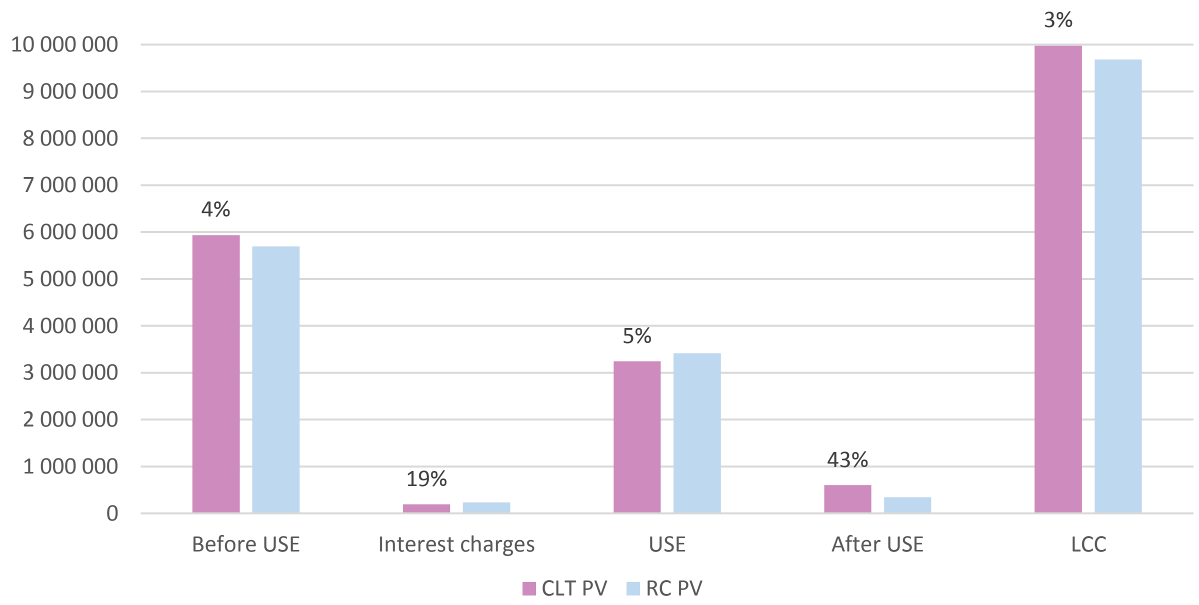
***After USE phase***

*After Use* phase was comprised of ***Demolition*** and ***Waste management*** costs and made **6%** of life cycle costs. Compared to previous studies, it seems that 6% is a generous share for end of life costs. Hossaini et al. (2014) concluded the allocation of 2% of six-story wood building's total costs for demolition, recycling and reuse of building materials is optimal. However, the study period for that case is 60 years, whereas the current case wood building will be theoretically deconstructed in 30 years after the year 2011. Han et al. (2014) showed that demolition costs will not exceed 1.5% of the total cost, no matter if demolition will occur in 30 years or in 60 years after the construction.

According to the LCC analysis of the case wood building, one of the main reasons of high Demolition and Waste management costs is the amount of additional fireline boards, which are required to be stripped down and sorted separately. This increases the amount of manual labor, hence the increase in the *After Use* phase cost. Barber (2015) also associated high costs with no familiarity with the material and a lack of experience in wood construction industry. Thus, to improve the economic impact of the *After Use* phase, more research and education attention could be given to the investigation of wood buildings fire performance. Greater consideration of innovative fire protection systems, building designs and wood elements to comply with building codes may reduce the fire protection costs (Gerard et al., 2013).

### 5.1.1 Economic Competitiveness

This section will interpret the results of the comparative LCC assessment between the case wood building (CLT) and the alternative concrete building (RC) illustrated on Graph 17. The section also intends to draw a conclusion on the economic competitiveness of wood buildings in comparison with those of alternative concrete buildings.




**Graph 17** Life Cycle Costs comparison between CLT building and RC building

As can be seen from Graph 17, ***Before Use*** cost of the **CLT building is 4% higher** than the RC building, where *Building* construction cost was the main component to cause the difference. This corresponds to previous studies (Jones et al., 2016; Woodworks; Riala & Ilala, 2014; Wang et al., 2014), where the price of CLT material is discussed to be higher than that of steel or concrete. However, there are studies (e.g. Hossaini et al., 2014; Thomas & Ding, 2017; Petersen & Solberg, 2005; Švajlenka et al., 2017) showing the opposite resulting with conclusions that construction costs are lower for wood buildings compare to brick and concrete buildings. Yet all this research acknowledges that wood must be cost-effective to be competitive on the market against other traditional construction.

Further, due to prefabrication and less foundation works (Burback & Pei, 2017; Karakusevic Carson Architects, 2011; Švajlenka et al., 2017; Gasparri, 2015), the CLT case building was reduced in construction time with 13 months as opposed to the RC case with 15 months. This shows that wood building has a quicker construction time than traditional building and results entirely confirm the literature review (Thomas & Ding, 2017; Heralova, 2014; Alinea, 2017; Cazamier, 2017; Koppelhuber et al., 2015). The two-month difference resulted in an earlier revenue flow for the CLT case building due to a quicker occupation process which happened straight after the construction is completed. Reduced construction time also allows a faster rate of repaying loans. Thus, ***Interest charges*** **for the CLT building are 19% lower** in comparison with the RC building. It is fair to note that industrial prefabrication does not necessarily equal to cost benefit adding potential cost for production equipment, transportation and heavy machinery (Puu, 2017). However, findings also show that shorter construction time with the CLT building structure can produce cost saving benefits for time-related factors as shown in the literature (Cazemier, 2017; Arif et al., 2017; Klussel, 2008; Huang et al., 2017).

Due to the thesis scope, the input data for the RC building maintenance and replacement costs assumed as similar to the CLT building (Thomas & Ding, 2017). Additionally, the RC case building is a hypothetically constructed building to estimate its operational costs average utility rates on energy consumption, which taken from the statistical data appropriate for the location. As a result, the **CLT building has lower *Use* costs** than the RC building **by 5%**. This is in line with the study by Hossaini et al. (2014), where the energy consumption and maintenance costs of a wood building in a sixty-year study came out to be lower than for a concrete building. Still, it can be conceived that a number of previous studies underpin that operational costs are fluctuating from case to case and not highly dependent on the building material itself (e.g. Thomas & Ding, 2017; Gustavson, 2015). Accordingly, several studies (e.g. Dodoo et al., 2011; Marceau & VanGeem, 2002; Gadja, 2001), maintain that wood buildings almost always have operational costs similar or higher than buildings from other heavy materials.

For the present study, demolition and waste management costs were estimated involving professional experts in the field. The **CLT building resulted with 43% higher *After Use* cost** compared to the RC building. The reason of such a high cost difference is due to the implemented fire protection systems for the CLT building, which was also noted in the studies by Gerard et al. (2013) and Barber (2010). Yet, similarly, to construction cost end of life cost is a debatable factor in the LCC analysis and can vary depending on different external factors. For example, Thomas and Ding (2017) show that wood buildings would be more cost-efficient at the end of life with 30% less of demolition costs than traditional buildings, mainly because of the required heavy equipment to strip down concrete structure, whereas Hossaini et al. (2014) estimated end of life costs to be similar for wood and concrete buildings.

In summary, the LCC comparison result showed that during the study period of 30 years, ***Life Cycle Costs*** **for the CLT building are 3% higher** than LCC for the reinforced concrete equivalent.

However, this study approves that CLT has high reuse and recycling opportunities to generate income value at the end of life cycle (Ormondroyd et al., 2015; Wang et al., 2013). Based on the waste management rates sourced from the industry experts, CLT elements are assumed to have high levels of reuse as secondary material for new production and have increased recovery potential as further energy source. This agrees with the study by Wang et al. (2016) that wood construction produces 16% less waste in comparison with concrete and steel, which adds to wood's *After Use* cost reduction. Adding to that the rental income over the 30 years of the study period ***Income*** category **for the CLT building** resulted in a little **increase of 1%** against the RC building (Table 11). This difference made an impact on the economic performance comparison results and shows that ***Net Present Value of costs*** **for the CLT building is** only **0,2% higher** than NPV of costs for the reinforced concrete equivalent. In theory, according to the result *wood building is less cost-efficient* than the same building built with heavy materials like reinforced concrete.

Nevertheless, the difference in 0,2% is relatively insignificant and it is fair to conclude that at the end of life cycle the NPV values for wood and concrete buildings came out to be similar. Further studies could be relevant to see the impact of longer assessment periods on the life cycle costs of wood buildings. Also, one critical matter of the study is accessibility, reliability and accuracy of input data, which may have an effect on the results of the study. Again, this confirms that quality data collection is one of the most essential processes prior the actual LCC assessment also as mentioned in previous studies (e.g.

Cole & Sterner, 2010; Hua Goh & Sun, 2015; Risitmäki et al., 2013).

On the whole, comparative analysis showed that wood buildings may result in higher construction and demolition costs (Thomas & Ding; Hossaini et al., 2014), but an increased internal rate of return, less interest charges (Huang et al., 2017; Cazemier, 2017) and high wood resource efficiency at the end of life cycle (Goverse et at., 2001; Gustavsson, 2015; Gustavsson, 2009; Kutnar & Muthu, 2016) demonstrate economic efficiency potential. Also, assumption of similar NPVs of costs for CLT and RC buildings support Green (2012), Høibø et al. (2015) and Svajlenka et al. (2017) studies that wood buildings show market competiveness in comparison to traditional concrete buildings.

In conclusion, this study demonstrated that an economic performance assessment is an essential part of the optimization development to provide high quality and long-term stability for modern wood construction systems. LCC can be a supportive method in the decision-making as a tool to assess economic efficiency of projects early at the stage. However, costs data gathering also showed how each stakeholder sees and separates their own responsibilities in the project, often reluctant to share any cost data with concern to reveal a company's business logic. Low interconnection between project actors may follow with the ambiguity in definitions and cost data groupings for each stakeholder (Gluch et al., 2004).

It is important to note the final estimated LCC number does not represent the real future outcome or probable results. Anything related to predicting the future has some level of uncertainty and it is a product of assumptions. Thus, the next section will demonstrate where it is required to bring assumptions and the level of uncertainty.

### 5.1.2 Uncertainties

According to the provided cost model (Appendix 4) Bridport House construction cost is *£5,936,965*, where the biggest and the main variable according to the study is CLT *Frame Structure* which is *£1,022,760*. To make a valid economic assessment of wood buildings, it is important to understand the formation of the CLT *Frame Structure* cost and each cost factor. This can be challenging, specifically when the related data is coming from several different data sources. The main task is to connect cost data to provide a holistic and credible cost model representing (or close to) actual construction costs.

For CLT *Frame Structure* cost, the following data is received:

Actual costs for the main structural material - CLT retrieved from Stora Enso sources

Costs for additional component materials (i.e. plasterboard, gypsum, insulation) taken from the independent cost data tool BCIS (Building Cost Information System) Online

CLT package cost including design, supply and installation provided by Eurban

The recreation process of the *Frame Structure* cost started with counting the amount of CLT volume considering all architectural details, like wall configurations, doors and windows cuts, additional ceiling and wall layers for each floor. Table 15 summarizes the facts for Bridport House on frame cost and material volume with estimated figures. It also shows the difference between the information collected from main stakeholders (given parameter) and self-estimated version (estimation).

**Table 15** Comparison of facts and estimated CLT volume and frame cost of case wood building

| | Given parameter | Estimation |
|---|---|---|
| **CLT volume** | 1576m3 | 1516m3 |
| ***Difference*** | 60m3 - 3,8% | |
| **Frame Costs** | £1 022 760 | £957 306 |
| ***Difference*** | £65 454 - 6,4% | |

The main reasons causing the difference in figures is the inconsistency of the data provided, which can be explained by different degrees of responsibilities for different stakeholders. This means that certain actors were involved in the project only for a limited time; using different accounting systems might cause of incomplete data recoding. (Gluch & Baumann, 2004)

Further, the *Use* and *After Use* phases require future cost estimations, which induce the study to use assumptions supported by the scientific literature, professional experts' consultation and collected statistical data from historical sources. Also, for the comparative LCC analysis, it necessary to bring a certain amount of assumptions into the calculation to produce a hypothetical reinforced concrete (RC) building based on Bridport House (CLT) frame costs. Table 16 represents a list of cost/income categories where assumptions were made and reveals the grounds for the assumptions, the manner in which they were calculated and based on which data sources. The cost/income category column has color coding to separate assumptions for the two buildings. Blue colored cells indicate cost/income assumptions for the RC case, while green stands for assumptions made for the CLT case. White or blank cells are common categories and those assumptions apply for both buildings. After the table, there are a number of links to demonstrate the origin of the assumptions.

**Table 16** Cost and income assumptions for LCC assessment of CLT and RC buildings

| Cost/ Income category | Assumption | Application Ground | Source of data |
|---|---|---|---|
| ***Before USE*** | | | |
| Preliminaries | "£70 000 preliminary saving"<br>£637817+£70000 = **£707817** | The CLT 8-week program gain provided time saving in comparison with RC case | Architecture company, Karakusevic Carson Architects [1] |
| Overhead and profit | **6%** from overall construction costs = **£322 235** | O&P assumed to be 5% of construction costs (e.g. it is 6,6% for CLT case) | Building Economics Manager, Stora Enso |
| Substructure Foundations | RC > CLT by 31,813%<br>£363 501+31,8% = **£479 131** | Difference between total amount of concrete and reinforcement for foundations | Bridport House carbon cost comparison. Main contractors, Willmott Dixon |
| Internal wall finish | **£0** - no cost for concrete wall finish | No additional plasterboard required for the concrete walls finish except sanding and coat work (e.g. cement) | Building Economics Manager, Stora Enso |
| Ceiling finishes | **£24 765** | Plasterboard is required only in the common areas (e.g. corridors, hallways etc.) and above apartments' entrances | Building Economics Manager, Stora Enso |
| Design fees, Site clearance, Roof, Brick cladding, Internal partitions, Doors, Windows, Floor finish, Stairs, Fittings and furnishing, Service installations, Externals, Drainage | The cost category assumed to be the same as for the CLT case, due to lack of access to architectural pricing for building's design. | Other cost categories assumed to be the same in order to keep comparison focus between buildings' structural materials. | |
| Basis of construction costs | 2010 construction rates, Location London Borough of Hackney | Carry out comparison of actual costs based on 2010 rates, when the CLT case was approved | Building Cost Information Service Online, RICS [2] |
| Interest expense | Annual interest rate **7%** | Estimate the debt difference due to CLT less annual capitalized interest paid | KIS, Keep It Simple Finance [3] |

| | | | |
|---|---|---|---|
| ***USE*** | | | |
| Maintenance cost | 30 years study period<br>£78 000 * 30 = **£2 340 000** | Annual planned and responsive maintenance costs are included | Life cost model, Randall Simmonds LLP. Client, London Borough of Hackney |
| Energy use cost | Average energy consumption rates from 2010 to 2017 | Oversee future gas and electricity costs based on two data sources: CLT case operational costs for 3 years and the UK statistical data | Client, London Borough of Hackney<br>Department for Business, Energy and Industrial Strategy. Energy Consumption in the UK, 2017 [4] |
| Replacement cost | **£2 506 982** | Cyclical replacement cost based on the median life expectancy in period of 30 years | Life cost model, Randall Simmonds LLP. Client, London Borough of Hackney |
| Maintenance cost & Replacement cost | | The cost category assumed to be the same as for the CLT case, due to no direct relation to the building frame structure | |
| Operational cost | Average energy consumption rates from 2010 to 2017 | Simulate gas and electricity consumption per year based on average UK household consumption rates | Department for Business, Energy and Industrial Strategy. Energy Consumption in the UK, 2017 [4] |
| ***After USE*** | | | |
| Demolition and waste management | Average demolition rates | No previous case studies describing multi-story CLT buildings demolition (i.e. no rates for the demolition costs) | Current waste and disposal rates plus estimation for the CLT deconstruction, McGee |
| Recycling cost | **50%** of CLT materials go to **recycling** | Oversee future recycling costs (i.e. costs from recycling) | Experts estimation on reuse and recycling costs, McGee |
| Demolition costs | CLT wood specie – spruce Average **mass density 450kg/m3** | Calculation of demolition costs in tones of materials | Stora Enso CLT image brochure [5]; Brandner et al. (2016) |
| Demolition and waste management | Average demolition rates | Oversee demolition cost at the end of building study period based on average UK demolition rates | Building Cost Information Service Online, RICS<br>Average rates, McGee |
| Recycling cost | **100%** of RC case materials go to recycling | Oversee future recycling costs (i.e. costs from recycling) | Experts estimation on recycling costs, McGee |
| **INCOME** | | | |
| Rental income | **£78 400** per 1 month for the whole property<br>**3-7%** annual overhead percent for 30 years study period | Estimate average rent prices in London Borough of Hackney<br>Average yearly increase in rental prices in London area, UK | London rent maps, www.london.gov.uk [6]<br>House price forecast, Savills research; Land registry Hoemsandproperty.co.uk [7] |
| Reuse income | **50%** of wood **reused** as a base material for CLT production<br>**£400,8** per **1 m3** CLT (2010) | Oversee wood recovery potential (e.g. revenue from reuse) | Experts suggestion on reuse, McGee<br>Reuse rate, Stora Enso contract price |

| | | | |
|---|---|---|---|
| Energy income | **500KWh** electricity from **1 ton** of wood | Oversee revenue from energy recovery | European Commission DG Environmental News Alert [8] |
| **LCC** | | | |
| Discount rate | **3,5%** in the UK | Express time value of money to express future costs and benefits flow | Discount rate in project analysis. The Green Book, 2018. [9] |
| Study period | **30 years** | The most optimal period for the LCC assessment is between 25-40 years | Kneifel, 2009; Sarma & Adeli, 2002; Heralova, 2014. |

1. Bridport House CLT info2, pdf file provided by Karakusevic Carson
2. http://www.rics.org/fi/knowledge/bcis/online-products/bcis-online/
3. https://www.kisbridgingloans.co.uk/development-finance-calculator/#
4. www.gov.uk
5. http://assets.storaenso.com/se/buildingandliving/ProductServicesDocuments/CLT%20Imagebroschure%20[final%202016-04-22]%20-%20EN-WEB.pdf
6. https://www.london.gov.uk/what-we-do/housing-and-land/renting/london-rents-map https://www.findproperly.co.uk/london/area/hackney#.WorfuZPFL_R
7. https://www.homesandproperty.co.uk/property-news/buying/how-much-will-your-london-home-be-worth-by-2022-a116506.html https://www.homesandproperty.co.uk/property-news/house-price-forecast-could-the-average-london-home-cost-867000-by-2027-a107701.html
8. http://ec.europa.eu/environment/integration/research/newsalert/pdf/93na1_en.pdf https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Waste_to_Energy_2016.pdf
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At the end, the comparative LCC analysis was reviewed by experts from the construction industry representing the UK market. Based on a personal perspective and subjective experience, the reviewer concluded that estimations on construction costs specifically for the RC building are weak considering the level of uncertainty. Thus, to provide a strong base for the assumptions, a larger number of verifications is needed.

Nevertheless, this is out of the study scope and LCC assessment was not intended to provide 100% single-valued, probable results. LCC method can have definite level of uncertainty coming from the difficult and inconsistent process of data collection (Gluch & Baumann, 2004). Thus, implementation of an economic analysis method largely depends on key stakeholders' decisions to take LCC assessment into consideration in the project development process.

## 5.2 Stakeholders Decision-Making Factors: Benefits and Obstacles

The second research problem was addressed through conducting the Online survey and Individual Interviews with wood construction industry stakeholders and results are given in Subchapter 4.2 and Subchapter 4.3 respectively. This Subchapter intends to discuss the main findings and answer the second research questions "*What wood building **benefits** and **obstacles** determine stakeholders' decisions to implement wood construction practices?*"

The qualitative part of the thesis study found overlapping evidence from the multiples studies and literature sources examined. Moreover, most of the wood construction advantages and weaknesses indicated through the online survey match the benefits and obstacles found during the individual interview meeting minutes. Thus, the most mentioned benefits in combination with advantages and weaknesses together with obstacles presented in the Figure 7 as main Benefits and Obstacles of wood construction.

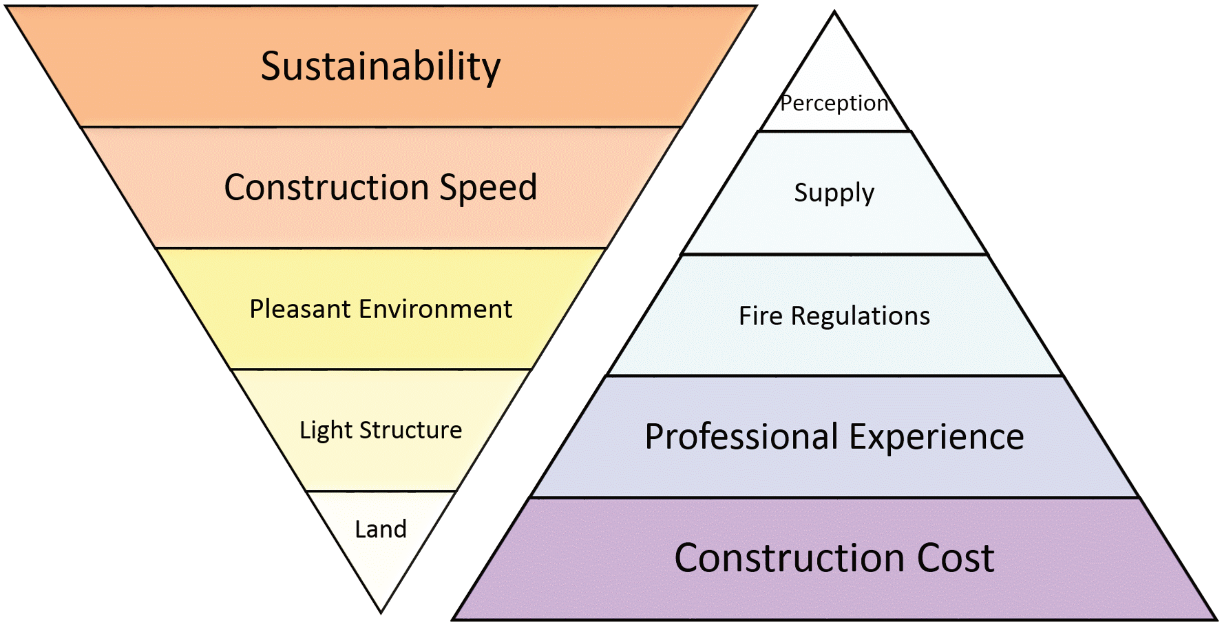


**Figure 7** Main Benefits and Obstacles of wood construction

The Benefits and Obstacles represent major factors of wood buildings, which support decision-making among construction industry stakeholders. There are five main Benefits, which are drivers and motivations for the adoption of wood materials. Those are Sustainability, Construction Speed, Pleasant Environment, Light Structure, Land and shown in reverse left pyramid with green-yellow shade. While five main Obstacles that have an impact on wood construction promotion have presented in the regular right pyramid and have a cold purple-blue tone to it. Those are Construction Cost, Professional Experience, Fire Regulations, Supply, and Perception.

Firstly, ***Sustainability*** *of wood materials* mainly from the environmental point of view was found to be one of the key benefits of wood construction also as the dominant literature reviewed (Gosselin et al., 2015; Jones et al., 2016; Jochem et al., 2016; Schmidt & Griffin, 2013; Toivonen, 2012; Toppinen et al., 2017). The effect of wood materials on the inner environment, creating enjoyable natural atmosphere and benefits of wood as renewable material were identified, but for the most part, participants highlighted the potential of wood to store carbon dioxide and wood buildings' ability to mitigate greenhouse gas emissions (Gosselin et al., 2015; Gold & Rubik, 2008; Werner & Richter, 2007).

However, some of the participants mentioned that environmental benefit is not the main determining factor for customers to choose wood buildings. Toppinen et al. (2017) indicated similar response and linked it with traditional (or conservative) mindset of experienced wood industry experts. In contrast, this study's findings are more inclined to the idea that construction stakeholders relate an unwillingness of consumers to pay for sustainability benefits due to limited knowledge about building materials and their impact on the environment. This is in line with Høibø et al., (2015) and Gold (2007), who suggest that with further education and with increasing concerns about environmental impacts and communicating environmental benefits with the quality of wood buildings, price and design end-users' decision-making can change. Indeed, consumers ***Perception*** *on wood buildings as easily flammable, less resistance to decay plus poor acoustic insulation* was mentioned several times during the thesis interviews with stakeholders and was indicated as an obstacle. Moreover, some said that any mistake can bring down the whole wood construction industry image. In a similar manner, Gold and Rubik

(2009), Mahapatra et al. (2012), Espinoza et al. (2015) described consumer misperception in their studies.

Further, stakeholders seem to be well familiar with the aspect of wood construction to reduce construction time and mentioned it as a benefit for time-related costs. Wood Construction Speed is considered a value factor for the economic efficiency of wood construction, specifically from a developer's point of interest, thereby increasing the number of completed projects in a certain period of time. This is in accordance with the study by Cazemier (2017), where it stated that reduced construction time allows faster rates of repaying loans with a quicker revenue stream due to early settlement. However, a limited number of ***Supply*** chains in wood materials production was mentioned to increase construction costs and can potentially affect the construction process and timeline. The material availability in the market was also discussed as a potential obstacle by Passarelli and Koshihara (2017), Espinoza et al. (2015), Nolan, (2011), Mallo and Espinoza (2015).

From respondents' perspectives, end-users highly value the ability of wood materials to create a comfortable and ***Pleasant Environment*** overall. End-users enjoy a sense of natural material, especially when the wood is exposed for the people's experience. This is mentioned in the findings of Gold and Rubik (2008) and Toppinen et al. (2017), stating that people have an increasingly positive attitude about wood building factors like well-being, design, aesthetics, and health. At the same time, in relation to Perception, the obstacle is that people have doubts with regard to the structural aspects of wood buildings, such as combustibility and durability, in comparison to other building materials (Mallo & Espinoza, 2014; Høibø et al., 2015)

Further on combustibility, findings show that building ***Regulations*** for wood construction (specifically excessive requirements related to fire and acoustic performance) and limitations on the height of buildings is perceived as unfavorable for wood construction. There are also opinions that additional fire resistance systems increase construction costs and require more thorough upfront design. This has also been discussed in previous studies (Mahapatra et al., 2012; Sundkvist, 2008, Roos et al., 2010), confirming that the wood construction process can become sensitive when trying to meet building regulation requirements on fire, sound, air-tightness, which can hinder wood construction implementation.

Then, the ***Light Structure*** of wood buildings reduces the construction time due to the quick and easy assembly of wood elements. This was noted as a potential benefit to reduce construction cost. Similarly, several of studies (Smith et al., 2017; Klussel, 2008; Wang et al., 2013; Roos et al., 2010) highlighted the lightweight of wood materials as a beneficial point of wood construction. Still, limited ***Experience***, lack of training and skills and appropriate education among construction professional indicate a low in-depth knowledge regarding wood construction techniques and methods, shielding the full range of benefits to view (Mahapatra et al., 2012), which is also confirmed in the findings.

Individual interview findings revealed one interesting moment related to ***Land*** acquisition for wood construction development. During the tender period, wood development projects were argued to have an advantage over other projects to get a plot from the city because of the environmental benefits of wood. This topic was introduced to the study by Hynynen (2015), who said municipalities tie together land-use planning and sustainable business development areas for more efficient urban development. In addition, Wang et al. (2013) found that wood construction is emphasized in government's sustainability agendas. Thus, considering wood construction benefits like environmental impact and the potential for bio-economy development (Petersen & Solberg, 2005; Kuzman & Sandberg, 2015; Wang et al. 2014), cities may support wood project plans and provide land plots more readily to those projects. The land price might not be the subject of change, but quick land acquisition can have an impact on the economic efficiency of wood buildings. In contrast, Riala and Ilola (2014) found that when town plans favor wood frame projects, it is a somewhat unfair competitive advantage of wood. However, this subject is not elaborated on in other studies or any scientific literature in greater detail. This could be explained by the fact that it is prohibited for public authorities to promote or prescribe any single building material that may exclude others (Hynynen, 2015; Roos et al., 2010).

In regards to cost efficiency, wood buildings are still associated with *higher **Construction Cost***. Gustavsson et al. (2015) mentioned that material, construction, long term maintenance and risk-aversion costs are considered to be on the top three obstacles for extended wood use in construction. This was also maintained throughout the other literature review (Hemström et al., 2011; O'Connor et al., 2004; Bartlett & Howard, 2000; Jones et al., 2016; VTT, 2017). Although, it is important to note that the study results also show optimism and expectations on the development of the wood building industry among construction stakeholders. The majority stated that with the right design, correct wood application and consideration of cost saving benefits, wood construction can become cost-effective. A similar outcome can be traced in a few previous studies as well (Bartlett & Howard, 2000; Wang et al., 2013; Riala & Ilola, 2014; Roos et al., 2010).

### 5.2.1 Opportunities for Wood Construction Development

This Subchapter concludes the answer to the second research question by discussing stakeholders' perspectives on wood construction and its future development potential. It elaborates on the results of the wood buildings market situation and its development opportunities plus further steps and actions to improve wood construction practice.

***Market demand and development potential***

Regarding the wood construction market, stakeholders, in general, consider wood buildings number to be relatively low with about 5% to 10% of market share. Wang et al. (2012) noted that in the UK wood construction cover 25,6% of all new housing. However, as noted by Pei et al. (2014) the market share for tall modern wood buildings has not been developed until recently. Thus, there is no conclusive evidence to suggest comprehensive statistics on the market share of modern wood buildings (Mahapatra et al., 2012).

Nevertheless, results of the study show that stakeholders have a positive perception pointing to the increasing market demand for wood construction. The majority pointed that wood construction itself has great development opportunities and in coming ten years with appropriate engineering and marketing the demand presumably will rise by 20%. Bowyer et al. (2016) also demonstrate that there is considerable potential for wood buildings, specifically for tall ones which represent the greatest opportunity for market expansion.

The findings indicate slow but steady and definite progress of wood construction development and stakeholders feel the potential of wood construction taking the leading position in the market by coming years. Key wood construction stakeholders are confident that big construction industry players demonstrate the interest in wood construction. This is in correspondence with Jones et al. (2016) that the interest and awareness about wood construction practice are increasing among construction industry. However, the study also found that traditional construction industry stakeholders are not rushing to get into the modern wood construction, but slowly getting familiar with it by taking smaller steps. This can be close to the findings of Rissanen (2018), saying that there is still remains some prejudice towards wood construction among construction industry.

Wood construction itself has great development opportunities in coming years (e.g. Smith et al., 2017). With indicated slow but steady progress, wood construction has the potential to take the leading position in the construction market within 10 to 15 years. This is in correspondence to the notion that interest and awareness about wood construction practice are increasing among construction industry (Jones et al., 2016).

***Actions and Solutions***

Stakeholders' opinions showed that there have been four major growth actions in promoting wood construction: *Professional Education, Cooperation and Involvement, Knowledge Share* and *Scale-up Wood Buildings number*.

As was discussed earlier, the findings of this study indicate a large number of stakeholders are concerned about the low level of knowledge among wood construction actors and also noticed minor representation of wood construction methods and techniques in the education system. Findings show that the construction industry is in a transitional period, where the benefits of wood construction are acknowledged but the practical implementation is still in the process of acceptance. This is mainly due to the long dominance of traditional concrete construction and the novelty of timber construction, resulting in a lack of experience in the field and weak knowledge about wood construction (Jones et al., 2016; Riala & Ilola, 2014; Roos et al., 2010). Therefore, ***Professional Education*** was pointed to as long-term investment to enhance wood construction development. This is somewhat in line with the findings from earlier studies on information and knowledge gaps. For example, Gosselin et al., (2015) talked about the need for knowledge extension to make wood materials as easy as to work with other materials.

Next, to strengthen wood construction industry and its relationship within the market, more attention is required to establish ***Cooperation and Involvement*** among the wood industry main actors. One of the findings is that developers and engineers highlighted the need of more active engagement from wood suppliers to provide individual business approach during the development, construction and demolition processes rather than just materials sale. The similar conclusion made in the study by Roos et al. (2010) where engineers and architects were expecting material suppliers to provide hassle-free timber-based solutions and solve any occurring problems.

Thus, to improve wood construction potential and productivity in the market, stakeholders need to take on new responsibilities and share risks through collaboration (Hurmekoski et al., 2015). It was also found that early collaboration practice between wood building project stakeholders indicated as the essential element for well-planned logistics, fast design and building time and results in better construction practice. Smith et al., (2017) found that early collaboration of all actors including an owner, architects, manufacturer, contractor can improve the design process to avoid mistakes and considerably speed up the project's schedule.

Moreover, *Cooperation and Involvement* imply raising an adequate awareness of material values and knowledge about its technical quality, economic competitiveness, and environmental performance through the network of the main actors and ***Knowledge Share***. Acknowledgment and integration of sustainable thinking are also perceived as having marketing potential to promote the benefits of wood buildings and deliver long-term values for the end-users. These findings endorse the study by Toppinen et al. (2017) which propose to analyze further consumer's behavior about sustainability concept around wood buildings.

The findings presented by Riala and Ilola (2014) can be used as a basis for a discussion on how the increased number of wood buildings is one of the actions to improve the image of wood construction and boost bio-economy. The thesis resulted that simply use of more wood in commercial and public construction projects will increase the practical knowledge, spread positive knowledge and improve the competitiveness of wood materials in the market. Thus, ***Scale-up Wood Buildings number*** is noted to be one of the best drivers to motivate opportunities for wood construction following the principle of learning by doing.

# 6 CONCLUSION and FURTHER RESEARCH

This study contributed to meeting the need for more research in the field of economic optimization of wood construction by comprising two research methods. The main quantitative method of the study included the economic assessment framework described in the European Standard EN 16627:2015. It is implemented in the case of a wood building to demonstrate which of the life cycle cost indicators impact the economic efficiency of modern wood buildings. In addition, to analyze economic performance of the wood building and determine its cost competitiveness the study produced comparative economic assessment between wood and alternative concrete buildings.

The second research method consisted of the online survey and individual interviews to obtain professionals' perspective regarding wood construction development. In turn, it demonstrated key stakeholders decision-making to implement wood construction practices.

Together the two research methods allowed to touch diverse aspects of wood construction and the thesis presents three main findings as conclusions including suggestions for further research.

***Economic Efficiency of Wood Building***

Comprehensive LCC assessment showed that the wood building is able to demonstrate economic efficiency throughout the life cycle. In thirty years of the study period, construction costs take the major share, where the building cost, including wood materials and the frame structure, make the most contribution to the economic efficiency of the wood building. At the same time, there are indicated cost reducing opportunities coming from specific properties of wood construction. Wood material's lightweight, prefabrication, and fast installation during the *Before Use* phase allow reducing the construction costs. While recycling and reuse of wood materials at the *After Use* phase brings income generation opportunities and affect the overall cost-efficiency of the wood building.

Limitations of this study related to the uncertainty level inherent for future costs assessment and the shortage of input data. The challenge to collect cost data seems to indicate stakeholders uncertainty towards the LCC method. The economic assessment process showed how each stakeholder sees and separates own responsibility for the project, which may also reveal the deeper need for cooperation between construction main actors. Thus, further research could be required to show the LCC method not only as the economic assessment tool but also as involving process bringing the learning benefit to key stakeholders about the diversity of important aspects in building's life cycle. Continuing study on the implementation of LCC in wood buildings assessment may raise the level of understanding about the complexity and interdependence of the building development processes. Whereas cooperation and information share can be key instruments to improve building's economic, environmental and social performance.

***Economic Competitiveness of Wood Building***

Comparative LCC assessment between wood and concrete buildings enabled to provide economic performance analysis identifying the most cost-efficient design solution. Generally, the cost-effectiveness of wood building estimated to be similar to concrete building showing only 0,2% lower value in NPV of costs. Hence, the thesis argues that wood building is able to demonstrate economic competitiveness in comparison with alternative building from heavy materials. Moreover, the findings correspond to studies by Høibø et al. (2015) and Svajlenka et al. (2017) and suggest to communicate appropriate design, reduced construction time and enhanced environmental benefits of wood buildings to lead economically efficient investment decisions.

Nevertheless, to define wood buildings definite cost competitiveness in compassion with other buildings is a wider task. Thus, it would seem that to bring deeper understanding on correlating processes contributing to the economic performance during life cycle a bigger number of building case studies need to be examined. Possible further research could focus not only on the investigation of economic performance but provide the assessment to portray how economic, environmental, technical and social benefits support each other. This approach could demonstrate the range of possibilities for wood buildings, as well as objectify the ground for the definition of wood building cost competitiveness.

***Stakeholders' Decision-Making***

The main qualitative findings maintain previous studies, which determine key stakeholder's perspective on wood construction and detect factors influencing decision-making to implement wood as a building material. On the one hand, the results could indicate key stakeholders familiarity with the potential benefits of the wood construction. Sustainability, Construction speed, Pleasant environment, Wood light structure, and Land acquisition were emphasized the most. In agreement with Jones et al. (2016), the study also found that the construction industry demonstrates steadily growing interest towards the wood construction practice. Stakeholders acknowledge positive development potential for modern wood buildings, which is one of the decisive factors to get involved in the wood construction industry.

On the other hand, the current state of knowledge on the selection of building materials seems to be followed by the long-term prevalence of traditional materials in the industry. Indicated shortage and inconsistency in academic literature with regard to wood buildings' technical and economic performance also seem to have a strong influence on stakeholders' decision-making of predominantly used construction materials. Thus, Construction costs, Lack of professional experience, excessive Fire regulations, Limited supply and biased Perception are among main obstacles to hinder wood construction development.

Therefore, the study suggests that the initial step for successful implementation of wood construction practices related to the ability to communicate the knowledge concerning wood buildings performance to the construction industry stakeholders and other involved parties. The thesis stresses the need for further research to accent the importance of practical implementation of wood construction and raise an adequate awareness about wood materials technical qualities and cost-competitiveness among the construction industry actors through investigative studies and research projects.

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# APPENDICES

## APPENDIX 1: Online Survey Questions

1. In which country are you working at?

2. Which of the following age groups do you fall into?

20-25
26-35
36-45
45-60
60 <

3. Which best describes your field of working?

Construction
Consultancy (i.e. project management, construction management, cost management etc.)
Engineering
Design
Architecture
Other

4. What are main advantages of wood materials in construction?

| Potential advantages | *No advantage* | *Neutral* | *Advantage* | *Big advantage* | *Hard to tell/ No answer* |
|---|---|---|---|---|---|
| Competitive price (i.e. construction costs, materials costs, low labor costs) | | | | | |
| Speed (i.e. reduced construction period) | | | | | |
| Materials structural quality (i.e. lightweight, durability, strength etc.) | | | | | |
| Easy, safe to use (i.e. low level of site injuries, fast installation process etc.) | | | | | |
| Natural material (i.e. health benefits/ non-toxic for workers) | | | | | |
| Aesthetics (e.g. appearance; raw material can cut on special finishing) | | | | | |
| Site release conditions (i.e. in some locations it is allowed to build only wood buildings) | | | | | |
| Other | | | | | |

5. What are weaknesses of wood materials in construction?

| **Potential weaknesses** | *No weakness* | *Neutral* | *Weakness* | *Big weakness* | *Hard to tell/ No answer* |
|---|---|---|---|---|---|
| Construction costs (i.e. high professional fees, materials costs etc.) | | | | | |
| High maintenance (e.g. re-arrangement, storage of wood elements can add costs) | | | | | |
| Building's structural properties or appearance (e.g. sound susceptible; rotting) | | | | | |
| Fire safety regulations (i.e. flammability, additional fire sprinklers add costs) | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Policy limitations (e.g. longer time to get permits due to unfamiliar building system) | | | | | |
| Other | | | | | |

6. What building use phase indicators are the most important to consider during construction phase?

| | *Neutral* | *Low importance* | *Important* | *High importance* | *Hard to tell/ No answer* |
|---|---|---|---|---|---|
| Energy performance during building's life cycle | | | | | |
| Building's life span (e.g. longevity; future adaptability) | | | | | |
| Building optimal operation and functionality (e.g. refurbishment forecasting; efficient facility management etc.) | | | | | |
| Investments' profitability | | | | | |
| Environmental impact (reduction of carbon footprint) | | | | | |
| End-users satisfaction and comfortability | | | | | |
| Other | | | | | |

7. What is the construction cost for modern wood building in comparison with traditional building?

Low price
Equal
Reasonable
High price
Hard to tell/ No answer

8. How construction costs allocated in modern wood construction?

| **Construction Cost Shares** | *Allocation of total timber construction costs, 100%* | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***0-5%*** | ***5-10%*** | **10-20%** | ***20-40%*** | ***30-40%*** | ***40-50%*** | ***>50%*** |
| **Design and planning** cost (i.e. upfront and rigorous planning process, experts: fire, acoustics etc.) | | | | | | | |
| **Building elements** (i.e. foundations, ground floor, frame, internal space elements, façade, roof) | | | | | | | |
| **Site elements** (i.e. ground works, site equipment, site construction etc.) | | | | | | | |
| **Building service elements** (plumbing, air conditioning, electrical elements, mechanical elements: lifts, escalators; laundry, kitchen equipment) | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Property management** (i.e. land acquisition, rent, taxes, property development, planning etc.) | | | | | | | |
| **Construction site services** (i.e. energy supply, heating, ventilation, materials storage, cleaning, site transports etc.) | | | | | | | |
| **Professional tasks/** costs (i.e. project management: construction preparation, supervision etc.; construction management: quantity and cost surveying) | | | | | | | |
| **Waste management** (i.e. transportation from building site; final disposal fees etc.) | | | | | | | |
| **Transportation** (i.e. to the site and from site: materials, products and | | | | | | | |
| **Risks and price level changes** (i.e. design, construction changes etc.) | | | | | | | |
| Other | | | | | | | |

9. What are main obstacles for modern wood construction system to become a wider practice?

| **Obstacles** | *Not important* | *Low importance* | *Important* | *High importance* | *Hard to tell/ No answer* |
|---|---|---|---|---|---|
| Lack of experienced professionals (i.e. limited knowledge) | | | | | |
| Lack of reference projects (i.e. limited experience) | | | | | |
| Poor network of interdependent construction actors (i.e. no early collaboration) | | | | | |
| Low market demand (i.e. negative media coverage; bad image among non-wood experts) | | | | | |
| Threat to natural resources (i.e. deforestation) | | | | | |
| High construction costs (i.e. high demand on knowledgeable experts and quality raw materials) | | | | | |
| Construction regulations limitations (i.e. fire safety; no standardized building systems) | | | | | |
| Limited scale of construction material production | | | | | |
| Unknown risks and additional costs | | | | | |
| Other | | | | | |

10. How to improve wood construction system practice?

| **Possible solutions** | *Not important* | *Low importance* | *Important* | *High importance* | *Hard to tell/ No answer* |
|---|---|---|---|---|---|
| Educate professionals in wood construction, design and engineering | | | | | |
| Improve network system between main actors (i.e. early stage collaboration between | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| owner, architect, manufacturer, contractor etc.) | | | | | |
| Improve building/ construction regulations (i.e. update regulations on fire safety, number of allowed floors) | | | | | |
| Research and development | | | | | |
| Efficient construction management (i.e. optimization of implementation of timber construction techniques; logistics) | | | | | |
| Transparent building system methods | | | | | |
| More integration with other (forest) industries, government and knowledge sharing | | | | | |
| Other | | | | | |

11. What is the market share of modern wood buildings in your local market?

| **Range of wood buildings' market share** | | | | | |
|---|---|---|---|---|---|
| < 5% | 5-10% | 10-15% | 15-20% | 20% < | Hard to tell/ No answer |
| | | | | | |

12. What is the market demand for modern wood construction in your local market?

| State of timber construction | **Wood construction demand, %** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *At the moment* | | | | *In 5 years* | | | | *In 10 years* | | | |
| | < 2 | 2-5 | 5-10 | 10 < | < 5 | 5-10 | 10-15 | 15 < | < 10 | 10-15 | 15-20 | 20< |
| Rising | | | | | | | | | | | | |
| Declining | | | | | | | | | | | | |
| Still | | | | | | | | | | | | |
| Hard to tell/ No answer | | | | | | | | | | | | |

13. What is the potential for modern wood building construction development?

| State of timber construction | **Wood building construction development potential, %** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *At the moment, %* | | | | *In 5 years, %* | | | | *In 10 years, %* | | | |
| | < 5 | 5-10 | 10-15 | 15 < | < 5 | 5-10 | 10-15 | 15 < | < 5 | 5-10 | 10-15 | 15 < |
| Rising | | | | | | | | | | | | |
| Declining | | | | | | | | | | | | |
| Still | | | | | | | | | | | | |
| Hard to tell/ No answer | | | | | | | | | | | | |

## APPENDIX 2: Individual Interview Questions

1. What is your background and current position? Could you please tell little bit more about the company and its strategy and main goals?

2. What is your biggest interest in wood building's design and construction? (Growing Business, Sustainable and environmentally friendly, Appearance, Construction costs, Market Demand etc.)

3. In your opinion, what are main differences in constructing with wood materials to compare with traditional materials? How about construction costs (i.e. €/m2)?

4. What main challenges you faced when developing/ realizing/ managing wood building projects?

5. What relationship do you establish with other stakeholders when working on wood building project? How closely do you collaborate with other wood construction industry players, like designers, architects, engineers, RE developers, materials suppliers and clients?

6. Do you use same building system pattern or start from scratch for each wood building project?

7. What is the situation with wood buildings market in Finland/ Europe?

8. Is there demand from public, residents? If yes, does it seem to be growing/ falling? Have you made similar market research or investigated on market demand?

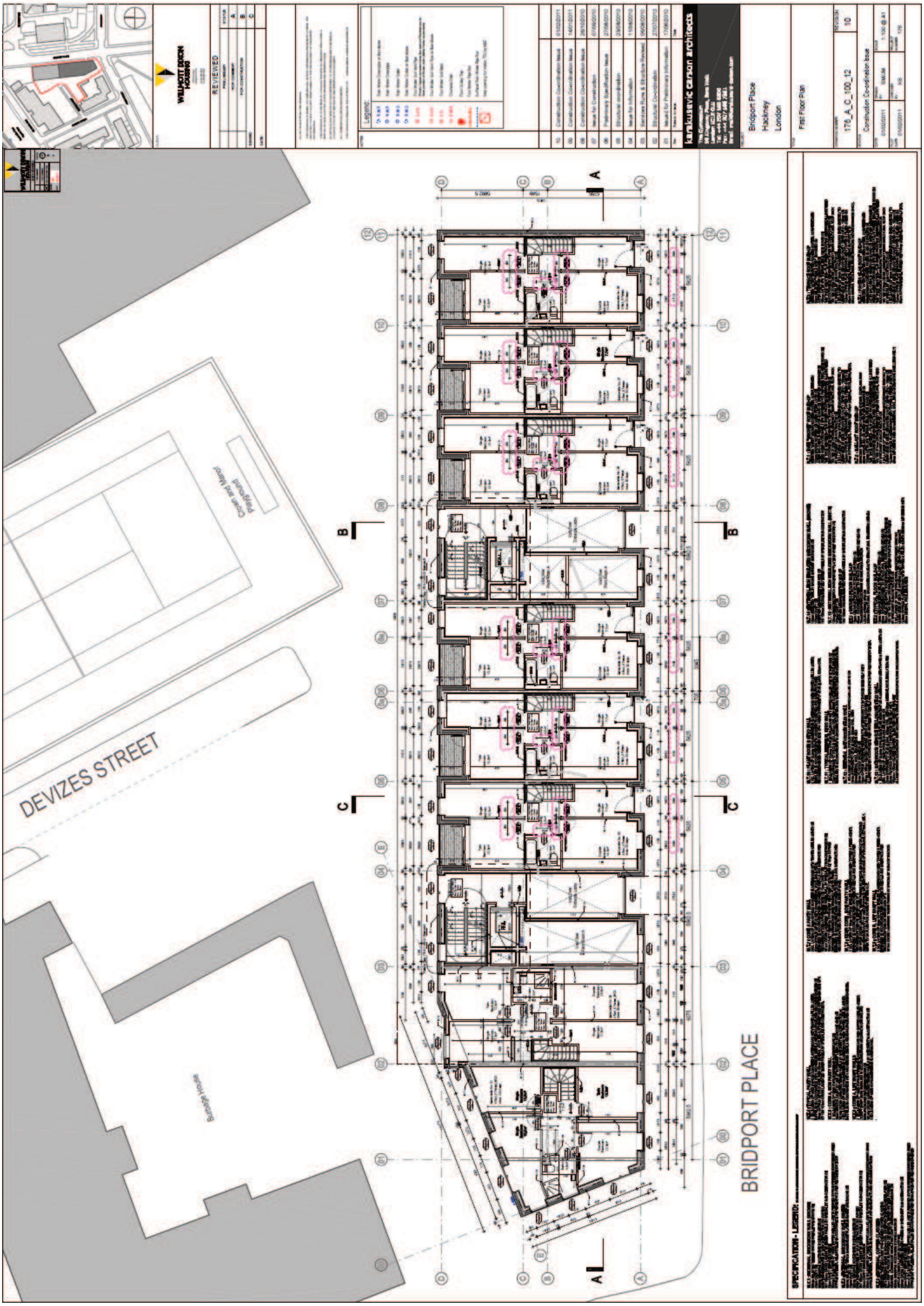
9. What factors of wood construction can limit it to become worldwide practice? (What are the reasons to prevent the construction industry to build more with wood?)

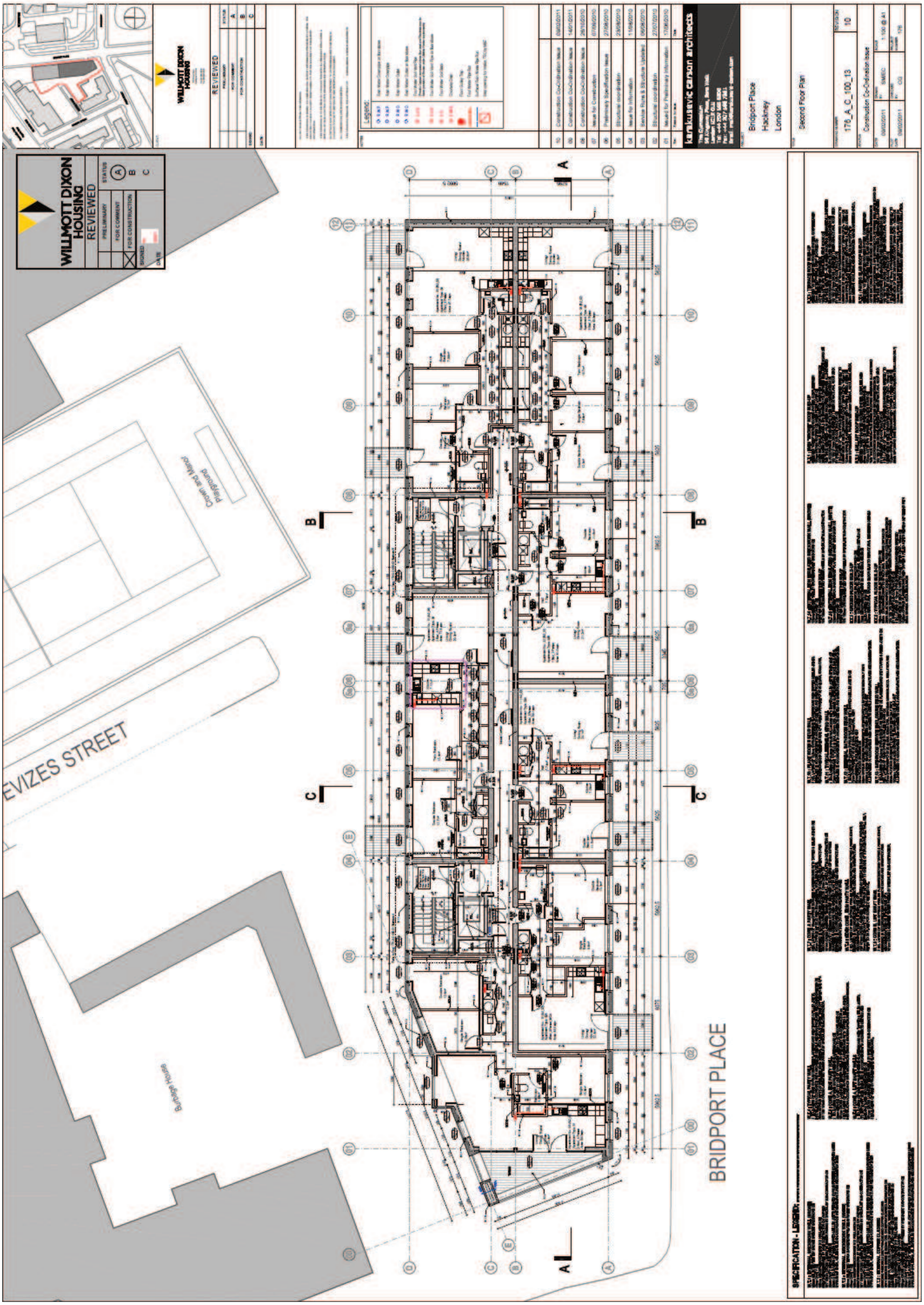
10. How to increase economics of wood construction? How to increase overall value for wood building (i.e. rental price/ demand) and at the same time decrease its construction costs?

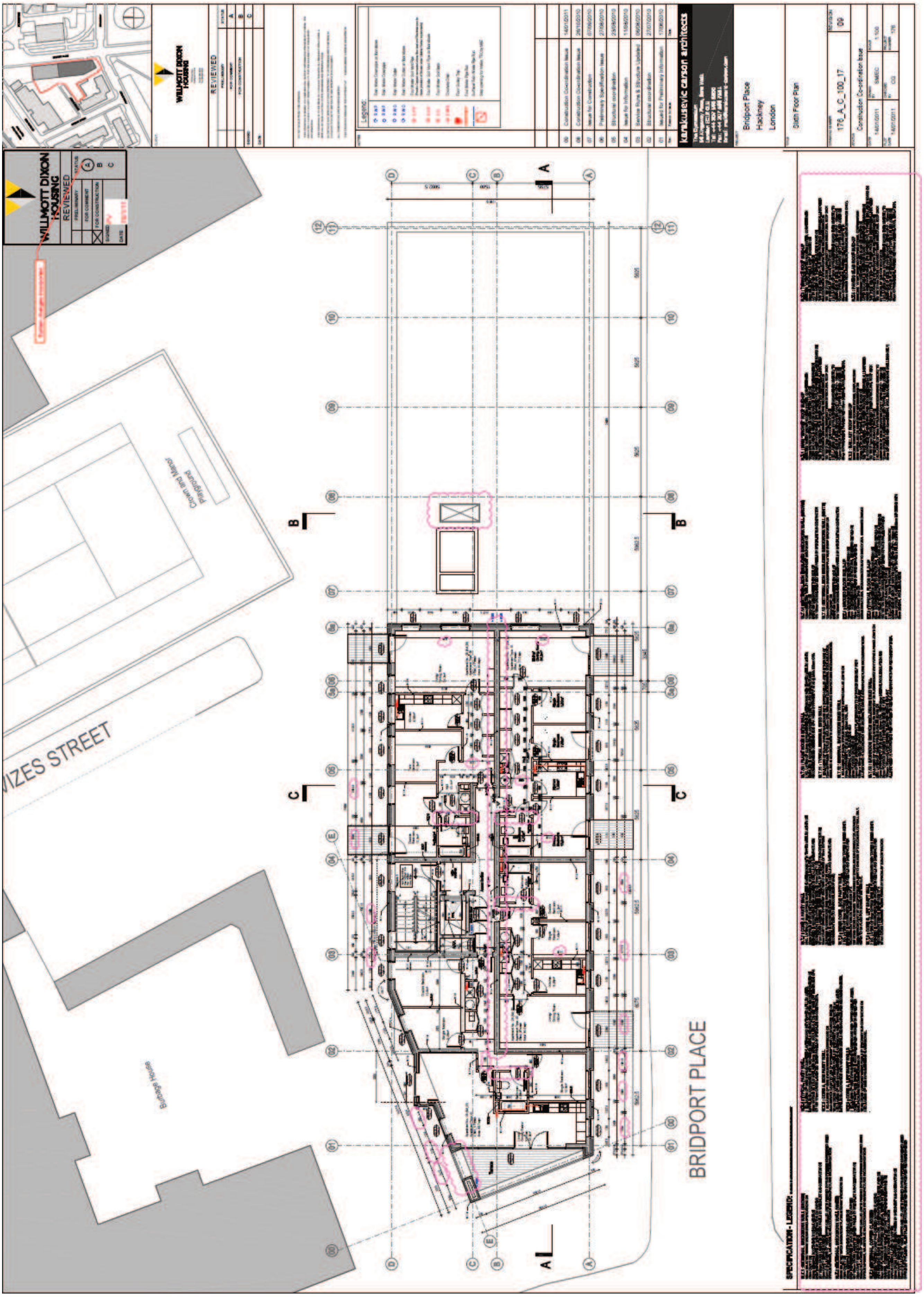
11. Do operational costs (energy, water consumption, replacement and management) associated with construction material? What is the difference in operational phase of wood and concrete buildings?

12. What is your approach in promoting sustainable building development practices?

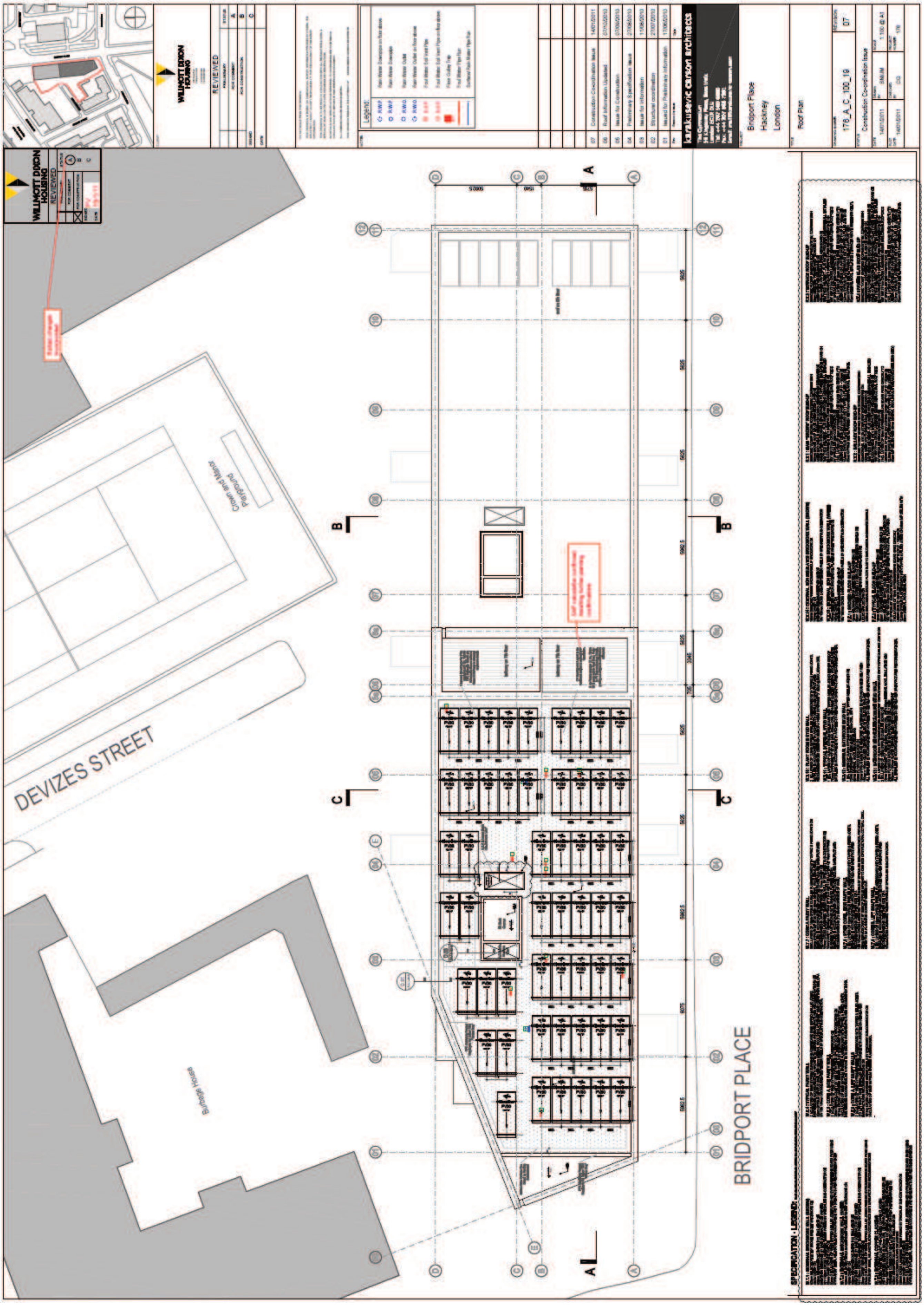
## APPENDIX 3: Bridport House Floor Plans




WILLMOTT DIXON HOUSING
REVIEWED
PRELIMINARY
FOR COMMENT
FOR CONSTRUCTION
STATUS
A
B
C
SIGNED
DATE
DEVIZES STREET
BRIDPORT PLACE
Playground
Burbage House
karakusevic carson architects
Bridport Place
Hackney
London
Second Floor Plan
176_A_C_100_13
10
Construction Co-Ordination Issue
SPECIFICATION - LEGEND
Legend



WILLMOTT DIXON HOUSING
REVIEWED
BRIDPORT PLACE
IZES STREET
karakusevic carson architects
Bridport Place
Hackney
London
Sixth Floor Plan
176_A_C_100_17


DEVIZES STREET
BRIDPORT PLACE
Burbage House
WILLMOTT DIXON HOUSING
REVIEWED
Bridport Place
Hackney
London
Roof Plan
176_A_C_100_19

# APPENDIX 4: Bridport House Cost Model

**Whole Life Costing Model**
**BRIDPORT HOUSE**

**Life Cycle Analysis**

| | | | |
|---|---|---|---|
| Projects | Nr | 1 | I |
| Units (HCA Funded Flats Only) | Nr | 41 | b |
| Gross Area | m2 | 4250 | |
| Net Area | m2 | 3310 | |
| Build cost (£/m²) exc. Contingency | £/m2 | 1,397 | |
| Capital cost (£) exc. Contingency | £ | 5,936,965 | |
| Discount rate | % | 2.5% | |

**NPV of Estimated Maintenance costs x 100**
**Scheme Capital Costs**

| | |
|---|---|
| Maintenance Capital Ratio | 72.3% |
| £/m²/yr LCC | 24 |
| Costs in-use NPV (£) (exc. VAT) | 4,290,000 |

| BCIS code | Replacement (Cyclical) Costs | Life Expectancy in Years | Quantity | Unit | Capital cost (£/Unit) | Scheme or Unit Item | Quantity in Scheme | Capital cost (£/scheme) | Replacement cost factor | Replacement cost (£/Unit) | % Replaced | Replacement cost (£/scheme) | Replacement NPV £ (ex. initial cost) | Sub totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Substructure** | | | | | | | | | | | | | |
| | Foundations; including site drainage and groundworks, screeds and insulation | 100 | 1 | item | 363,501 | b | 1 | 363,501 | 0 | - | 100 | - | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | - | b | 1 | 0 | 0 | - | 100 | - | £0.00 | £0.00 |
| 2B | **Upper Floors** | | | | | | | | | | | | | |
| | Primary frame and floor structure; | 100 | 1 | item | 1,022,760 | b | 1 | 1,022,760 | 2 | 2,045,520 | 100 | 2,045,520 | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0.00 |
| 2C | **Roof** | | | | | | | | | | | | | |
| | Roof Coverings etc. | 23 | 1 | item | 151,269 | b | 1 | 151,269 | 2 | 302,538 | 100 | 302,538 | £171,447.45 | £171,447.45 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0.00 |
| 2D | **Stairs** | | | | | | | | | | | | | |
| | Stairs, balustrade and handrail | 60 | 1 | item | 101,659 | b | 1 | 101,659 | 1 | 101,659 | 100 | 101,659 | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0.00 |
| 2E | **External Walls** | | | | | | | | | | | | | |
| | Brick facing | 75 | 1 | item | 946,302 | b | 1 | 946,302 | 1 | 946,302 | 100 | 946,302 | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0.00 |
| 2F | **Windows and External Doors** | | | | | | | | | | | | | |
| | Windows and Doors | 40 | 1 | item | 384,553 | b | 1 | 384,553 | 2 | 769,106 | 100 | 769,106 | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0.00 |
| 2G | **Internal Partitions** | | | | | | | | | | | | | |
| | Interior Partitions | 60 | 1 | item | 184,332 | b | 1 | 184,332 | 2 | 368,664 | 100 | 368,664 | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 2H | **Internal Doors** | | | | | | | | | | | | | |
| | Internal Doors; timber doors | 30 | 1 | item | 74,250 | b | 1 | 74,250 | 1 | 74,250 | 100 | 74,250 | £35,398.14 | £35,398 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 3A | **Internal Wall Finishes** | | | | | | | | | | | | | |
| | Wall Finishes; plasterboard etc | 35 | 1 | item | 86,611 | b | 1 | 86,611 | 1.5 | 129,917 | 100 | 129,917 | £0.00 | £0 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 3B | **Floor Finishes** | | | | | | | | | | | | | |
| | Vinyl Finishes | 15 | 1 | item | 129,217 | b | 1 | 129,217 | 1.2 | 155,060 | 100 | 155,060 | £180,987.78 | £180,987.78 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 3C | **Ceiling Finishes** | | | | | | | | | - | | | | |
| | Ceiling Finish; plasterboard | 38 | 1 | item | 86,389 | b | 1 | 86,389 | 1 | 86,389 | 100 | 86,389 | £0.00 | £0 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 4 | **Fittings and Furnishings** | | | | | | | | | | | | | |
| | General fittings | 15 | 1 | item | 53,791 | b | 1 | 53,791 | 1.5 | 80,687 | 100 | 80,687 | £94,177.95 | £94,178 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |

Randall Simmonds LLP

6

**Whole Life Costing Model**
**BRIDPORT HOUSE**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5A | **Sanitary appliances** | | | | | | | | | | | | | |
| | Sanitary Appliances | 15 | 1 | item | | b | 1 | 0 | 1.5 | - | 100 | - | £0.00 | £0 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| 5C | **Services Installations** | | | | | | - | | | | | | | |
| | Typical Mechanical Component | 15 | 1 | item | 419,695 | b | 1 | 419,695 | 1.5 | 629,543 | 100 | 629,543 | £734,807.19 | £734,807 |
| | Typical Electrical Component | 15 | 1 | item | 316,200 | b | 1 | 316,200 | 1.5 | 474,300 | 100 | 474,300 | £553,606.87 | £553,607 |
| | Lift Installation | 15 | 1 | item | 73,951 | b | 1 | 73,951 | 1.5 | 110,927 | 100 | 110,927 | £129,474.33 | £129,474 |
| | BWIC | 15 | 1 | item | 28,400 | b | 1 | 28,400 | 1.5 | 42,600 | 100 | 42,600 | £49,723.07 | £49,723 |
| | Spare Component | 1 | 1 | item | | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| | | | | | | | | | | | | | | |
| 6C | **Externals** | | | | | | | | | | | | | |
| | Typical Externals Component | 20 | 1 | item | 195,542 | b | 1 | 195,542 | 1.2 | 234,650 | 100 | 234,650 | £143,200.32 | £143,200 |
| | Block Paving | 25 | 1 | item | 43,413 | b | 1 | 43,413 | 1.2 | 52,096 | 100 | 52,096 | £28,099.88 | £28,100 |
| | Play Equipment | 10 | 1 | item | | b | 1 | 0 | 1.2 | - | 100 | - | £0.00 | £0 |
| | Drainage | 100 | 1 | item | 42,558 | b | 1 | 42,558 | 0 | - | 100 | - | £0.00 | £0.00 |
| | Spare Component | 1 | 1 | item | - | b | 1 | 0 | 1 | - | 100 | - | £0.00 | £0 |
| | | | | | | | | | | | | Total | 2,121,000 | |
| | | | | | | | | | | | | Total / Unit | £51,732 | |