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A Study of the Viability of Cross Laminated Timber for Residential Construction

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Master Thesis

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Abstract

This report presents an overview into cross laminated timber (CLT) as a construction material and how it compares to traditional methods of construction. CLT is also examined in the context of a move to off-site manufacturing (OSM) and a greater emphasis on sustainability in the construction sector. In this context it is found to perform well with mass timber products such as CLT being the only carbon negative building materials capable of building mid and high-rise buildings.

The barriers and opportunities for CLT are explored looking at literature, industry reports and case studies. The main barriers to wider use of CLT still come from uncertainties around the material. Although they have been proven to not be a problem, worries over issues such as how it performs during fires and the lifetime of buildings persist. A lack of standardisation may be the primary cause for this as a range of products and specifications across different manufactures and countries creates confusion and means that each building needs to be individually specified. The opportunities identified for CLT include its carbon saving properties which could benefit governments wanting to reach their carbon reduction targets. In addition, the ability to use CLT on a wider range of sites such as unstable brownfield land and over service tunnels lends to its strength in aiding with urban densification.

In terms of costs, these are found to be comparable to those of traditional construction methods with high material costs being offset by reduced foundations and construction time. CLT buildings do, however, face a premium in insurance costs. Transport costs, resulting from a concentrated production base in central Europe, also add a considerable amount to the overall cost of the finished product. This in turn encourages domestic production in countries outside of Europe.

The possibilities for CLT in the UK residential construction market are investigated with a focus on mid-rise and high-rise flat construction as that is what the economics and material properties of CLT most lend itself to. Although CLT currently has a low market share of less than 0.1% of homes in this sector there is the potential for this to increase to 20-60% over time. The lower range of this estimate is not predicted to be reached before 2035 and this is also dependant on rising CLT production levels. The volume of timber that is needed to manufacture enough CLT to reach these increased construction volumes can be sourced sustainably from existing forests production in Europe and North America. In addition, the UK has enough excess timber harvesting capacity to provide for the entirety of CLT buildings in the UK, however, large scale domestic CLT production is required to make this a reality.

Sammanfattning

Denna rapport presenterar en översikt över korslimmat trä, KL-trä (cross laminated timber, CLT på engelska), som byggnads- och konstruktionsmaterial och hur det står sig jämfört med traditionella byggnadsmetoder. CLT undersöks också i samband med så kallad prefabricering (eng. 'offsite manufacturing', OSM) och en större tonvikt på hållbarhet inom byggsektorn. I detta sammanhang finns en stor potential med massiva träprodukter, såsom CLT, vilka är de enda möjliga kol-negativa stommaterialen för flervåningshus.

Barriärerna och möjligheterna till CLT utforskas baserat på litteratur, branschrapporter och fallstudier. De främsta hindren för ökad användning av byggsystem med CLT antas bero på osäkerheter kring brand-, akustik- och beständighetsfrågor. Även om det inte går att påvisa att användning av CLT som stommaterial i flervåningshus leder till en försämrad brandsäkerhet och livslängd, så bekymrar sig byggindustrin och försäkringsbolag över dessa frågor. Brist på standardisering kan vara den främsta orsaken till detta. Skilda produkter och specifikationer finns vid olika tillverkare och mellan länder vilket skapar förvirring och innebär att varje byggnad behöver specificeras individuellt. De möjligheter som identifieras för CLT inkluderar minskade koldioxidutsläpp, vilket kan gynna regeringar som vill nå sina koldioxidreduktionsmål. Möjligheten att använda CLT vid svårbebyggd industriell mark och över servicetunnlar är andra exempel på dess fördelar vid stadsförtätning.

När det gäller kostnader är dessa jämförbara med traditionella byggnadsmetoder. Höga materialkostnader kompenseras främst av kortare byggtid och reducerad kostnad för grundläggning. CLT-byggnader innebär dock generellt högre försäkringskostnader. Höga transportkostnader, orsakade av att tillvekningen är koncentrerad till Centraleuropa, bidrar också till en betydande del av den totala kostnaden för slutprodukten. Detta uppmuntrar i sin tur inhemsk produktion i länder utanför Europa.

Möjligheterna med CLT på den brittiska marknaden undersöks även avseende nybyggnation av flervåningshus, ett område där CLT antas ha störst fördelar. Även om CLT för närvarande har en låg marknadsandel på mindre än 0,1% av de nybyggda bostäderna inom denna sektor, finns det potential för att detta stiger till 20-60% över tiden. Den lägre nivån beräknas inte vara nåbar före 2035 och detta är också beroende av stigande CLT-produktionsnivåer. Den mängd trärvara som behövs för att nå dessa ökade byggvolymer med CLT kan erhållas hållbart från befintliga brittiska skogar. Storbritannien har alltså tillräckligt med skog för att tillhandahålla all träråvara för en kraftigt ökad inhemsk CLT-marknad, men storskalig inhemsk CLT-produktion krävs för att detta ska bli verklighet.

Preface

This master thesis has been carried out at KTH, Department of Civil and Architectural Engineering, Division of Building Materials, in Stockholm.

I would like to acknowledge my supervisor Magnus Wålinder for his help and ideas during this project.

Stockholm, June 2018

Max Smyth

Abbreviations

BSI – British Standards Institution

CLT – Cross laminated timber

GHG – Green house gas

LVL – Laminated veneered lumber

MMC – Modern methods of construction

OSM – Off-site manufacturing

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I. Introduction

1.0 Background overview

1.1 The construction industry in a wider context

Two of the greatest future challenges facing humanity in the next century are arguably climate change caused by anthropogenic emissions (IPCC, 2014) and the severe global housing shortage resulting from rapid population growth and chronic undersupply (Tipple, 1994; Angel, 2000; Wetzstein, 2017). Housing shortages not only create environmental and social problems (Brown, 2003) but also by nature necessitate the building of many more homes. It is these homes in question that will not only contribute to climate change but also place tremendous strain on the planet's finite resources.

1.2 Environmental footprint of the construction industry

The construction industry is responsible for a large portion of the total green house gas (GHG) equivalent emissions globally. In 2008 it corresponded to about one third of the GHG emissions (UNEP SBCI, 2009). It is important to note that this comprises of both the operational 'every day' energy use and construction materials. The production of construction materials such as steel, bricks, concrete and aluminium, they are responsible for 17% of the worlds fossil fuel energy use yearly. However, not all these materials are used in the construction industry, so the total is, in fact, closer to 10% of world's fossil fuel energy (Oliver *et al.*, 2014). The largest emitter by far is cement production which in 2015 account for approximately 8% of the global CO_2 emissions (Olivier et al., 2016), accompanied with a threefold production increase from ca 1.5 to 4.6 billion metric tonnes between years 2000 and 2015 (Scrivener et al., 2016). There are, however, improvements for some materials. For example, new factories and production methods for steel have resulted in greater efficiency requiring less energy (Buchanan and Honey, 1994; Buchanan, 2007). Regardless, the production of these 'traditional' construction materials remains carbon intensive and contributes a considerable portion to the carbon footprint of the construction sector.

Traditionally, if viewing a building over its lifetime, operational energy usage is a much larger contributor to carbon emissions than the materials that it is built from (Iddon and Firth, 2013). However, over the last several decades there has been extensive research on energy efficiency in homes both from an environmental and a cost saving perspective (Pullen, 2000; Feist et al., 2005; Iddon and Firth, 2013; Laconte and Gossop, 2016). These developments alongside higher government standards for home insulation (DBEIS, 2017a) have led to increased efficiency and reduced emissions. A reduction in operational emissions without a proportional reduction in construction related emissions will lead to construction emissions increasing their share of overall emissions (Buchanan, 2007) and so becoming more important to address. The use of renewable energy sources also means that it is theoretically possible for homes to become carbon neutral from an operational energy standpoint. As a result, there is now greater awareness about emissions from building materials which were previously underestimated (Pullen, 2000; Ibn-Mohammed et al., 2013). This, combined with the possibility of emissions from operational usage becoming negligible, therefore places greater emphasis on the need to reduce the carbon emissions of the materials themselves. The only building material that is carbon negative and is widely available, is timber (Marcea and Lau, 1992; Buchanan and Honey, 1994) which is used to make products such as cross laminated timber (CLT) which will be the focus of this study.

1.3 Current major trends in UK residential construction

1.3.1 Increasing costs of building materials

An uptake in construction after the downturn in 2008 has resulted in a shortage of building materials, in particular bricks and blocks. This has led to supply issues for builders and increased prices. As a result, manufacturers have increased production levels in the UK, but this has been insufficient to avoid needing to increase imports (AMA Research, 2018). These imports have suffered from cost inflation due to the depreciation of Sterling (EEF, 2017). This has placed further pressure on the construction industry where over 70% of companies have already reported price increases (Lawrence, 2017), especially for goods such as steel and concrete (Allen, 2017a). A shift to domestic timber use would reduce dependence on the imports of concrete, steel and bricks which have risen in double figures over the last 5 years (ONS, 2017). Timber prices have, however, also increased with some businesses already reporting a 20% increase in imported timber prices (Lawrence, 2017).

1.3.2 Low productivity & skilled labour shortages

The decline of productivity in the UK construction industry was highlighted in the Farmer Review (Farmer, 2016) which was commissioned by the government to review the UK's construction labour model. This report emphasised a lack of research and development (R&D), innovation, adequate training and collaboration in the construction sector.

The report highlights the shortage of workers in the construction industry which continues to increase and the resultant increase in wages has driven cost inflation in construction projects. The threats of Brexit are recognised in the report and due to the reliance on foreign workers (Tetlow and Giles, 2017), which are already showing early signs of declining (ONS, 2017), it is likely that the shortage of workers will continue and possibly worsen. The reliance on a largely human workforce is seen as one of the main causes for low productivity. However, incentives are lacking for contractors to train their workforce appropriately as they are increasingly reliant on self-employed staff, non-permanent staff and a disjointed supply chain (Farmer, 2016).

In response to this report the British government have pledged to pursue a modern industrial strategy which will remove barriers to innovation and develop a collaborative innovation programme (Prior et al., 2017). The Government's Housing White Paper (MHCLG, 2017) goes further to outline specific ways in which they aim to stimulate innovation.

1.3.3 Prefabrication and off-site manufacturing (OSM)

Off-Site Manufacturing (OSM) is a process whereby sections of buildings are prefabricated under controlled conditions in a factory setting. This has become a growing area of interest, due to its low labour requirements, as demand for skilled workers has outstripped supply (Smith *et al.*, 2015). Currently OSM only accounts for approximately 10% of the UK's total construction output (Hurn, 2018).

Four of the ten main recommendations from the Farmer Review (Farmer, 2016) focus in R&D and innovation within the construction sector with an emphasis on premanufactured solutions. These have also been identified in separate government reports as a good way of increasing energy efficiency and meeting its carbon emission reductions (DECC, 2012). It has been enacted into law via an increase in the minimum standards for energy efficiency in some homes (DBEIS, 2017a). Current homes will likely look to use insulation to meet this standard but OSM, which can increase the air tightness of building envelopes, is one option for new buildings.

A push for support for 'precision manufacturing' is supported in the London Housing Strategy policy 3.4-part C (GLA, 2017). The Mayor wants to modernise the industry and is supporting this by making funds available to allow affordable homes to be precision manufactured and making the shift to precision manufacturing of homes a key priority for investment via a new construction academy.

The UK Government is currently looking to learn from other countries, particularly Germany, and their approaches to OSM. This is not purely to increase productivity in the sector but also to find a solution to the need to build homes faster to address the national housing shortage (Offsite Hub, 2015). One tenth of new homes built by 2020 are aimed to come from OSM which is a 55% increase on current figures (Morris, 2018).

2.0 Research motivation

Timber that origins from sustainable managed forests is our only widely used building material that is truly renewably, and therefore also sustainable. The production of timber operates near to a 'human timescale' of decades with sustainable forestry cycles taking from 35 to 70 years (Liski *et al.*, 2001) rather than the centuries and millennia taken to form materials such as ore for metal and limestone for concrete.

As urbanisation and population growth continue to exert pressure on finite areas of land there is the need to build at increased densities. This commonly translates to taller buildings. The properties of timber, mainly related to being combustible, mean that it has been traditionally constrained to only being able to build low-rise buildings. However, new performance-based fire regulations combined with the advances in timber engineering and the creation of mass timber elements, such as cross laminated timber (CLT), now mean that timber products exist which can be used to build mid and high-rise buildings. These can be built to the same standards as concrete and steel buildings and so offer a viable alternative.

3.0 Mass timber as a material

3.1 What is mass timber?

Mass timber differs from traditional timber products as it is engineered timber product that exploits the advantages of timber. By layering timber perpendicularly, it can be made into custom shapes and to specific technical standards such as load bearing beams and panels. This allows it to be used to build a far wider variety of buildings than traditional timber construction allowed (Zumbrunnen and Fovargue, 2012) while also retaining the positives of being a carbon negative building material

(Cole, 1998). The UK National Specification publication for timber has recently been published showing that prefabricated timber no longer has the limitations of traditional wood buildings (TRADA, 2016a). There are many different forms of mass timber including cross laminated timber (CLT), glue-laminated timber (GLT) or Glulam, Laminated veneer lumber (LVL), parallel strand lumber (PSL), dowel-laminated timber (DLT), nail-laminated timber (NLT) and interlocking cross-laminated timber (ICLT) (Smith *et al.,* 2015).

3.2 Most common types of mass timber

3.2.1 Cross laminated timber (CLT)

The most widely known example of mass timber is cross laminated timber (CLT), sometimes referred to as XLAM, which will be the focus of this report. Invented in Austria, it is now used across Central Europe, the Nordic regions, North America and the Asia Pacific region.

It features strips of timber that are layered and glued perpendicularly under pressure (laminated) to form a strong singular piece (Figure 1) which is inherently stable and therefore can span floors and be used as load bearing walls (Mohammad *et al.*, 2012). The panels are made symmetrically around a central layer resulting in the panels having an odd number of layers, most commonly 3, 5 or 7 layers thick with the total size of the panel only limited by it needing to be transported to site (BM TRADA, 2015).

The most commonly used timber for CLT is Spruce but Pine and Larch are also known to have been used. Before being made into panels this timber is kiln dried so that the moisture content has been reduced to approximately 12% to prevent any future warping, shrinking, insect damage or rot TRADA (2016b). The adhesives used in the lamination process are now commonly formaldehyde free which prevents toxic emissions which effect indoor air quality once constructed (BM TRADA, 2015). For greater detail on the grading process and material specifics please see Brandner *et al.* (2016).

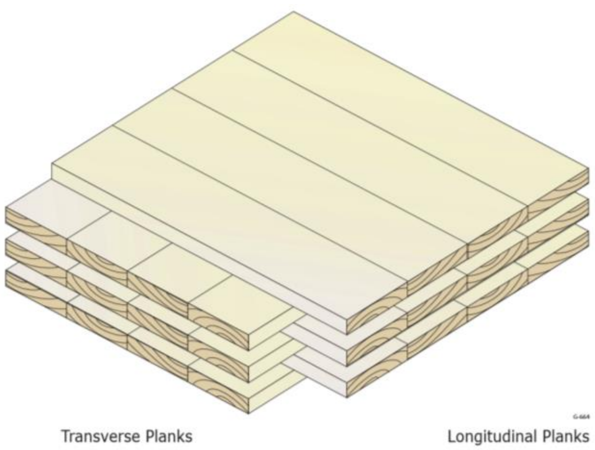

Figure 1 – Cross laminated timber assembly

Figure reproduced from the CLT Handbook (Canadian Edition) (FPInnovations, 2011).

3.2.2 Glulam

Glue laminated timber, known as glulam, is very similar to CLT in how it is made with the fundamental difference being that the layers are glued together in parallel rather than perpendicularly. This makes glulam much more suited to linear building elements such as columns and beams rather than structural walls. These columns and beams form framed systems but utilise non-structural materials to infill the areas between the structural supports forming walls (BM TRADA, 2015). Glulam beams have the advantage of being able to be produced curved for use in creating arched structures (TRADA, 2016b) although these are not common in residential buildings.

3.2.3 Laminated veneer lumber (LVL)

Laminated veneer lumber (LVL) is constructed in a similar fashion to plywood where the finished product is made of many thin layers of timber. To achieve this, logs are rotary peeled into sheets which are subsequently bonded together under pressure and heat with the grain of all piles running in the same direction (Eckelman, 1993). These are then sawn into set sizes and are commonly used as a structural beam or joist in timber frame buildings and prefabricated building elements (Stora Enso, 2016).

II. Objectives

1. Investigate how CLT construction compares to traditional construction methods and what barriers and opportunities it faces
2. Determine the possibilities for CLT in the residential construction market

III. Research questions

1) How do CLT buildings compare to traditional construction methods on cost, safety and quality?

2) What are the main disadvantages of and opportunities for CLT construction?

3) What are the key challenges CLT faces in becoming more widely used?

4) With emphasis in the UK, how is the market share of mass timber predicted to change and can this be supported in a sustainable way?

IV. Methods

4.0 Overview of methods

To answer the proposed research questions numerous methods will be needed. To start, an overall literature review is required to gain insight into CLT as a material, other forms of mass timber and the construction sector. An in-depth critical literature review will then be conducted to build on, and add more detail to, the introduction to CLT. This section will focus on how CLT performs compared to other construction methods which will be analysed and discussed in later sections.

As others have noted (Manninen, 2014), the limited data on mass timber products presents difficulties when performing numerical and economic analyse of CLT in the global and even national scale. Therefore, this report will take several different approaches to establish what are the real challenges for CLT across many markets and what factors make CLT more used in some versus others. The lack of detailed, consistent and comparable information on CLT will mean that sometimes that mass timber products as a whole are used as a proxy for CLT. In some instances, studies and information pertaining to tall timber framed building will also be used to aid in the analysis and understanding of the market.

4.0.1 Literature review

The literature review will focus on using peer review journals for much of the information regarding discussions surrounding mass timber. However, although there are many journal entries (Figure 2), there are many gaps in the literature. Due to the relative newness of CLT and the constantly changing regulations and viewpoints surrounding it, it is necessary to use other sources of information. Government reports and standards guidelines are extremely helpful in this respect as many of those cited in journals are now out of date and have been superseded by newer versio ns. Like these, company reports, organisations websites, technical and market reports were valuable sources of information.

For the most up to date information on CLT and other mass timber products industry magazines, newsletters and websites were all especially useful sources of information. When using these it was necessary though to always go to the route of their sources. Many articles used headline figures, which although being true, when taken out of the context of their original publication could b e misleading. These types of sources were also particularly useful for gathering opinions on mass timber, although it is important to realise that the often strong, positive opinions which are voiced in these types are sources are not always a balanced vie w.

4.0.2 Interviews

Interviews are also used as a source of data collection. Interviews with industry experts and politicians were carried out to gain additional insight into the topic and determine whether their opinions align with that of the scientific and wider literature. These will be conducted in a semi-ridged fashion with a series of set questions but the freedom to explore topics as they arise.

Overall, in the interests of time, only a couple of interviews will be carried out. There are several relevant research papers and reports in which large numbers of interviews and surveys have been conducted on the subject matter of timber buildings and mass timber across industry professionals and manufactures. For the purposes of this report these studies provide much more information than would be easily acquirable given my time and resources.

4.0.3 PESTLE analysis /comparative studies

PESTLE, sometimes written as PESTEL (Professional Academy, 2018), is an analytical tool used mainly in business planning. It uses an approach where the political, economic, social, technological, legal and environmental issues surrounding a topic are examined. This then allows an overview and understanding of the external factors influencing the subject matter (CIPD, 2018; Process Policy, 2018). In the context of this report each of these topics will be investigated specifically in regard to CLT, as outlined below:

- Political – Government policies influencing timber buildings
- Economic – Cost competitiveness of CLT
- Social – Perceptions of timber buildings, especially regarding safety
- Technological – Can CLT buildings perform in the same way as current and traditional building methods
- Legal – What government regulations affect CLT
- Environmental – How does building with timber address environmental concerns and assist in environmental policy goals

This approach will be used to get a clearer picture of the barriers to the widespread use of mass timber and CLT. It will be later used in a less rigid structure when looking at areas of opportunity for CLT. This approach offers the advantage of not needing large amounts of quantitative data and providing a simple analysis to further understand the context of the problem. Conversely, the inherent risk with this method is the fact that the analysis may be too simple and lack enough detail to be meaningful (CIPD, 2018).

4.0.4 Collation and analysis of data

To make tangible conclusions for the future possibilities of CLT in the residential construction market quantitative data is needed. Finding such data is difficult as CLT is often not referred to in any general statistics and official production figures for Europe do not exist (CBI, 2017a). Even other mass timber products do not have statistical data collected on them. For example, in the national and global statistics collected by the FAO (2015;2016;2018) the closest items to CLT are in the category of wood-based panels. Here figures for veneer and fibreboards among others can be found. There is a section labelled other but with no indication of what other is and as part of an aggregated dataset this is not helpful. Although it may be possible to infer certain production values of larger mass timber elements from these, with nothing to suggest correlation between them it would be inaccurate and misleading to do so. Mass timber is also not recorded as a category in UK national statistics nor does it say which sub category it is included in (DBEIS, 2018).

In depth studies of the market for CLT in scientific journals are lacking. As other authors (Manninen, 2014) and those working in the industry (Stora Enso UK 2018, personal communication, 5 January) have found, it is difficult to locate consistent and accurate statistics on mass timber products with many previous studies are founded in anecdotal evidence and no empirical data (Beyreuther et al., 2016). There are many reports issued by private consulting companies such as IMARC (2016) and Wise Guy Reports (2017) which create forecasts for the industry. These reports are, however, prohibitively expensive to academics costing several thousand dollars each. Moreover, these reports are not peer reviewed and, as other researchers have found (Hetemäki and Hurmekoski, 2016), not only are these reports not peer reviewed, but it is difficult to judge the robustness of the analysis. Talking to companies in the industry they also view these sources as not very reliable but the only place that has collated figures on the topic (Stora Enso UK 2018, personal communication, 5 January).

To compare CLT usage, statistics need to be complied from many separate data sources which have varying degrees of reliability. This will be done using company reports, industry news articles, academic journals and interviews. Thankfully forestry and general building statistics are more available although not explicitly in relation to CLT. Simple calculations will be done using these figures to arrive at estimates for the potential for CLT in the UK residential market, the volume of CLT required for this and its impacts on forest harvest levels.

V. Critical Literature and Theory Review

5.0 History of mass timber

Beam elements such as Glulam were developed in the late 19th century as a means to make larger timber elements with increased strength and consistency (TRADA, 2016b). More recently the use of computer modelling of Glulam structures has allowed more advanced and complicated structures to be designed without the need for physical testing making the material more cost effective (TRADA, 2016b). Innovations in wood processing in Switzerland towards the end of the 20th century allowed timber to be specially engineered into mass panel timber elements such as CLT. This breakthrough created many new possibilities due to the improved structural strength of the timber (BM TRADA, 2015).

Modern cross laminated timber has its origins in Austria and Germany where it was first used in the early 1990s (Mohammad et al., 2012). It arose through efforts of sawmill operators to create higher value products from side boards (Brandner *et al*., 2016). By the mid-1990s research in academia and industry had resulted in the current form of CLT, although it took a further decade of testing, product approvals and improving distribution channels before it became more widely used (FPInnovations, 2011).

Since the turn of the century there has been a rapid increase in research into CLT with more research publications being published in the last 5 years (2013-2017) than in the 30 years from 1980 to 2009 (Figure 2) and public interest continuing to increase (Figure 3). For a more detailed account of the history and development of the product please see Brandner *et al*. (2016).

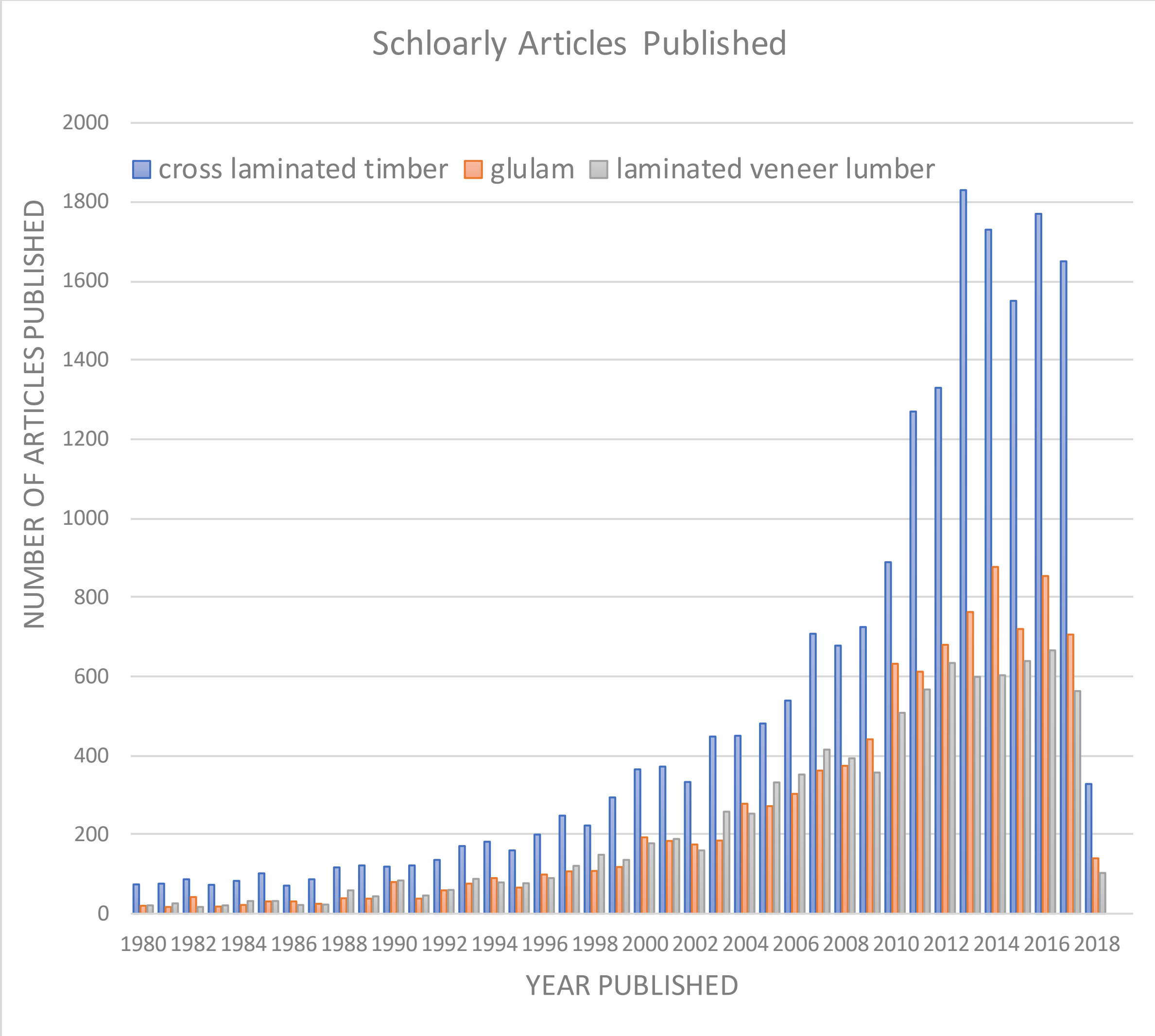

Figure 2 – Scholarly articles published concerning mass timber

The number of scholarly articles listed as published on Google scholar when searching the terms 'cross laminated timber', 'glulam' and 'laminated veneer lumber'. Note that the figures for 2018 only account for those articles published in the first 10 weeks of the year therefor appear substantially lower than for 2017.

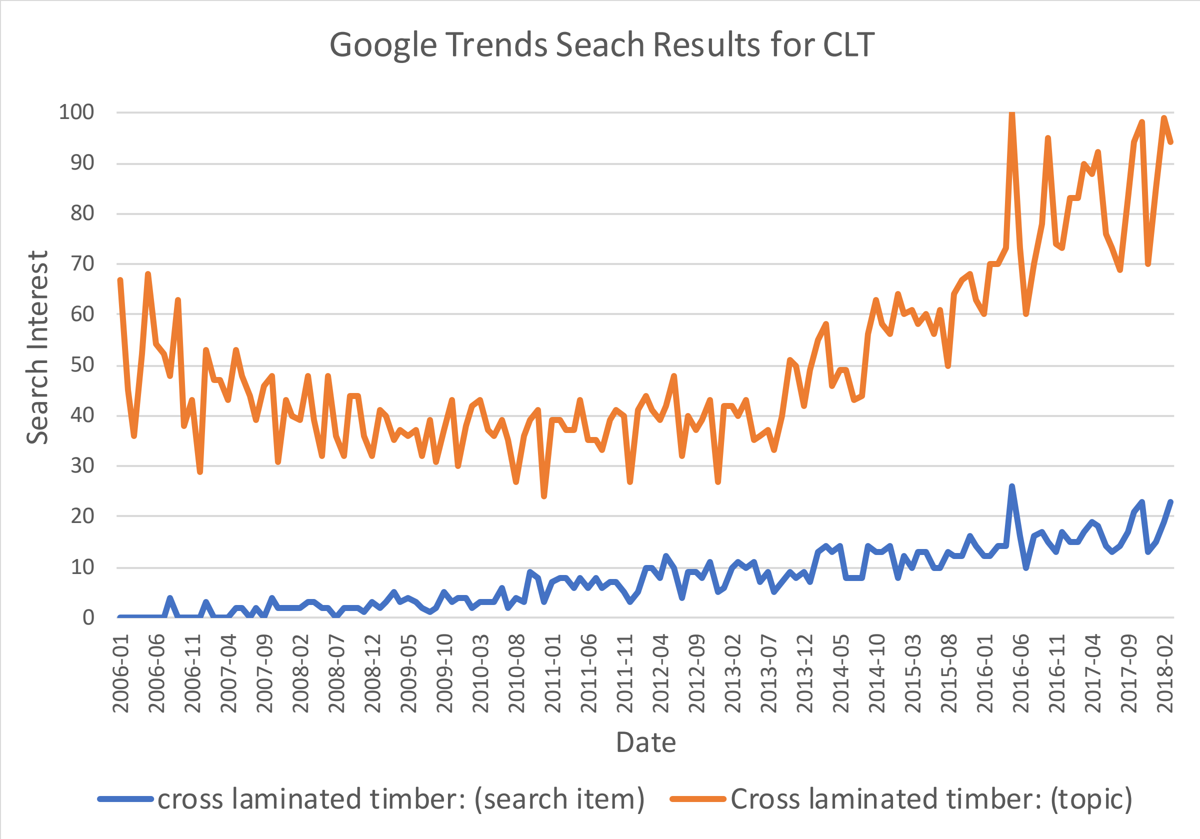

Figure 3 – Google Trends Search Results for CLT

Trends for both searches and topics of cross laminated timber on Google are shown from 2006 to present. The data was generated by Google Trends (Google Trends, 2018a). The difference between search items (lower blue line) and topics (upper orange line) is that search items only represent searches with those exact words 'cross laminated timber' whereas topics can be a "group of terms that share the same concept, in any language" (Google Trends, 2018b) such as the German name for CLT, Brettsperrholz (BSP), thereby giving many more results. Search interest is listed by google as "relative to the highest point on the chart for the given region and time. A value of 100 is the peak popularity for the term. A value of 50 means that the term is half as popular. A score of 0 means there was not enough data for this term." (Google Trends, 2018a)

6.0 What is mass timber used for?

6.1 Market for CLT

From a technical perspective mass timber can be used to build almost any type of building with examples ranging from wind turbines (Timbertower, 2018), ship building (Stora Enso, 2016) and bridges (Nordic Structures, 2018). However, mass timber is primarily used for constructing buildings. In the UK, from 2003 to 2011, there were approximately 110 educational buildings, 55 residential buildings and 40 public buildings constructed with CLT (Crawford *et al.*, 2013). By volume over half of all CLT now produced is used in residential applications with the next largest sectors being educational institutes, commercial spaces, and government and public buildings (IMARC, 2016). CLT panels are commonly used as floor spans and walls but can also be used for other structural elements such as stairs and service cores for elevators (BM TRADA, 2015).

However, CLT and other mass timber products are not commonly used low rise housing (below 4 stories) since the same buildings can be built more cheaply with less wood by using timber frame methods (Ramage *et al.*, 2017) and by brick and block methods (Crawford *et al.*, 2015). Mass timber is more cost effective when used in taller buildings as it is expensive to produce, and its strong load bearing properties allow for both greater building heights and the ability to cover large spans while supporting loads under its own weight (Ramage *et al.*, 2017). However, it has been used for individual homes in several instances (Stora Enso, 2014; BM TRADA, 2015). CLT is mainly used for mid-rise apartment buildings and for large voluminous structures that are not overly high such as schools and office buildings (BM TRADA, 2015).

Most national building codes regarding timber were designed before CLT was widely use d and were based on light timber frame buildings. Prior to 2002 this restricted the height of timber buildings in many countries to 3 stories (Liu *et al.*, 2016). Height limits for timber buildings have since been raised to between 5 and 8 stories for most developed countries (Gerard et al.,2013; Östman and Källsner, 2018) although it is possible to build taller. There are ongoing efforts to have the maximum allowable heights for timber buildings increased in different parts of the world such as in Ontario, Canada where a bill has been tabled to increase the allowable height to 14 stories (Meckbach, 2018). It is still possible to build CLT buildings which currently exceed these set height limits in some countries. But to do so, each individual building must demonstrate that it meets the building performance requirements for tall buildings on a case by case basis (Gerard *et al.,* 2013).

The maximum height of CLT and mass timber buildings is currently unknown. It is theorised that current CLT construction using the platform system and economic wall thicknesses enables buildings to be built to 15 stories high. Using a different joining method and some joint reinforcement this height can be increased up to 25 stories (Wells, 2011). Other reports have claimed that mass timber buildings incorporating CLT can compete with concrete buildings up to 30 stories high (Green, 2012). Above this height reinforced concrete cores are required for structural stability in CLT buildings up to 150 meters high (Kuilen *et al.*, 2011). There are, however, already buildings planned that exceed this height with a 40-story building planned for Stockholm and an 80-story building designed for London (McPartland, 2017).

6.2 Current examples of mass timber buildings

This section will briefly provide some examples of recently built tall residential CLT buildings and those planned and under construction which act to showcase the possibilities for CLT. Some of these notable buildings have been constructed purely from CLT, while others feature hybrid systems including combinations with other forms of mass timber, concrete and steel. A lengthier list ranking the heights of the most iconic, current and planned projects prior to 2017 is provided by the Confederation of Timber Industries (CTI, 2017a). For further reading on the history of CLT buildings and current global CLT projects as of early 2018 please see Fourthdoor (2018).

Some of the key existing CLT buildings in the UK include Murray Grove in Hackney, designed by Waugh Thistleton (2018b) Architects and built in 2008. This nine-storey residential block was the tallest modern timber structure in the world when it was completed and is seen as a pioneer of tall mass timber buildings (Waugh Thistleton, 2018b). Also located in Hackney, the social housing block Bridport House was subsequently built in 2011. Although only eight-stores high, on completion it became the largest timber building in the UK (Karakusevic Carson, 2018). Subsequently Wenlock Cross became the tallest hybrid CLT structure in the UK standing at 10 stories high (Hawkins\Brown, 2018). At an equal 10 stories high, the much larger residential development Dalston Works has since became the world's largest CLT building, by volume, in 2017 (Waugh Thistleton, 2018a).

In Europe the tallest mass timber building is The Tree (Treet) in Bergen, Norway. A hybrid of glulam columns and CLT this residential building reaches 14-stories and was completed in 2017 (Doyle and Lewis, 2017). Outside of the UK in the Asia Pacific region the tallest CLT building is Forté in Melbourne. Designed and built by Lend Lease, the 10-storey apartment block was the world's tallest CLT structure prior to the construction of The Tree however it still retains its title of the tallest pure CLT building (Architecture & Design, 2014).

In North America, Brock Commons student residence in Vancouver, Canada, which was built for the University of British Columbia, is currently the world's tallest building using CLT. It incorporates a hybrid design with a concrete core allowing it to reach 18 stories tall. (Healey, 2018). This record is set to be broken when HoHo, a 24-storey wooden skyscraper mixed development in Vienna, Austria, is completed this year. This is also a Hybrid structure but with 76% still built from Timber (CTI, 2018). These examples for around the world illustrate the continued progress of CLT construction with a new building breaking height and size records regularly.

There are also many mass timber buildings still in the planning stages. These buildings aim to reach heights which would place them in the ranking of not only the tallest mass timber buildings in the world but some of the tallest buildings regardless of construction method. One of these is the HSB Landmark Project in Stockholm. The proposed 34-storey timber skyscraper will be built with mass timber beams and panels and aims to be completed by 2023 to celebrate HSB's 100-year anniversary (C.F. Møller, 2018). There are also even taller CLT buildings which have been designed. Although not predicted to be complete until 2041, a 70-story tower in Tokyo is the tallest CLT building currently planned (Marsh, 2018). The hybrid structure will be 90% timber but incorporate steel to aim in seismic proofing. This building will be over 3 times higher than the tallest CLT building currently built but still 10 stories shorter than the current tallest conceptual design of Oakwood Tower in London. This building would stand 80 Stories high and would become the second tallest building in the UK regardless of construction method (Marsh, 2018). The concept currently faces regulatory restrictions regarding fire standards, which apply to all very tall buildings, that would need to be resolved prior to construction (Marsh, 2018).

These examples show the scale of projects in which mass timber is planned to be used. These iconic buildings, although impressive, do not comprise a high proportion of the homes in the built environment. It is important to look at the number of buildings that are produced with mass timber products rather than the maximum height they can obtain. These examples of tall builds are nevertheless important as they show it is possible to replace traditional materials with CLT and other mass timber products for mid and Highrise buildings.

7.0 Current state of the mass timber market

7.1 Production and usage by region

7.1.1 Overview of global market

The global value of the CLT market in 2016 was $480m and this is predicted to nearly double to $880m by 2022 (IMARC, 2016). The CLT market is currently very centralised with 95% of production in 2012 coming from Europe and 66% of this being from Austria alone (Brandner *et al.*, 2016). This is partly due to the extensive areas of accessible high-grade forests in Europe which are lacking elsewhere (FEA, 2017) and is probably also attributable to the origins of CLT being in Austria and therefore the existence of a more established industry. Predicted increases of an additional 1 million m^3 of capacity in Europe (Ebner, 2017a) is likely to keep Europe as the main producer of CLT for some years to come.

Even though Europe remains the centre of CLT usage, with North America consumption still only 7% of that of Europe (FEA, 2017), other markets around the world are growing. CLT usage and production is now beginning to spread globally in a meaningful way although it is still mainly confined to countries in temperate or cold climates (Figure 4) in which CLT is most suited. The key to increasing usage outside of Europe has been establishing or increasing domestic production of CLT.

7.1.2 Overview of regional markets

Europe is the main producer and consumer of CLT with this production being centred around the DACH region of Germany, Austria, and Switzerland (Brandner et al., 2016; CBI, 2017a). Production and consumption is also considerable in Scandinavia with CLT proving a popular material in the construction sector there (Jauk, 2017). New manufacturing facilities are also being constructed in Sweden and Finland to increase production in these regions (Ebner, 2017c).

The UK currently has no domestic CLT production. Manufacturing facilities have been built but are not yet operational (see Section 20.3) so for now the UK relies on imported CLT. The UK imports roughly 7% of all European exports (CBI, 2017a), however, its overall consumption compared to production levels is less than 2% (Wood for Good, 2018a). Imports have been steadily increasing over time with imports now over 50% greater than they were in 2011 (Crawford *et al.*, 2015).

There are numerous documents and reports on market opportunities for increasing production in North America. These include both an American (Dagenais *et* al., 2012) and Canadian (FPInnovations, 2011) CLT handbook, research papers and market feasibility reports for Canada (Crespell and Gaston, 2011) and the U.S., with the majority focusing on the Pacific NW of the U.S. (Beyreuther et al., 2016; Oregon BEST, 2017). CLT usage in North America is still relatively new but Canada currently has the world's tallest wooden structure; the 18-storey Brock Commons Student Residence in Vancouver (Lim, 2018). The first commercial building in the U.S. was completed in 2011 and it was not until 2015 that the first CLT manufacturer, Johnson Wood Innovations, was certified to build structural CLT panels by the American Plywood Association (Beyreuther et al., 2016). North America is a fast-growing market for CLT with many new companies opening new factories (Jauk, 2017), joining the existing companies, such as SmartLam who became a certified producer in 2016

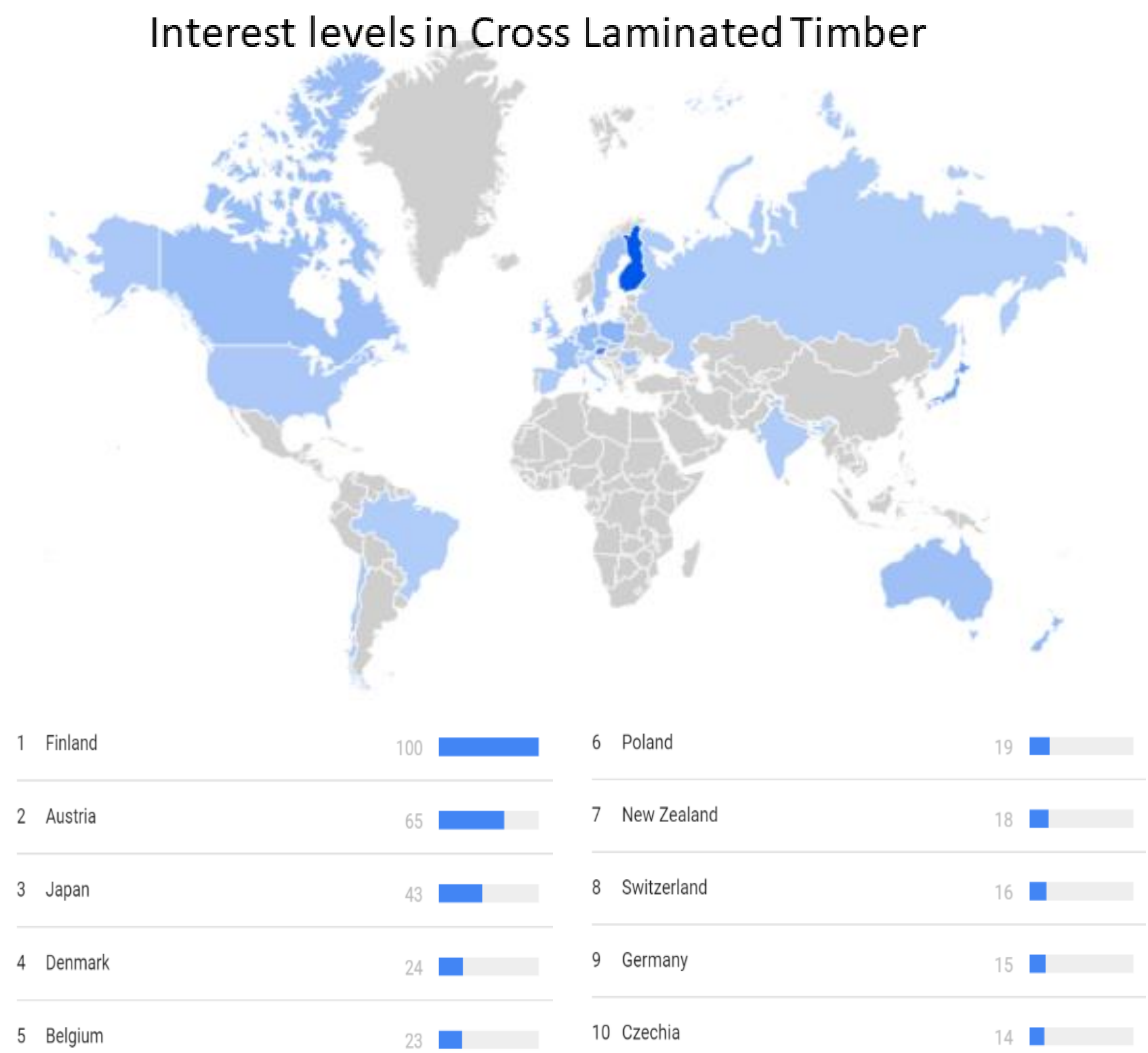

Figure 4 – Regions with an Interest in cross laminated timber

Highlighted are all the regions where CLT is of interest when the topic 'cross laminated timber' is inputted into Google Trends and the top 10 countires where interest is exhibited per population so is proportional to population. The "values are calculated on a scale from 0 to 100, where 100 is the location with the most popularity as a fraction of total searches in that location, a value of 50 indicates a location which is half as popular. A value of 0 indicates a location where there was not enough data for this term." The resulting map and figures (both above) is a product of Google Trends (Google Trends, 2018a) and is replicated from their site.

(Beyreuther et al., 2016). The U.S. market is affected by the state system which causes differences in regulations. For instance, in 2015 CLT was approved for use in Heavy Timber Buildings but neighbouring states are all at different stages of acceptance and developing their own building codes for CLT (Beyreuther et al., 2016). This however only effect use of CLT and not production.

In the Asia-Pacific region Australia is the main market for European CLT exports (Stora Enso, 2018), however it is still a niche market (Lim, 2018). Elsewhere, Japan has set ambitious goals to increase

CLT production to 500,000 m^3 in the decade from 2014 until 2024, as part of a government imitative to increase wood use, whihc will be a tenfold increase (FEA, 2017). They surpassed their intermediate goal of producing 50,000 m^3 in 2016 by 20% (Jauk, 2017) and so appear to be on track to meet their goal. The world's largest timber skyscraper is also planned for completion in 2041 in Tokyo and will be 70 stories and 350 meters tall (Lim, 2018). China is also exploring the possibility of domestic CLT production with native timber. However, the lack of specification for using other sources of wood is hindering its progress (Liu et al., 2016).

7.2 Main actors in the mass timber market

The majority of CLT producers are forestry and timber products companies which have branched into CLT as an added value timber product. One of the first companies to produce CLT on a large scale was KLH Massivholz who opened their first factory in 1999 in mainland Europe (Alinea, 2017). There are now over 20 manufacturers of CLT in Europe with the top 3 producers being Binderholz Stora Enso and KLH Massivholz which supply roughly 42% of European production (Ebner, 2017c).

Many of these manufacturers have subsidiaries or joint venture partnerships in the UK which act to promote, sell and advise on their products in the UK. (Crawford et al., 2015). A full list of producers and suppliers to the UK canbe found at TRADA (2016b).

7.3 Current regulations

Across the EU CLT products need, at a minimum, to comply with the European Union Timber Regulation (EUTR), the European Union General Product Safety Directive and the Conformité Européene (CE) requirements (CBI, 2017a). Also applicable to the treatment of timber and the gluing of CLT is the European Registration, Evaluation, Authorisation and Restriction of Chemicals (REACh) legislation. CLT also has specific regulation in the U.S which include the American National Standards Association Standard for Performance-Rated cross laminated timber (APA, 2017) and was included in the 2015 US International Building Code (IBC) (ICC, 2015). Although not a necessity many CLT producers will also look to comply with sustainable sourcing and forestry standards commonly adjudicated by the Forest Stewardship Council (FSC) (CBI, 2017a).

The ETA (European Technical Approval) Standard for CLT, BS EN 16351, (BSI, 2015) now regulates the manufacture and use of CLT in Europe and allows certified manufactures to use the 'CE' mark on their products. When used in construction CLT must meet product and design standards. In the EU Eurocode 5 BSI (2004) pertains to the design of timber structures. This has featured many versions with the most recent one influenced by the Construction Products Directive (CPD) which was adopted by the EU in 1988. This directive changed building regulations from being prescriptive to being functional and performance based. Although national building codes will remain in place, this directive and these new standards aim to create more common practices across the EU. A good overview of how these regulations affect multi store wooden buildings can be found in Östman and Källsner (2018).

These changes will prove positive for mass timber buildings. Firstly, the performance-based approach means that no direct regulations regarding mass timber buildings are required, instead they can just be built to perform in the same way as existing buildings. In addition to this the standardising of building codes across the EU should make it easier for mass timber usage and knowledge to be replicated and transferred across borders. For example, after these changes in building regulation there is now nothing specific in UK regulations which means that timber buildings cannot be built to any height apart from building standards which include all tall buildings (Miller, 2012).

8.0 Innovation in the construction sector

Innovation is seen as a function of the characteristics of firms in an industry, the interrelationship and rivalry among them. The overall characteristics of the industry and the characteristics of the innovation (Beyreuther et al., 2016). Innovation is brought about by a number factors which have been classed into 5 main characteristics by Rogers (2005). Relative advantage is seen as the most important aspect and includes the benefits of the new product from economics to social prestige. Trialability and observability are also important and although constructing a new building is not simple once there are a few proven examples it overcomes this. Compatibility and complexity are the 2 other key characteristics. Although CLT buildings are constructed in a similar way to traditional buildings the different regulations and technical specifications for using CLT complicated the build process. Although there have been few empirical studies on innovation adoption and diffusion within the residential construction industry, CLT diffusion is modelled by Beyreuther et al. (2016) using these factors as a combination of the perceived utility gained from using it, how informed the market is, how quickly information is disseminated and prior beliefs of the perceived utility of CLT before using the product.

In general, large traditional Builders wary of trying new methods due to many cycles of boom and bust in the construction and property sector and are therefore are wary of the upfront capital expenditure required for OSM. The ingrained behaviour of lowest cost tendering in the construction industry has resulted in companies driven by cost and risk aversion. These companies, although capable lack the financial incentive to use non-traditional methods of construction which could increase costs or risks (Jones et al., 2016). Research instead indicates that large firms are more likely to gradually introduce innovative materials into their business over time while smaller firms will actively allocate a much larger proportion of their business to new innovate materials (Ganguly *et al.,* 2010) most likely as they try to gain market share from industry incumbents.

It is often these smaller companies whom take extra risk by adopting innovations and showing whether they can be a market success. In this instance CLT projects managed to get build due to project specific contexts which favoured the use of CLT, such as constrained sites, and on completion of the project was able to showcase CLT (Jones et al., 2016). It is in this beginning period when the innovation (CLT) must be more widely used to reach 'critical mass' to be adopted more broadly (Manninen, 2014). The percentage of market share at which an innovation is thought to become mainstream is at 15-18% (Rogers, 2005). Although still a long way off that threshold (Section 19.1) those in the industry saw 2016 as the year of market breakthrough with a much larger focus on mass timber materials and a growing trend in CLT use (Ebner, 2017a).

9.0 How CLT construction compares to traditional materials and other prefabricated products

CLT either needs to differentiate itself from other materials by having technical advantages over traditional materials or being able to compete on cost to become widely accepted (Jones et al., 2016). This section will provide a descriptive and numerical comparison between CLT and other building materials. It will present a generalised overview to some of the key aspects that a building material needs to be competitive in and how CLT compares to other materials in these categories. A more detailed assessment of CLT's performance as a building material and how limitations are addressed is provided in Part VII.

9.1 Lifetimes of buildings

It is important for the structural elements of buildings to be able to last the expected lifetime of the development. Modern CLT has been in use for less than 40 years so there are no existing examples of the material lasting for extended periods of time. Glulam has, however, been used for longer and after one of the oldest Glulam structures was decommissioned, after 75 years of use, researchers found minimal structural degradation to the structural elements (Rammer et al., 2014). Traditional timber buildings have been around for even longer, with the oldest timber frames house in Europe being over 700 years old (SWI, 2018). So, there is no reason why CLT could not last a similar timeframe with the possible exception of the lifetime of the glue holding the laminated pieces together, although there is little research into this. Ultimately for construction purposes, mass timber elements are assumed to have a similar lifetime to traditional timber homes and other structural materials (Barbara *et al.*, 2011) although worries persist about building durability (Gosselin et al., 2016).

Whether modern mass timber buildings will last 100s of years like traditional timber frame and concrete structures is unknown. It is, however, not strictly necessary for this to be the case anyway. The old British Standards Institution's guide to durability of buildings and building elements, products and components (BSI, 1992) suggested a 60-year lifetime for buildings. Other national governments such as New Zealand suggest a minimum of 50 years (Building Performance, 2017) while insurers, who base their figures on building renewal rates, say 70-100 years (SwissLife, 2018). The ongoing change in styles and building regulations in the urban environment leads to constant renovations or demolition and reconstruction of residential property. This means that the structural element of a building may not be used beyond these reference frames. One empirical study by the Athena Institute (2004), focusing on Minnesota, USA, found that 30% of all buildings demolished in the study area were actually less than 50 years old. Interestingly a greater proportion of wood buildings were aged 51 or over than those made from concrete or structural steels with percentages of 85% 63% and 80% respectively. Overall the main reasons given for demolition were area redevelopment (35%) and poor building condition (31%) which usually resulted from lack of maintenance rather than the age of the building (The Athena Institute, 2004). Although this is an isolated study it demonstrates that concrete and steel are not necessarily longer lasting that timber construction and that redevelopment, and a lack of maintenance means that buildings do not always serve their full lifetime.

The high rate of urban renewal and the replacement or modification of buildings at least once a century mean that the ease at which it can be decommissioned is important. The disposal of timber buildings can not only provide a source of energy and divert material from landfill, but is a much simpler process (Robertson *et al.*, 2012). Therefore, it may be more prudent to focus on the ease at which a building can be upgraded or replaced in the future rather than its total lifespan.

9.2 Build quality

The build quality across all prefabricated products is generally higher (Prior et al., 2017). This is a result of being able to work in a controlled environment and the greater use of machinery and technology in the process which results in fewer errors and greater precision.

CLT as a material has good airtightness of 2 – 3 $m^3/(m^2/hr)$ (Alinea, 2017) which is similar to traditionally constructed building renovated with insulation at 2.5 - 2.9 $m^3/(m^2/hr)$ (Borodinecs *et al.*, 2016). Additionally, the joints between the panels incorporate expanding insulation tape or the outside of the joins are tapped to provide extra air tightness (BM TRADA, 2015). This airtightness means that the finished buildings have a high energy efficiency. The air changes per hour (ACH) for CLT at 50pa is specified for a maximum of 0.8 (KLH, 2018) which is much lower than the estimated 2.3 of concrete block buildings (Becker, 2010). However, actual studies of CLT show that this rate is in fact higher with glued edged boards having a rate of 1.8 (Skogstad *et al.*, n.d.). This figure is without any additional insulation though which is normally used in CLT buildings and these rates are also variable with different thicknesses of CLT panels which make direct comparisons more difficult.

When used in buildings CLT is naturally insulating with sound insulation high as well as air tightness (BM TRADA, 2015). However, mass timber has low thermal connectivity 0.13 W/m2K (BM TRADA, 2015), meaning that, compared to materials such as concrete (The Concrete Centre, 2015), it produces a less stable indoor air temperature as it cannot accumulate heat throughout the day and then release it at night. This means that more emphasis is needed on heating systems. However, the air tight build with and the low 'U values' (thermal emissivity) of 0.87 (Wells, 2011) can offset this somewhat. In addition, the low thermal connectivity of the material is known to also make rooms 'feel' warmer (BM TRADA, 2015) meaning that residents may be content with lower indoor air temperatures.

Air quality is also an important factor in build quality. The hygroscopic properties of CLT panels mean that they enable moisture to pass through them allowing for the regulation of indoor moisture content and improved air quality (BM TRADA, 2015). However, as most CLT surfaces are clad on the outside and covered up internally, usually with plaster board, then the transfer of moisture ultimately depends on permeability of the encapsulating materials.

Indoor air quality is also influence by the building materials used. CLT now uses a polyurethane adhesive when gluing the panels together which is formaldehyde-free and non-toxic during all stages of the product's lifecycle (Alinea, 2017). However, tropical timber species do not glue as well due to their increased density so different types of adhesive are needed (CBI, 2017a). Instead a modern melamine adhesive is used (Hairstans, 2018). This chemical is also not considered acutely toxic with it needing to be ingested to have harmful effects (Skinner *et al.*, 2010) however, as it is made with formaldehyde there may be a potential for it to affect indoor air quality. As hardwood and tropical timber is not often used to produce CLT panels or other forms of mass timber (TRADA, 2016b) this is not a well-researched area. However, the potential to use tropical hardwoods for their higher durability for external use (CBI, 2017a), means that this should be investigated.

9.3 Build times and ease of use

Building with CLT offers design and construction advantages due to being made from timber and its large weight bearing area which means that the positioning of doors and windows is more flexible (BM TRADA, 2015) and a simple roof profile can be used (Alinea, 2017). Since the structural elements are made from timber this makes it easier for follow on trades to complete their jobs "without the time or co-ordination associated with fixing wall plugs into masonry or identifying timber stud locations for fixings." (BM TRADA, 2015 p14). There is also no need for secondary framing or brackets (Alinea, 2017) and repair and alteration work are far easier to carry out (Brandner *et al.*, 2016). Similarly, when using CLT for wall assemblies the clear separation of layers between the structural element, the insulation and the cladding enable easy execution of the build process (Brandner *et al.*, 2016) and allows for the removal of many 'wet trades' (BM TRADA, 2015). The uniform quality of CLT means that it is advantageous for small construction companies to use as they do not need to grade and check the timber they use. In addition, it is also lighter, so smaller machinery is required (CBI, 2017b).

These advantages mean that construction time is estimated to be between 10-30% less, depending on the site (Wells, 2011; Smith *et al.,* 2015; Alinea, 2017; Morris, 2018). This is a large advantage in dense urban areas where quick and quiet construction is desired (Institution of Structural Engineers, 2018). However, it is important to be aware that structural timber if often not been treated or coated and is meant to be used within a dry building envelope. This mean careful storage is required. Without appropriate storage moisture levels in the timber can increase which can lead to shrinking and cracking once erected (Ramage *et al.*, 2017) and to moisture problems such as rot. Solutions to this problem are explored in Section 14.2.

Although quicker than traditional methods CLT does not have the same speed advantages over other prefabricated materials. Precast concrete panels are like CLT in the fact that they are a more expensive material but deliver cost savings through reduced construction times and labour requirements (Section 9.4). One study estimated that Precast construction methods could save developers up to 60% of their time (Offsite hub, 2015) with others highlighting that it typically takes 7 days to use concrete onsite rather than one day to installed prefabricated panels (Turai and Waghmare, 2015). Similarly curing conditions are controlled and weather conditions do not affect construction when using prefabricated concrete (NCP, 2018) which is an issue that needs to be considered when building with timber (See Section 14.2).

9.4 Cost

It is important when assessing a new building material to determine whether it can compete on cost. This is crucial for many construction projects which have small profit margins. It is also doubly important for increasing the market share of the material. Even if there are advantages to using CLT as a material such as carbon savings (Section 9.6) and better build quality (Section 9.2) if it cannot compete on price there is a reduced likelihood that builders will switch to using it (Jones et al., 2016).

In one study, in 2011, the base cost of materials for a CLT building is estimated to be between 10-20% more expensive than the equivalent reinforced concrete building (Wells, 2011). This is in a similar range to a UN review in 2015-16 which found materials were 10-15% more expensive (Doyle and Lewis, 2017). The decrease in the value of the upper range from 20% to 15% may be due to differences in the studies or could possibly suggest that material became cheaper over this period. Other studies have, conversely, found that mass timber construction to be 4% cheaper (Smith *et al.*, 2015). This may however reflect a blend of mass timber materials and not a purely CLT structure.

It is important to consider that material costs do not represent the total costs for an entire project. For CLT construction there are considerable savings in construction time which can translate into cost savings. It is estimated that time savings of 30% can be achieved by using CLT through factors including the elimination of wet trades on site (Wells, 2011). A recent, more detailed study, of a 300-unit residential development with ground floor retail space in London found that construction aboveground using CLT was 10-15% quicker (Alinea, 2017). One benefit of time savings is that revenue can be acquired earlier (Morris, 2018). This, however, depends on the purpose of the building and who is constructing it. If the units are for sale and forward sold, then this is not such a large benefit, although it does free up staff to work on other projects. A larger advantage comes to those who are building for rent as they can acquire rental income sooner (Smith *et al.,* 2015).

Some cost savings for CLT arise from the reduced need for foundations which offset the higher superstructure costs. Some buildings still chose to use standard foundations though due to worries over the procurement of CLT and the potential need to revert to traditional building methods (Wells, 2011) which negates this cost advantage. As the CLT supply chain is improved and the material is more widely used, it is likely that this concern will reduce and that cost differences will decrease (Alinea, 2017). Overall, when including all aspects of the build, it was found that there was less than a 1% difference in building costs between a CLT and equivalent concrete building in the UK (Alinea, 2017). A Canadian study found that it was, in fact, cheaper to build with CLT that concrete for both 12 and 20 story buildings (Oregon BEST, 2017).

It is important to note that CLT is best used in standard lengths and configurations with spans of 6-12m. Irregular designs and lengths are likely to add to the build costs which would make concrete more favourable (Alinea, 2017). This means that CLT is ill suited for large spans such as 9x9 meters used in commercial spaces as greater thicknesses and beams are required increasing costs (Institution of Structural Engineers, 2018). In addition, in 2012 when some of the first CLT buildings were being constructed in London it was the case that they were only cost competitive up to 7 or 8 stories (Miller, 2012). However, this report is only concerned with residential construction. In this instance building with CLT is advantageous as thinner structural floors and walls can be used which increase living space and decrease the overall height of the building (Institution of Structural Engineers, 2018). Those in the mass timber industry believe that costs will reduce and when they do, the build qualities of CLT combined with the reduced cost will render traditional construction approaches obsolete (Devlin, 2017).

Mass timber construction allows for greater control of costs that traditional on-site construction methods. Costs are more fixed so there is less uncertainty and a reduced number of change orders during construction. One study across 11 case studies found that the average number of change orders was 3.7 which was considerably below that of traditional construction methods (Smith *et al.,* 2015). Change orders along with other problems with traditional construction projects, result in 37% of projects running overtime and 51% running over budget each year in the UK (Hart, 2018). Although not obvious when comparing material costs side by side, this budgeting advantage may make CLT construction even cheaper when comparing the cost to the actual cost of traditional construction accounting for average delays.

Time savings and therefore cost savings are, however, achieved when using other prefabricated martials such as precast concrete (Section 9.3). Precast concrete panels are also more expensive than poured concrete with one study placing the figure at 35% more (Turai and Waghmare, 2015). Assembly costs of precast concrete walls, beams and planks have been found to be higher than those of CLT (Crespell and Gaston, 2011) most probably due to the increased weight of elements and joining panels not being as simple as CLT. However, overall time and labour savings are thought to deliver overall cost savings in the region of 10% (Turai and Waghmare, 2015) which is greater than that of CLT buildings. The prefabricated concrete market benefits from economies of scale and being more established with a market value of $12.2 billion in the U.S. alone (NCP, 2018). This compared with the forecast of the global CLT market reaching $880m by 2022 (IMARC, 2016) shows the differences in scale. CLT is already cost competitive with traditional construction materials and in some cases is seen to outcome them (Oregon BEST, 2017). With advances in CLT manufacturing and growing usage CLT it may be the case that CLT also becomes cost competitive with other more widely used prefabrication methods such as precast concrete, but it is hard to predict this with much certainty.

9.5 Safety

9.5.1 Fire safety

Fire safety is one of the most citied issues when building with timber and is seen as the main precondition for allowing timber buildings to be built (Östman and Källsner, 2018). Even though the recent fire at Grenfell Tower in London which killed 71 people (BBC, 2017) did not happen in a timber building it has brought fire safety back to the front of everyone's mind. One of the first issues to address is the widely prevalent fear of fire in wooden buildings (Espinoza *et al.,* 2016) and the difference between mass timber buildings such as CLT and timber framed buildings. For a more detailed analysis of how CLT performs in a fire and the current regulations regarding its use please skip to Section 14.1.

Mass timber, unlike timber framed buildings, can perform in a similar way to concrete buildings in a fire. It can keep its structural integrity and, once a char layer forms, not add any further fuel to the fire (Drysdale, 2011). The low thermal connectivity of wood, which presented an issue with regulating indoor temperatures (The Concrete Centre, 2015), also aids in its resistance to fire as less heat is transferred through it. This is unlike steel which is a good conductor and can buckle and become structurally unsound at very high temperatures (UKTFA, 2013). Wood, although it can quickly lose half its strength when heated to 100^{o}c, will remain structurally sound at elevated temperatures (Ramage *et al.*, 2017) therefore making fires more predictable.

Overall, CLT must be designed and tested to meet fire regulations for it to be built with. In this respect there in no real difference between a mass timber building and one built with traditional methods in terms of safety for residents. A small difference though, is that, depending on the extent of the fire, repairs to CLT are not necessarily possible and the whole building may need to be rebuilt rather than repaired (Business Vancouver, 2016). If the building is insured this should not make a large difference though as the quicker build times of CLT mean that it may actually be quicker to demolish and rebuild than assess and repair an existing building. This may, however, lead to adverse effects on insurance premiums (see Section 12.1).

9.5.2 Construction safety

Off-Site Manufacturing (OSM) is seen as inherently safer than traditional construction methods. A reduction in wet trades coupled with the possibility to join panels with lightweight tools results in sites being quieter and safer than those with concrete superstructures (BM TRADA, 2015). For example, one small study of mass timber construction projects found that there were zero reported safety incidences during construction (Smith *et al.*, 2015). Using prefabricated mass timber also helps to reduce deliveries by ready-mix concrete trucks. The construction of Dalston Lane in London, which was the largest CLT building in the world in 2017, had 80% fewer site deliveries that is the equivalent building had been constructed with traditional materials (Mills, 2017). Not only does this lead to less disruption (BM TRADA, 2015) but it also minimises the risk of deaths as construction lorries have been found to be responsible for a disproportionate amount of road deaths (Walker, 2013).

9.6 Carbon footprint

There are many ways of calculating carbon emissions of buildings. These range from calculating the emissions produced during the construction process to the embodied energy of building materials to the life cycle approach amount of energy a building will use over its lifetime once built and the carbon cost of decommissioning it. Also included is the impact of substituting one building material for another and the resulting differences in carbon emissions. For a detailed and comprehensive overview and compilation of academic studies into the carbon effects of using wood in the place of other building materials please see Sathre and Gustavsson (2009).

There are clear carbon savings when looking at the embodied carbon of timber buildings versus other construction materials including steel and concrete with CLT outperforming concrete in every aspect of a Life Cycle Assessment (LCA) (Mohammad *et al.*, 2012). UK studies have shown a 34% reduction in embodied carbon from both the change in materials and onsite fossil fuel usage during construction (Monahan and Powell, 2011). Interestingly, the majority of savings do not come from the stored carbon in wood but the substitution of wood for more carbon intensive materials and the burning of timber waste products as biomass (Gustavsson *et* al., 2006). Specific case studies have shown that non-timber building methods produce more than 2.5x the amount of CO_2 and that when sequestration of CO_2 in timber is accounted for that buildings can become net negative emitters (BM TRADA, 2015).

Although average savings of 3.9kg of CO_2 have been recorded per kilogram of wood used (Sathre and O'Connor, 2010) this varies between different wood products. For example, floor beams offer much higher CO_2 savings than wall studs (Oliver *et al.*, 2014). This is most likely due to both the different amounts of timber used for each part and the materials that they are replacing. Another metric for examining carbon savings is by floor area of buildings with an estimated 350 tonnes of CO_2 saved for every 1000m^2 of building which equates to approximately 10 years of operational emissions (Alinea, 2017).

It is important not to forget, though, that timber products must be kiln dried before use. This is an energy intensive process, which accounts for ~90% of the total manufacturing energy used (Ramage *et al.*, 2017). Even so during this primary production the energy used per kilogram of softwood is less than half that of structural steel (Ramage *et al.*, 2017). Moreover, as 1kg of timber has a greater volume than steel a lower total weight will be used in the same size building meaning that the real savings are probably higher. In addition, waste wood products often substitute fossil fuels as an energy source for manufacturing timber products. Studies have found that this to be the largest source of carbon savings (Buchanan, 2007) providing up to 15x the carbon savings of CO_2 sequestration (Buchanan and Levine, 1999). Others have found that this does produce CO_2 savings but the largest CO_2 savings, instead, come from avoiding the fossil fuels needed in the production, transportation and construction of materials such as concrete and steel (Oliver *et al.*, 2014) instead.

Comparing the carbon in timber and non-timber products is challenging with much effort placed on finding a functional unit which can allow for clear comparisons (Gustavsson and Sathre, 2010). Wherever the exact carbon savings are made the consensus is overwhelmingly clear that timber building has a much lower carbon impact than traditional materials and additionally has very minimal construction waste (Alinea, 2017).

There are, however, still restrictions in many European countries preventing the use of wooden surfaces, both exterior and interior, in mid and high-rise buildings (Östman and Källsner, 2018). This therefore means that other materials, which most probably have a higher carbon content, need to be used as cladding. Although this is unlikely to lower the overall carbon savings of timber buildings in a meaningful way, it is one area that should be addressed if carbon savings are to be maximised.

10.0 How does CLT compare to low and zero carbon alternatives?

CLT can perform to similar specifications as traditional building materials and can be built for a similar cost, therefore, the main advantages of using it are the benefits of offsite manufacturing and its carbon negative properties. The advantages of OSM are shared by prefabricated concrete and steel elements therefore this advantage is not unique. The carbon negative nature of wood, however, is. It is worth investigation whether there are any other carbon neutral or n egative building products which can be used in the place of mass timber.

When compared to other mass timber products, CLT has greater carbon savings than others. It has a lower non-renewable primary energy consumption than LVL or Glulam and also has the l owest total transport distance from manufacturing facilities to the UK (Wood for Good, 2018b). However, Researchers agree that CLT should not and is not in competition with either existing timber construction or other forms of mass timber (Brandner *et al.*, 2006). These materials serve different purposes such as beams rather than floors and walls. This can be seen by some of the tallest mass timber buildings incorporating many types of mass timber (Mills, 2017). CLT should instead be viewed as a high-value alternative to mineral based building materials (Brandner *et al.*, 2006; 2016).

When promoting the use of mass timber as a carbon negative building material it is important to consider if any other building materials are also carbon neutral and renewable and can perform the same role as mass timber in mid and high-rise residential buildings. One such example could be rammed earth buildings. These are widely used with an estimated 1.5 billion people living in them globally (Niroumand *et al.*, 2013). They are commonly built from soil, sand and gravel which are low carbon options. However, for rammed earth construction to increase their strength and longevity, they commonly need to be stabilised (Cabeza et al., 2013). This is done with additives of either cement or lime, the extraction of which is associated with higher emissions although they are still far lower than those associated with equivalent concrete construction (Reddy and Kumar, 2010). The materials that these buildings utilise could also be classed as unsustainable as there is no way to create them on a human timescale and many of the same materials are used in conventional building material such as concrete. There are, however, attempts to use waste material from construction and mining instead (Reddy, 2009).

This material has an advantage over CLT in that it has a large thermal mass which helps to regulate indoor air temperatures and is a natural sound insulator. Similarly, being made from earth reduces the fire risk although wet weather does pose a problem if it is constant (Niroumand *et al.*, 2013). Adapting the construction style to account for higher rainfall environments can, however, mitigate this problem (Alter, 2014). For stability rammed earth buildings need to be constructed with very thick walls which will use up valuable floor space if used in dense urban areas. (Niroumand *et al.*, 2013). The construction process is usually very labour intensive and so in that regard is best suited to countries where labour is cheap (Sirewall, 2018). Overall this material, although it can incorporate plant-based materials, does not have the same carbon storage capacity as timber as it is mainly composed of earth.

When it comes to building heights, rammed earth construction can be used to build mid-rise buildings but is predominantly used for low rise buildings. In the thousands of years this construction method has been used buildings have rarely exceeded 10 stories (Niroumand *et al.*, 2013). The tallest one currently in existence is 100 feet tall and newly built in Pakistan (Sirewall, 2018). The largest rammed earth building by volume is actually located in Switzerland and serves as a warehouse. Moreover, this building does not use concrete additives and instead is prefabricated into large blocks offsite (Alter, 2014). This method is like the offsite production of CLT, however, the product requires finishing and joining together when onsite in a similar way to blockwork (Alter, 2014). It is also unlikely that the same precision could be achieved as wood is easier to machine into different shapes.

These may be reasons why rammed earth is not commonly used in towns and cities in the West. Other influencing factors are thought to be the lack of knowledge concerning rammed earth buildings and no regulation regarding their construction and use (Ciancio, 2015). While this is similar to CLT, Europe and the U.S. have a strong history with timber buildings. This coupled with the availability of the material are likely key factors here. So, although rammed earth buildings may be a competitor for CLT when it comes to the construction of large volume buildings such as warehouses and schools it will not be considered as a substitute for mid and high rise residential buildings. Moreover, rammed earth buildings do not offer any carbon storage and when combined with cement are not renewable over human timescales leading some to claim that timber is the only truly renewable building material (Lawrence, 2018).

VI. Potential barriers and opportunities for CLT

11.0 Political environment

11.1 Government policies & priorities

Government policies towards building materials, methods and environmental standards can have a great impact on what gets built. They also act to set the general tone towards a specified topic. More stringent regulations on building emissions may be a key driver of more timber being used in the construction industry.

11.1.1 Climate policy

Across many European countries targets have been put in place to reduce carbon emissions. Although the end date for these targets is still many years away for some countries the reductions are drastic. For example, a selection of the countries with high emissions reduction goals in the EU are Sweden, Denmark, Germany and The UK which aim to have reductions of 100% (by 2045), 100% (in energy and transport) 85% and 80% respectively by 2050 (Carvalho and Fankhauser, 2017; Naturvårdsverket, 2018). In addition, non-European countries such as China also have ambitious goals of 40-45% emission reductions by 2020 (Zhang, 2011). Different countries have varying approaches to how they aim to achieve these targets. Many countries use the somewhat controversial land use loophole in which trees are planted to offset emissions (de Jong and Ambel, 2017). Alongside this some are advocating for the International Promotion of Wood Construction as Part of Climate Policy (Ministry for Foreign Affairs of Finland, 2010). It was estimated in 2010 that just a 4% increase in annual wood use throughout the European construction sector would avert carbon emissions to the tune of 150 million tonnes; nearly equivalent to that of the Netherlands (Ministry for Foreign Affairs of Finland, 2010).

Some climate policies, however, conflict with the use of timber in buildings. A general policy to increase burning of wood as biomass for energy in the UK has resulted from a desire to reduce carbon emissions. As a result, UK biomass imports comprised most of the year on year increase in biomass production in 2016 (FAO, 2016). Regardless of the downsides or merits of this carbon emissions reduction strategy, it puts pressure on the supply of wood resources and identifies biomass as a way of reducing carbon emissions rather than through timber construction.

11.1.2 Construction policy

Through construction policy there is the opportunity to promote the use of OSM techniques and also materials that are sustainable and carbon neutral or negative such as CLT. At a general level the European Directive on the energy performance of buildings keeps increasing the energy efficiency requirements for new buildings (CBI, 2017b). Individual countries are also implementing their own set of building energy efficiency regulations to encourage more energy efficient buildings such as rules implemented in Finland in 2012 meaning that building standards have carbon footprint reviews of buildings (Karjalainen, 2014. Many countries are also implementing green building initiatives such as BREEAM in Europe and LEED in the U.S. Although these are not part of policy or regulations it is thought that they will encourage more energy efficient products such as manufactured timber over traditional timber (CBI, 2017b).

Other governments decisions have been detrimental to the promotion of CLT such as when the UK scrapped its Zero Carbon Homes policy. It was aimed at increasing onsite energy production and energy efficiency of buildings, the latter of which would have been positive for CLT. Some in the industry called the change in policy a backwards move (Oldfield, 2015). In addition, a change in construction policy creates business uncertainty which makes it harder for investment and innovation to occur (Oldfield, 2015) affecting newer materials such as CLT.

As part of wanting to solve the housing shortage many governments favour the use of OSM. In Germany OSM has been used since the 1920s with ~1/3 of low rise homes being made using this method (Offsite Hub, 2015). In the UK the government wants to ensure more houses are built more quickly, while maintaining quality (Prior et al., 2017). This was set out in a Housing White Paper which laid out how to promote innovation and MMC in the construction sector (MHCLG, 2017) to meet these goals. Some of the proposals that apply to CLT construction were: to address how the planning system handles MMC developments, to stimulate growth of MMC via the Accelerated Construction programme and the Home Builders Fund and consider opportunities for offsite manufactures to access innovation and growth funding and support. However, when talking to a senior figure in the Greater London Authority (GLA) it was clear that there is no explicit support for mass timber buildings (GLA assistant director 2018, personal communication, 15 January). Although they have nothing against the use of mass timber buildings they are reluctant to choose a single method of construction to support. Overall, although many aspects of national construction policy are generally supportive of OSM there are none which specifically support the use of mass timber.

11.1.3 Specific policies regarding timber

Specific policies supporting the use of timber in construction can help facilitate its use. Political support for timber frame buildings is credited with helping to increase market share in the UK from 8% in 1998 to 25% in 2008 (Mahapatra & Gustavsson 2009) which has continued to grow to just below 30% last year (Egan Consulting, 2017). Other UK Government investment schemes such as the ‘Building Schools for the Future’ and the ‘Priority School Building programme’ have been credited with the widespread use of CLT in educational buildings (Crawford *et al.,* 2013).

Current schemes such as Finland’s National Forest Programme (MMM, 2008) and National Wood Construction Programme (Karjalainen, 2014) both aim to increase the use of forest products and reduce the carbon footprint of the construction industry by increasing the use of domestic wood products. These will support the Finnish Government’s goal of all multi-storey buildings being wood framed by 2020 (TEM, 2012). People within government also advocate for timber. The Programme Director in the Ministry of the Environment in Finland has a key role of promoting wood construction on behalf of the government in which he aims to lobby not only the government but the general public as well (Wood Products, 2016). These policies have been successful with 1500 planned units in 2015 made from timber which is 10-12% of all flats and 5-6% of all units built (Karjalainen, 2014) and 6000 timber residences being in the planning stages. As of 2016 there were, however, only 40 mass timber residential buildings (811 residences) built 3 stories or greater (Karjalainen, 2014) but this is still more than the UK (see Section 19) which has a much larger population.

Finland is not the only country with ambitions for greater timber usage in construction. The Japanese Promotion of Use of Wood in Public Buildings Act was implemented in 2010 (MRI, 2018) which requires all government buildings up to 3 stories to be constructed with wood. A report suggested that the main beneficiaries would be glulam, LVL, and plywood (Hayashi, 2012) but CLT was not mentioned. This makes sense given the low heights of the buildings and that CLT is normally used for larger buildings (see Section 5), although in has been widely used for schools which would be classed as government buildings. The restrictive nature of Japanese regulations regarding the use of timber in schools (Hayashi, 2012) may play a role in this. It is unknown why it was capped at 3 stories whether it be due to economic reasons, the lack of current capacity and skills to build taller timber buildings or concerns surrounding tall timber buildings. The last point is unlikely given the plans for the world's largest mass timber building to be in Tokyo (Lim, 2018). The Japanese government have also set the goal to increase CLT production capacity 10-fold to 500,000 m^3 by 2024 (FEA, 2017). This target, and other goals for greater timber use, highlight the commitment to CLT and other timber products and provides a supportive environment in which their use can be promoted.

The Chinese government has also acted to promote the use of timber as an alternative construction material. The Chinese Ministry of Housing and Urban-Rural Development (2015) created a plan that intends to promote timber as a construction material for public buildings. This followed on from the State Council Green Building Action Plan which mandated the use of China's 3-Star Rating System 'GBEL' for public buildings and affordable housing (Zhou, 2015). The Chinese government subsequently expanded their green building policy and changed it from voluntary participation to top down implementation of measures. This has resulted in a large rise in green building projects however research has shown that not even this state intervention has been able to overcome the profit motives of private developers (Zhou, 2015) and instead suggests that a more collaborative approach is used.

12.0 Economic restrictions

CLT already seen as broadly cost competitive (Section 9.4) but there are a few factors which either prevent decreasing construction costs and therefore market growth of CLT.

12.1 Mortgage and insurance barriers

Although the construction of mass timber buildings is possible, if the residents are unable to take out a mortgage or insurance then, not only will the resale value of the property be much lower, but they may not be able to afford it in the first place. With some in the Canadian industry already expressing concerns over insuring timber buildings (Business Vancouver, 2016), it may also affect the willingness of developers to build with the material.

The problem surrounding lending for non-traditional building techniques is complicated. It often varies from lender to lender with mixed success from those looking to find mortgages on non-traditional homes (Hollington, 2011). It appears that insurance premiums for CLT are priced as if they are timber framed buildings yet face greater premiums still as the buildings constructed are much higher and larger than average timber framed buildings. Lenders uncertainty arises in part from the lack of history in dealing with non-traditional building methods and not knowing how to price insurance for these buildings (Fisher, 2017). They need to know how the building will perform over its full life period to determine if it will keep its value. Perceived risks of factors that will affect the lifetime and value of a property are large determinants in insurance premiums (Globe Advisors, 2016). For example, Canadian insurers have voiced concerns over the uncertainty of how CLT performs in a fire. Although they recognise that mass timber performs differently to traditional timber they are concerned over the uncertainty of its behaviour during fire events; especially the possibility of delamination (Meckbach, 2018). This uncertainty reflects in the pricing of fire insurance which one report put at 7-11 times greater for wood than concrete (Globe Advisors, 2016). One survey of insurers in Germany found that premiums were nearly double those of equivalent concrete buildings (HAF, 2001). A Canadian study examining underwriter premiums found that insurance costs were 7.5x greater for timber buildings than for concrete ones (Globe Advisors, 2016). These higher figures not only reflect the uncertainty of a fire but the potential loss of the whole building due to fire as it cannot be repaired in the same way a concrete structure could be (Business Vancouver, 2016; Globe Advisors, 2016). The UK government is, however, currently looking to facilitate a working group of lenders, valuers and industry representatives to ensure that financing and mortgages can be widely accessed across tested methods of offsite construction (MHCLG, 2017).

Many insurers are currently trying to limit their exposure to timber framed buildings, which CLT is often classed as for insurance purposes (Globe Advisors, 2016). However, this does not seem to have stopped CLT buildings acquiring lending and insurance. When a CLT manufacturer was asked about insurance problems (Stora Enso UK 2018, personal communication, 5 January) they claimed to have no knowledge of any of their customers having issues with mortgage approvals. A large insurer, Legal & General, has also stated on its website that "major mortgage lenders are happy to lend on CLT-manufactured homes" (L&G Homes, 2018). The evidence of CLT buildings being built and sold should also stand as a testament to the ability to get a mortgage. It would, however, be much harder to know how many buildings do not get built due to this issue. There are, however, requirements that must be met for insures to be satisfied. Some specify sprinklers as a requirement, while others require buildings to be clad predominantly with masonry or other non-combustible materials (Meckbach, 2018). If fitting such as sprinkler systems were made mandatory, such as there are in Finland for timber buildings over 2 stories (Karjalainen, 2014), then this may remove some of the uncertainty that insurers face.

Overall, it is apparent that it is possible to get both mortgages and insurance for CLT homes. However, what is less clear is the impact that different pricing for these is having on CLT construction. Whether it is adding considerably to overall costs and if in the future it may deter people from buying CLT homes second hand due to the higher costs involved. This should be an area for future research to be conducted. Additionally, an examination of the dynamics between lenders of different positions, both for and against would be worthwhile. It could then be determined if the limited number of institutions that can be borrowed from means that the costs are more expensive and if there are opportunities for more liberal lenders to both specialise and capitalise on the growing trend of non-traditional construction.

12.2 Industry investment

12.2.1 Private investment

The capital-intensive nature of building and operating factories producing building material products means that there is a lot of illiquid capital tied up in sites and machinery. Additionally, considerable amounts of funding are required up front to build manufacturing facilities. For example, Legal & General have earmarked £600 million for investment with the first factory costing £55 million (GWMI, 2016). These factors are real barriers dissuading manufactures of traditional construction materials from switching to mass timber (Gustavsson et al., 2006). A move would also require the costly retraining of the workforce and a few years in which there would be no sales during the transition from one material to another. With this being so the costs of switching, without an impetuous to do so, are likely to be prohibitive.

Although traditional building products manufactures could start manufacturing mass timber elements alongside their existing products, the scale and new range of expertise required makes this unlikely. This means that it is likely that those who already manufacture timber products would look to extend their offering by creating more value-added wood products such as mass timber. In addition, new entrants to the market who view mass timber as a lucrative market may be attracted such as Legal & General have done (GWMI, 2016). There is also the potential that large construction firms may become interested in investing in their own manufacturing facilities to safeguard production and improve their supply chain. This has, however, been unpopular in the past with other building materials due to the cyclical nature of the construction industry and the illiquidity of such assets during a downturn. It has, however, been done by ‘pioneering; firms such as Laing O'Rourke (2018) and may occur more in the future as construction companies look towards precision manufacturing.

Those working in the industry have found that, although there is a push for OSM in the construction industry, which has been pushed for by the CITB (2017) in the UK, most manufactures are using what is described as a ‘building site in a shed’ approach rather than investing in full production lines and automation (ARV Solutions, 2018). This is said to be down to the lack of confidence needed for companies to make large scale investments and that a more mature market is needed before this will be the case. One opinion for the timeframe that it will take before such investments are considered is much more than 2 or 3 years (ARV Solutions, 2018). For manufactures they say that guaranteed commitments to purchase specific volumes are required to create confidence for investors and give large companies a multi-year business plan (ARV Solutions, 2018). There is, however, support from the UK government to address this issue. They aim to influence greater aggregation of demand from key strategic clients, while improving awareness of the benefits of innovative approaches (Prior et al., 2017).

12.2.2 Government funding and subsidies

The Transforming Construction Programme (DBEIS, 2017b) will see the both the government and industry fund a £420m project. This project aims to reduce the cost of construction by a third and half build times, greenhouse gas emissions and the trade deficit for imported building materials. Apart from its need to be imported, CLT can satisfy all these criteria. However, like policies described in Section 11.1, this policy does not explicitly advocate the use of mass timber as a material, yet it is an opportunity for CLT to increase its presence in the construction industry as construction companies look at ways to meet these goals. As discussed in Section 10.0, although CLT can outcompete traditional construction methods the OSM method of producing precast concrete is currently cheaper overall, so investment may be funnelled into there unless the case is made for mass timber.

Timber construction lacks the scale of subsidies present in the steel and construction industries (Timber Innovation, 2018). However, there has been some specific funding awarded to examine fire proofing of tall mass timber buildings such as £250,000 from the Engineering Physical Sciences Research Council in the UK (Marsh, 2018).

12.3 Concentrated production base and access to forest resources

A concentrated production base can both have its advantages and drawbacks. In the beginning the concentration of expertise and capabilities in central Europe allowed for the development of CLT at a fast rate. The extreme concentration is shown by 60% of European CLT is currently manufactured within a radius of 100 kilometres in Austria (Ebner, 2017d). It has contributed to Austria being a world leader in CLT with their products being used and trusted worldwide. Industry experts also do not view this increasing concentration as a problem due to the growing market (Jauk, 2017). However, when wanting the industry to expand in a meaningful way the lack of local production and the need for transportation over long distances is troublesome. For example, in the U.S. choosing CLT currently carries increased risk due to limited regional production which is means limited competition and using products which many not be specified correctly (Beyreuther et al., 2016). Product availability is a key reason cited as a barrier to wider CLT adoption (Gosselin et al., 2016). Nearly 40% of industry experts in one European survey reported this as an issue (Espinoza *et al.*, 2016). A much higher proportion of U.S. respondents (94%) were concerned over the same issue but this was prior to the start of domestic production (Oregon BEST, 2017). CLT is, however, already shipped all over the world from Europe to Australia (Stora Enso, 2018) so it may be that it is more the lack of familiarity with the material and foreign supplier which is the real issue.

A concentrated production base has also led to CLT being produced using only certain grades of wood which are found in or proximal to those places it is manufactured (See Section 13.3). Researchers have stated that, for there to be a globally established CLT market there is a need for a system in which different species and grades of timber can be used. They suggest the need for standardised product definitions which allow the properties of CLT to be reliably predicted (Brandner *et al.*, 2006) which is explored further in Section 14.3.

Decentralising production of CLT and encouraging the local production from nearby timber is both more economical and sustainable (Crawford, *et al.,* 2013) as it shortens transport distances One study, of small selection of mass timber projects, found that the average travel distance from factory to site was 1980 miles however when transatlantic and pacific shipping is removed the average was 550 miles (Smith *et al.,* 2015). Local Production in the UK would reduce this distance to a maximum of ~300 miles (Crawford et al., 2013).

Studies into domestic production in the UK have identified Scotland as a potential site as it is relatively close to the big population centres in the UK, therefore reducing transport costs. It is estimated that transport costs are 30-50% greater from Central Europe and Scandinavia than they would be from Scotland (Crawford et al., 2013). The breakdown of overall cost of CLT (excluding VAT of 20%) is roughly 20% for raw materials, 20% on processing, 5% for shipping, 25% for importing and processing and 10% during retailing (CBI, 2017a). Other figures exclude importing and processing and just list a shipping value of around 8% (Smith, 2018). If shipping and importing and processing are considered collectively as overall transport costs, then the reduction in transport costs, suggested above, would lead to a 7-10% overall saving on the cost of average CLT buildings (Table 1). Local production also removes issues with exchange rate risk which are said to add large variations to total project costs (Crawford et al., 2013). Although it is true that exchange rates fluctuate it is possible to fix your payment amount by either prepaying or by hedging currencies to fix your project costs, so this should not be such an issue. Additionally, in Europe with many countries using a common currency, so this is also not an issue. Production and supply are examined further in Sections 20 & 21 and assessed for their role in being limiting factors.

Table 1 - Transport cost savings from domestic production.

Transport estimates from (CBI, 2017a) [1] and Smith (2018)[2]. Saving based on estimates of transport costs being 30-50% greater from Central Europe (Crawford et al., 2013).

Transport costs	Europe Transport Costs (% of total)	UK transport costs (%) of Total		Overall Cost Savings (%) of Total	
		23% savings	33% savings	23% savings	33% savings
Shipping[1]	5	3.8	3.3	1.2	1.7
Shipping + VAT[1]	6	4.6	4.0	1.4	2.0
Shipping + Importing & Processing[1]	30	23.1	20.0	6.9	10.0
Shipping + Importing & Processing + VAT[1]	36	27.7	24.0	8.3	12.0
CLT transport Costs[2]	8	6.2	5.3	1.8	2.7

13.0 Social influences

13.1 Perceptions & confidence

Public perception is hugely important as it is the predominant driver of what get built. If a meaningful proportion of the public (buyers and renters) do not want to or are scared to live in timber buildings, then there will be no demand for them. Conversely, if timber buildings are desirable then they may experience greater demand. For instance, the world's first CLT Highrise building, Murray Grove, sold every apartment in 1hr 15 min (Devlin, 2017). This in turn may make them more desirable for builders to build. In the middle ground the public can have no strong view or be apathetic towards building material choice. In this case the building material which can either be built the cheapest or offers a higher standard, is likely to be more widely built with. In addition to this, due to factors discussed above, it is likely to be the incumbent material which is chosen over the new one.

13.1.2 Attitudes in the construction industry

Most important for the future of mid and high-rise timber buildings is the willingness of builders and architects to use the material. Many studies show that prejudices against timber construction exist with concerns over fire and the longevity of buildings (Gustavsson *et al.,* 2006). These prejudices often manifest themselves in risk adverse behaviour, with companies unwilling to take the financial risk of building with timber (Bengtson 2003). As well as individual preferences, standard practice in the industry is also thought to have a large role (Roos *et al.*, 2010).

There is also the element of the 'unknown' when working with CLT. One industry survey in Europe (Espinoza *et al.,* 2016) found that 98% of respondents thought that there were low or very low levels of awareness from construction mangers, contractors and land owners of CLT. Although this does not appear to be through a lack of expertise as in the same survey it was reported that 60% of engineers and architects had a high awareness of CLT. Interestingly a sperate survey of engineers and architects found that they believed that the influence of material choice did not lie with them but with developers and contractors (Roos *et al.*, 2010). This attitude is also believed to be influenced by the availability of alternate materials to them and their need to find the most price effective solution (Bengtson, 2003).

Although many agree on the benefits of timber construction those in the industry in Australia say that it is still a while away before timber becomes considered as a default building material as it takes time to change construction norms (Lim, 2018). The lack of independent, objective information is also viewed as a barrier by designers and other potential specifiers meaning that many will avoid mass timber until they feel it is 'more proven' (Hairstans, 2018). It is difficult to predict when this will occur, but it may be linked to increased education about the material and its use in younger professions which will be explored in Section 13.2.

13.1.2 Public perception and awareness

Public perception along with those in industry is often what drives government policy. Fire safety (addressed in Section 14.1) is one such area where public perceptions for many years drove regulations which hindered timber construction (Toratti, 2001). The public are perceived to have a very low awareness of CLT (Espinoza *et al.*, 2016). Without an understanding or awareness of what CLT is, it is likely that many people use the next nearest familiar building type. For many in Britain this will be prefabrication timber frame homes built in the post war period. These are synonymous with poor quality and these poorly prefabricated timber houses were known to have many issues with the stigma continuing onto timber frame houses of today (Jones, 2016). More recently in the 1980s a largely publicised documentary into timber frame houses, the World in Action, made claims that timber frame houses were not watertight. This was later proved to be untrue, but the reputational damage was already done with both the public and construction firms subsequently shunning timber frame construction (Hollington, 2011). Currently it is thought that approximately a 1/3 of the public in Europe thought to have misconceptions about wood or CLT (Espinoza et al., 2016).

A large-scale survey of UK consumers found that there is still much confusion over OSM and timber buildings (Hurn, 2018). For example, it revealed that half were unable to identify what a modular home refers to and 20% thought that prefabricated housing was poor quality and would not last as long as a traditionally built home. A sixth of people viewed prefabrication as old fashioned. However, over a quarter of people did think that more inventive ways were needed to solve the housing crisis (Hurn, 2018). Attitudes also differ from country to country. In Finland the public support for timber construction and research programs are thought to be some of the key factors in the increased use of sawnwood consumption (Manninen, 2014). While in other countries people, both the public and those in construction industry, have had reservations about the largescale use of wood due to the implications this may have on forests and deforestation (Becker, 1992) which will be examined in Section 22. However, generally it is often the case that final users are unaware of the structural material used in the building they reside in (Roos *et al.,* 2010). The public awareness of climate issues and their preference for more sustainable construction has, however, led to greater demand for timber buildings (Institution of Structural Engineers, 2018) even if not everyone feels this way.

Another key influence in public perception is advertising and lobbying. There is extensive lobbying both for and against mass timber. The cement and steel industries are acting to prevent CLT from establishing itself in mainstream mid and high-rise construction projects by promoting the durability that they have over it. Simultaneously the forestry industry is acting to promote the benefits of timber while countering concerns of fire and rot (Business Vancouver, 2016). Far less has been traditionally spent by the wood industry on advertising their products. Overall advertising spends are just 4% of that spent by the steel and concrete industries advertising their products (Burrows and Sannes, 1998). Although no figures are available for advertising spend one such notable Campaign by Svenska Skogen (2018) highlighted the use of non-traditional timber products including mass timber. Through such advertising campaigns it may be possible to increase awareness of the advantages of mass timber and thereby generate more demand for the products to be used in construction.

13.2 Poor education & training

Both the training and academic background of engineers, architects and building contractors influences their decisions in the workplace (Gustavsson *et al.*, 2006). It does not take much deliberation to agree with those who sate that those who have been educated in the use of brick and concrete construction are likely to advise these methods to clients (Bartelheimer, 1998). While there are many that are knowledgeable in traditional construction methods there are far fewer whom are skilled and have experience working with mass timber (Gustavsson *et al.*, 2006). This is partly due to the newness of the product even though academic research on the topic is increasing (**Error! Reference source not found.**). Architects and engineers also claimed that knowledge of timber construction did not enhance their careers (Roos *et al.,* 2010). This could well be the case due to the small role timber construction has had in the past which made knowledge of timber construction a less desirable skill. A BRE study found that lack of education, both in the industry and related industries, was the largest institutional barrier to increasing the use of wood in construction (BRE, 2004).

A lack of professionals in the field and their knowledge is a large concern (Östman and Källsner, 2018). This translates to higher costs for CLT projects as more time is needed to learn how to use new methods. However, once knowledge has been gained from previous projects this will act to streamline the costs of a project and increase productivity (Smith *et al.*, 2015). This may be the reason that specialised firms exist that focus either largely solely on mass timber projects such as Waugh Thistleton (2018b). It, however, does not help increase the education of people outside these organisations. Unless these organisations grow in size at a rapid rate and a number of large developers decide to build purely form mass timber, there remains a need for broader education in the sector if CLT is to become more widely used. This has been recognised by those in the industry who want timber engineering to be included as a core subject in university engineering courses (Pérez and Wallwork, 2016).

Changes are being made to address the skills shortage. In Finland, education of wood construction processes has been updated across all institutional education levels in in response to an increasing demand for more timber buildings (Karjalainen, 2014). National R&D efforts have also been combined to increase efficiency and cooperation amongst national actors (Karjalainen, 2014). Although the UK is lagging behind, it now is beginning to offer training courses rel ated to OSM. However, those in the industry claim that there are still no courses in the current college syllabus which offer the multi-disciplinary skills needed in the modular offsite industry (ARV Solutions, 2018). The UK government aims to rectify this by involving the construction industry's clients to address underinvestment in skills and innovation (Prior et al., 2017). Even with these changes in education, changes in the workplace are not guaranteed. It could take 20-30 years before someone educated today moves into a position of authority to determine the direct of a business or policy. During that time if those who are making decisions still advocate for traditional forms of construction then it will remain that knowledge of timber construction may not enhance peoples careers (Roos et al., 2010) in which case there may be limited demand for courses in timber construction. Alternatively, due to not many being educated or qualified in mass timber construction and the increase in its use, this may place a premium on these skills encouraging more people to gain them.

13.3 Tradition

Tradition plays a large role in determining the choice of building material and is seen as being more difficult to change than standards and regulations (Gustavsson *et al.,* 2006). The presence of a traditional wood construction industry is thought to increase the rate at which new timber methods are adopted (Mahapatra and Gustavsson, 2009; Hurmekoski *et* al.,2015). Those in the industry agree with this but state that, although mass timber buildings are mostly in countries with established timber construction, mass timber buildings are still isolated cases (Holmes, 2017).

13.3.1 Existence of timber homes

The UK has a long history of building with timber, but this declined after the Second World War in the 20th century when advances in steel and reinforced concrete made them the dominant materials in the market place (BM TRADA, 2015). Similarly, concerns over fire (see Section 14.1) meant that timber buildings were limited to low-rise homes. This change led to a reduction in the overall percentage of timber houses in the UK down to 20% of the total housing stock by the early 2000s (Gustavsson *et al.,* 2006). This figure has been steadily increasing since then though with timber frame houses making up just below 30% of all new houses (Egan Consulting, 2017).

Elsewhere in Europe such as the Nordic countries and in North America, timber housing has a much higher share of total low-rise construction with a percentage share above 75% (Gustavsson *et al.,* 2006). Researchers, acknowledging the differences between traditional low-rise and mass timber housing, have indicated that traditional timber building should be a good indication for the potential for mass timber buildings (Manninen, 2014). This is evident as there is a higher proportion of high rise buildings are currently built with a timber structural frame in countries where there is a higher percentage of low rise timber construction. For example, in Germany 10% of low-rise houses are built from timber and only 2% of the Highrise buildings (Gustavsson et al., 2006) Whereas in Sweden, which has 80-85% of low-rise houses are built from timber, 10% of high rise buildings are currently built with a timber structural frame (Swedish Wood Building Council, 2017). Although this correlation isn't the case for every country it supports the view that there may be a better chance of acceptance of tall mass timber buildings in countries which already have many timber buildings.

Although tradition may play a part in the readiness of people to accept large timber buildings, it is not a factor that can be altered. From this perspective it is, therefore, not an important factor to focus on trying to influence. It is, however, as useful tool for determining which markets and countries mass timber products are likely to do well in.

13.3.2 Access to forests

Having local access to forests has traditionally been a key influence in the prevalence of timber buildings. This can be seen in the differences between the high use of timber in North America and the Nordic countries, which have a high proportion of forest cover (Manninen, 2014), versus the much lower rates in France and the Netherlands (Gustavsson *et al.*, 2006). These same countries and states with access to forests, also happen to be some of the places with high CLT production and usage. For example, Portland in the U.S, is largely forested (nearly 50%) and has has a long forestry tradition (Devlin, 2017). For these reasons, and others, it has been identified as a great area for mass timber production and usage in the U.S (Oregon BEST, 2017).

Access to forests is, however, no longer required to construct a considerable portion of the housing stock from timber. In modern times, with the advent of globalisation, timber products are commonly transported over long distances such as Stora Enso transporting CLT from its manufacturing facilities in Austria to build a building in Australia (Stora Enso, 2018). Therefore, although access to local timber resources has been a determinant in the traditional use of timber it should not be viewed as an important limiting factor in the use of mass timber products. Domestic production may aid in overcoming some regulatory barriers though, but this could also be solved by creating products to the right specifications abroad. What domestic production does add though is shorter supply chains and reduced transport costs (as discussed in Section 12.3) although these may be offset by increased production costs for areas without access to forests and the associated forestry infrastructure.

13.4 Local government and private company support

Alongside central government policies, local government, companies and prominent individuals can have a large influence on the use of mass timber. One notable example of this can be found in the London Borough of Hackney's (2016) supplementary planning document. Here, explicit support is given for the use of CLT. The document highlights CLT's role in reducing the impacts of development in Hackney by being sustainable and having a lower embodied energy. The council expects developers in the borough to consider this and the council even mooted a 'timber first' policy but potential legal action from steel and concrete lobbyists meant that this never came about (Ravenscroft, 2018). Architects and developers have, though, taken the local councils views into account when building in Hackney. The building Wenlock Cross designed by Hawkins\Brown (2018) was originally designated to be built from traditional materials, but the architects allowed the option for it to be built from CLT. After consultation with the council the developer chose to proceed with CLT instead (Ravenscroft, 2018). This shows that by promoting mass timber at a level where planning decisions are approved can be an effective way to increase its prevalence.

There are currently 23 buildings in Hackney that have been built from CLT (including hybrids) built by a number of different architects and developers (Altheer, 2017). Waugh Thisleton (2018b), one of the world's leading Mass Timber architectural practices, is also based in Hackney. It has designed and built 11 fully CLT residential buildings in Hackney alone. It is very possible that this is one of the reasons why Hackney adopted its positive stance towards constructing with mass timber. The first 'tall' CLT building they built was Murray Grove in 2009 (Waugh Thisleton, 2018b) which was seen as the pioneer of tall mass timber buildings. For it to be built it had to pass planning approval from Hackney Council. This may well have been the council's first exposure to CLT buildings and after the project was successful this may have led to the council's positive stance. This would suggest people need exposure to CLT construction to see that it works and the benefits for themselves before being confident enough to promote it themselves.

Hackney is a world leader in timber construction (Waugh Thistleton, 2018). Other London boroughs are not without expertise though. Another leading architectural practice Hawkins\Brown (2018) is in the neighbouring borough is Islington. However, it has not built any residential CLT buildings there while building 2 in Hackney (Frearson, 2015; Hawkins\Brown, 2018). There is only 1 residential CLT building, which is known about, currently planned for Islington (MATA Architects, 2017) meaning that the total is far lower than that of neighbouring Hackney. This shows that, even with expertise, you need a supportive council (or members within the council) to create active support for mass timber which translates into buildings getting built.

A good example of a supportive local authority can be seen in Växjö, Sweden. Here the local strategy focuses on the area Välle Broar which is an 150,000 m^2 area for multi-storey timber buildings (Växjö kommun, 2018). There were also new goals set in a wood building strategy in 2013 where by 2015 and 2020, 25% and 50% respectively of all new buildings should be wood based. This is being achieved both through the municipal owner construction company, Växjöbostäder, building CLT buildings (Johansson and Schauerte, 2015) and incentivising developers to do likewise. For example, the Midroc Property Development Company was incentivised to use CLT by being allowed to double the building volume of a development if they did so (ANA architects, 2014). This goes to show that the support from local government can be even more important than that of national government.

14.0 Technological challenges

Mass timber faces several barriers in becoming a commonly used building material. Some of these are shared by all new materials that come to market such as a lack of specific regulations regarding their use whilst others including perceptions of fire risk are greater for wood. The main issues of fire, moisture and lack of standardisation will be examined in this section.

14.1 Fire safety

Fire safety in buildings is very important. They need to be designed to ensure that fires can be contained, that firefighters can fight the fire and most importantly that people can escape the building or remain in situ, protected from the fire, until they are rescued (Buchanan *et al.,* 2014). Most modern building codes have traditionally been based on prescriptive regulations (Gerard *et al.,* 2013) such as minimum thicknesses required for certain materials. There has, however, been a shift in EU regulations from prescriptive to performance-based regulations to provide improved fire safety. These new regulations require buildings to: stop the generation of fire and smoke and to stop these spreading both within the building and to other buildings, allow occupants to escape the building or stay in place and be rescued, consider the safety of fire fighters and to maintain the load bearing capacity of the building for a specific time (Östman and Källsner, 2018).

14.1.1 How CLT performs in a fire

In mass timber buildings resistance to fire is usually demonstrated one of two ways. The passive approach, where timber is left exposed to fire but overengineered to account for potential fire damage or the timber can be encapsulated in a material which is 'fire proof' so that the structural integrity of the timber element is not compromised (Drysdale, 2011).

The passive approach, also known as the reduced cross section method, utilises the inherent fire-resistant properties of wood. Mass timber's unique properties allow it to char rather than burn. As the fire causes the timber elements heat up they release a natural flammable gas which burns at its surface producing a ridged carbon layer on the outer surface know as char. This char acts as an insulating layer which reduces the amount of heat which can reach the centre of the timber and so slows the gas release. When the char layer reaches a critical thickness gas stops being released in sufficient quantities to maintain the fire, thereby preserving the remaining structural integrity of the timber elements (Drysdale, 2011). This principal forms the basis for the design rules found in BS 5268:4-1 and Eurocode 5 (BSI, 1978; 2004) which were the first Europe-wide guidelines for fire safety in wooden buildings (Östman and Källsner, 2018).

Although the passive approach has been successfully used for mass timber beams such as Glulam, research has suggested that it should not be used in exactly the same manner for CLT (Deeny *et al.*, 2018) with Eurocode 5 having limited applicability to CLT buildings (Arup, 2016). The larger surface area of CLT and the way it is manufactured from laminated layers means that traditional timber fire safety solutions, which do not use an encapsulation system, may not be fully applicable for CLT. Fot instance the large surface areas of the walls contribute to the fuel load of the fire (Frangi et al., 2008; Deeny *et al.*, 2018). The passive method is at risk of being ineffective as tests have shown that delamination occurs (McGregor, 2013). This is when the laminated layers of CLT panels fall off as the adhesive between them is weakened. This, in turn, prevents the build-up of a thick char layer, allowing the fire to continue (Emberley and Torero, 2015). There have, however, been trials with different adhesives which are mean to be heat resistant and therefore prevent delamination, although they do not appear to be used in commercial CLT yet (Deeny *et al.*, 2018). Although less common, there are also non-glued variants such as dowel laminated timber (DLT) and nail laminated timber (NLT) (BSLC, 2017; Hairstans, 2018) which may not face the delamination issues of glued variants.

It should also be noted that testing of some encapsulation products has also shown poor repeatability in performance (Deeny *et al.*, 2018). As a result, research is continuing into this area for greater clarification and to find solutions to this (Klippel and Schmid, 2017). There are, however, examples of CLT products in Australia and New Zealand where this glue line failure and the resulting char rate have been considered and passed full scale laboratory testing (XLam, 2018). There are also examples of tests including both encapsulated and uncovered CLT in which building structural stability has been preserved and the fire has self-extinguished due to the reduction in available fuel (Emberley et al., 2017). Overall encapsulation methods are favoured in tall and very tall mass timber buildings as they limit burning and allow more time for residents to escape and remain in situ awaiting help (Buchanan *et al.,* 2014). There remains an issue of if the encapsulation system fails then extensive burning will take place; in which case it may be best to pursue the passive system.

14.1.2 Regulations concerning fire safety in timber buildings

The performance of structural building elements, which are responsible for stopping the building collapsing, are usually rated in 30-minute intervals within the EU. This is often done via testing or engineering calculations in standard buildings which relate to the BR 128 standard (British or

Eurocode) (Deeny *et al.*, 2018). These fire resistance recommendations can, however, vary widely depending on factors including the use and occupancy of the building as well as which country you are in (Dagenais et al., 2012).

There are cases when performance-based criteria are already in use. Currently in Germany and Australia performance-based standards are used where encapsulating materials must stop the transfer of heat through to the CLT below preventing charring. The temperatures that should not be exceed on the unexposed surface temperatures, are set at approximately 250-270°C (Deeny *et al.*, 2018), although, in the U.S. a much lower limit is set with a maximum average of 140°C with no greater than 180°C at a specific location suggested (Dagenais et al., 2012). This approach allows for buildings to be constructed so that they meet fire safety specifications. This does, however, require individual testing for each CLT producer as they use different types and grades of timber as well as the testing of different encapsulation products and the specification of which encapsulation products can be used with which CLT panels (Stora Enso, 2013).

What appears to be the main challenge is that there has been no specific guidance for how CLT should be prepared and or protected during a fire in the UK. It has instead just adopted the same fire specifications for materials such as glulam, which, although similar, perform differently during fires (Section 14.1.1). To overcome the confusion surrounding how CLT should be fire-proofed there have been calls for a specific performance-based criterion (Gerard *et al.*, 2013). These criteria are calculated by measuring how CLT performs in a fire and what types of fires in can withstand and for how long. These standards would allow a certified fire resistance periods to be obtained (BSI, 2016a). Although there have been attempts to create specifications for mass timber such as The National Structural Timber Specification for Building Construction (TRADA, 2016a) in the UK it lacks specifics on fire performance. There has been other design guidance for mass timber buildings published by European research institutions and work to improve the specifications in Eurocode 5. The rate of progress of CLT and the development of new panels from current and new manufactures has meant that design guidance has lagged behind (Alinea, 2017). Similarly, despite continued research there is still a lot of uncertainty around fire modelling with mass timber (Buchanan *et al.,* 2014). This should especially be considered when accounting for fire behaviour in hybrid CLT buildings.

As more testing is completed and CLT becomes more widely used it is probable that this understanding will improve. Increased knowledge would mean that CLT could have prescriptive building regulations stipulating thickness and the need for insulating materials which would both act to simplify the design and building process and give greater confidence to the use of the material.

14.1.3 Current issues regarding fire safety

Mass timber is not alone in its difficulty to model and prevent fires. The recent fire in a traditionally built London apartment block which killed 71 people (BBC, 2017) has led to a government independent inquiry into fire safety in all mid and high-rise buildings in the UK, known as the Hackitt Review, which will be published later this year. The interim report of the review has found that current systems for ensuring fire safety in high-rise buildings do not work (Hackitt, 2017). The Association of British Insurers (ABI) also commissioned a review of the British Standard (BS) testing system to be done in response to this incident. This review examined fires under conditions more representative of the 'real world' and found that laboratory tests are inadequate when assessing the safety of building materials (Price, 2018b). The regulatory system is thought to also be at fault as it is highly complex which creates confusion over roles and responsibilities during the build. The National Structural Timber Specification for Building Construction (TRADA, 2016a), although not detailing the specifics of fire performance, has been published to solve this accountability for timber builds. There is work ongoing for new fire specification documentation for CLT (Stora Enso UK 2018, personal communication, 5 January) which is hoped to coincide with and implement the suggestions of the final Hackitt Review in late 2018. One of the most relevant part of these reviews is looking at the role of cladding in fires as CLT products usually require both external and internal cladding. Fire proof panels that are installed incorrectly on any type of building have been seen to increase the extent of fires (Price, 2018a).

There are potential solutions to the issues of standardising products and making sure that fireproofing panels are fitted correctly. One such solution would be to incorporate fire proofing panels into the prefabrication process. It the modular presses in which CLT are made could be modified to include the façade and fire proofing material this would save needing it to be added on site and would aid in standardisation and boosting confidence in the fire rating /safety of the product. Such a process could also be used to include sound insulation either within or on the panels which is discussed below in Section 14.2.

It is important to also take a widen perspective of the built environment when considering safety in buildings. Fire safety is not just determined by the materials used in a building. Studies and statistics point towards economic class and poverty being key factors in fire prevalence (Jennings, 2013). Although this point will not be explored further, it highlights the need to sometimes look beyond the obvious. For example, it may be the case that factors other than construction material could play a larger role in fire safety. A good place for those who wish to start further reading on this topic is an online article by Hastie (2017). As it stands fireproofing methods and treatments do currently exist and without them the CLT buildings already in existence would not have been able to be built. There is an obvious need for them to be standardised to simply the fire safety process. Norms and preferences in the industry are, however, still seen as a greater barrier to large timber buildings than the development of new fireproofing treatments (Holmes, 2017).

14.2 Moisture and acoustics

In a European survey of industry members moisture performance was the second most highly ranked research need for CLT, after structural performance and connections, with over three quarters of participants ranking it medium or high importance (Espinoza *et al.*, 2016).

Damp and moisture can lead to fungi which cause decay. There is the need to minimise the chance of this by protecting possible areas of ingress such as eaves and end joints, using fasteners correctly so that cracks do not appear and using appropriate surface coatings (Östman and Källsner, 2018). Similarly, there are concerns over mildew forming where mass timber elements have gotten wet during construction (Business Vancouver, 2016). To counter this weather protection should be specified in the planning process to provide flexible, high-quality protection (Institution of Structural Engineers, 2018). Construction tents attached to mobile cranes are thought to work best in this instance (Östman and Källsner, 2018). Therefore, these issues do not necessarily have to become problems with many of the best practice recommendations and solutions outlined in an advice note by the Structural Timber Association (STA, 2017a). However, the practice of covering a construction site to prevent rainwater damaging building materials (e.g. CLT) is not always followed. Although common in Europe the process is not codified in Canada leading to these beneficial practices not being generally followed (Globe Advisors, 2016). This means that either greater regulation or education is required in places to ensure that building materials are not damaged, and the construction process goes smoothly. External facing sections of CLT are already often treated with a moisture barrier during the manufacturing stage to protect from weather (CTI, 2017b) so are protected from the elements. If a similar coating could be applied to internal sections as well this would remove some of the need to provide protection for these materials during construction.

The most common acoustics problem when building with mass timber is poor sound insulation. This is especially so at low frequencies such as the impact of people walking across the floor (Östman and Källsner, 2018). Although the light weight of mass timber elements is an advantage when constructing larger buildings, it is also a disadvantage when regarding acoustic performance. The lack of mass of CLT means that vibrations pass more easily through it and can also travel from floors into walls, known as flanking transmission, (Forssén et al., 2008). This is currently solved by adding insulation (Forssén et al., 2008) onto of the panels. Double wall construction with insulation on the inside of two layers of wall is also used (Forssén et al., 2008). It may in the future even be possible to combine this with the same cladding that is used for fire proofing so that the additional panel on the surface of the CLT has dual roles. To add the correct amount of insulation in the right places sound prediction models are required. The existing models are, however, best suited to work for concrete buildings so there is a need for models of lighter weight wooden structures to be developed (Östman and Källsner, 2018). If these are successfully developed this could decrease the cost of using mass timber by more efficiently locating the correct amounts of insulating material (Institution of Structural Engineers, 2018).

Combing acoustic insulation, fire protection and moisture barriers within or to the surface of CLT panels during the manufacturing stage would add great synergies to the construction process saving time and removing uncertainty from the construction process.

14.3 Lack of standardisation

Technical standards for each CLT panel are provided by the manufacturer, however, these properties including structural strength and fire rating vary between each manufacturer (Pérez and Wallwork, 2016). In response there have been calls for standardisation of products or sorting of products into strength classes which follow specific design rules (Brandner *et al.*, 2006).

There are also a large variety of panel thicknesses available such as Stora Enso offering 30 different panels ranging from 60 to 320cm (Stora Enso, 2017, p.5) and KLH offering 31 from 57 to 320cm (KLH, 2012, p.7). Although this array of choice may prove confusing for some, it is important to maintain a range of products as each thickness of panel will allow for a different type of building to be built. This range should not be an issue as different thicknesses of different panelised products are already used in construction such as plyboard and OSB (Orientated Strand Board). In addition to this, although no sales figures could be obtained, it is probable that standard buildings only use a few of the total range of panels with some panels in KLH's specification being marked as special order only (KLH, 2012).

What is likely to cause issues though, is that different manufacturers have the same thickness panels and use C24 grade timber, but the compositions of these panels differ. This is evident in different individual board (lamella) thicknesses used and different material properties of CLT panels from different manufacturers (KLH, 2012; Binderholz, 2017; Stora Enso, 2017). This variation could be addressed using minimum standards across products as suggested for fire in Section 14.1. Currently the differences in products hinder the use of CLT as developers must decide on a manufacturer when designing the building to make calculations to their specifications (Pérez and Wallwork, 2016). This adds uncertainty to construction as the supply chain is limited to one producer. If that producer is unable to fulfil the order the whole building may need redesigning. Manufactures in Europe are, however, addressing this by aiming for a standardisation of lamella thicknesses of 20, 30 and 40mm thick (Crawford et al., 2013).

There is an absence of an overarching standard design code for CLT buildings. European manufacturers began standardising CLT in 2008 but it wasn't until 2014 that the first European product standard was drawn up for CLT (BSI, 2015) and shortly after the European timber design code Eurocode 5 (BSI, 2004) was amended to include CLT. However, CLT was still largely absent from European design standards and instead buildings were built using design regulations specific to each CLT product (Brandner et al., 2006). This means that technical design data had to be collated from numerous sources including manufactures, timber associations and independent expert reports. It has been suggested that this could be solved with a European version of the Canadian & American 'CLT Handbook' produced by FP Innovations (Pérez and Wallwork, 2016). Other attempts to address the issue include a proposed attempt to standardise timber building regulations across all the Nordic countries (Pousette et al., 2008). Currently Eurocode 5 is scheduled to be updated to include a design procedure for CLT which will solve many of these problems, but not until 2020 (STA, 2017b).

15.0 Environmental issues

15.1 Failure to price carbon and energy efficiencies into buildings

There is currently no pricing of carbon into building products. Environmental assessment tools for buildings such as LEED and BREEAM, which are meant to encourage the use of energy efficient products also do not account for embodied energy in building materials and energy obtained from burning construction waste (Buchanan, 2007). Academics therefore argue that it could be necessary to alter carbon sequestration incentives and building codes to echo the carbon savings that wood provides (Ruddell et al., 2007).

Current incentives aim to offset emissions by storing carbon in forests, however, this would be counterproductive if a reduced timber supply led to a greater usage of concrete and steel (Oliver et al., 2014). A proposed solution involves crediting landowners for additional carbon stored at a landscape level and giving CO_2 credits to builders when they substitute wood for steel or concrete construction products (Green, 2012). It is thought that this will then result in money feeding back to the forest owner through increased timber prices which would then provide a dual incentive for landowners to grow timber and to store carbon (Oliver et al., 2014).

Taxation could be another route to price carbon into building materials. Study results indicate that increased carbon and energy taxes would increase the competitiveness of timber construction materials through timber requiring less energy to produce and the increased values of timber and other biomass products (Sathre and Gustavsson, 2007). Another study based on Swedish industries found that although timber products would have a small cost increase the effect of taxes would be much higher for the cement and metals industry (Johansson, 2006). Environmental taxes like these are proposed as a possible catalyst to encouraging innovation within companies, leading to not only environmental benefits but also economic ones (Porter and Linde, 1995).

If wanting to tax carbon in building materials it is important to consider where the tax is applied. Taxing a sector in its entirety can be ineffective as companies move abroad to avoid the tax, known as leakage (Sathre and Gustavsson, 2007). Instead border tax adjustments are recommended (Ekins, 1999) which impose tariffs the same as which would be experienced by domestic producers. These coupled with tax rebates on exports allow domestic industries to continue to compete abroad. The problem with this approach and many carbon taxation systems is that it is difficult to precisely calculate what should be paid (Ekins, 1999). An alternate method may be in the form of a sales tax instead. This could occur when the material is bought/sold for the first time. This would still prove problematic to calculate unless a flat rate was applied to each standardised building product e.g. per tonne of cement. Although this would make timber products more competitive, a flat rate would, however, unfairly penalise materials which had lower carbon contents e.g. low carbon cement. It is likely that this would dissuade the use of such products and work counter to the goal of decreasing carbon emissions.

16.0 Legal barriers

16.1 Building regulations

Building regulations have great power to dictate what can and cannot be built. They normally act across a range of products such as CLT being included within the broader range of mass timber products. Restrictive building regulations hinder the usage of CLT while, conversely, supportive regulations are likely to aid in its increased usage. Current legal requirements and restrictions on large timber buildings are see by those in the industry as a far greater hindrance than technical aspects of the build (Holmes, 2017). Such regulation can cause designers to prefer to or need to specify incumbent traditional materials (Crespell and Gaston, 2011).

Historically regulations have prohibited tall timber buildings. Post World War II, there was an increase in fire safety measures brought into building regulations especially in highly populated areas of Europe. Such legislations banned the use of wood in multi-storey buildings and led to the growing use of concrete which achieved a market share of 70-80% (Gustavsson *et al.,* 2006). Other events have led to the banning of tall timber buildings including the Sundsvall fire in 1888 in Sweden after which tall timber buildings were banned until a change in regulations in 1994 (Bengtson, 2003). Subsequent alterations to the building codes allowed the use of timber in buildings up to 8 stories in some areas of Europe (Karjalainen, 2014). Current regulations affecting the use of CLT can be found in Section 6.3.

Although it is perceived that CLT faces many legal and regulatory obstacles, a study by BRE (2004) into the regulatory barriers to large wooden residential buildings concluded that, in fact, no such barriers exist. This conclusion was reached in part due to the government being unable to discriminate against any certain type of building material. The study did, however, highlight the fact that there are still many regulatory limitations affecting the use of mass timber in buildings. These are broadly classified as: uncertainties over fire and acoustic performance, a lack of familiarity with Eurocodes and regional differences in regulations such as different maximum building heights, a lack of familiarity with the regulations surrounding timber and the use of wood externally on a building is limited by fire regulations. Other studies support this view with over half of respondents in one survey viewing building code compatibility as a large barrier to adoption (Espinoza et al., 2016). These studies highlight the fact that although there are not legal reasons why CLT cannot be used in construction the uncertainty surrounding building regulations acts to discourage its use in construction.

16.2 Difficulties transferring products and knowledge between countries

A lack of product standardisation and different timber building regulations in each country creates difficulties when transferring CLT products and knowledge between countries. For example, one producer, Stora Enso, will not produce CLT from British timber due to it being a different grade (C16). Although it is technically possible to use C16 timber, as all Stora Enso products are specified for C24 grade timber, it would require costly new testing and specification (Stora Enso UK 2018, personal communication, 5 January). Although it is possible to manufacture CLT from C16 timber (Crawford et al., 2013) most products are specified for C24 timber and grade C24 timber is specified in the British standard for CLT (BSI, 2016b).

The lack of standards for the manufacturing of CLT using locally sourced timber is also hampering its uptake in China (Liu et al., 2016). CLT is not included in timber design standards in China so Eurocode 5 (The European Union, 2004) is used instead alongside existing design standards (Liu et al., 2016). However, the height restrictions for timber buildings in China and the need for standardisation of CLT product manufacturing prevent CLT from being widely used (Liu et al., 2016).

A global standard for CLT panels is recommend by some (Brandner *et al.*, 2016) which would make transferring products and knowledge easier. However, as most countries have different building codes and manufacturing regulations the feasibility of this approach is unknown.

17.0 Specific opportunities for CLT

Out of all the potential opportunities that CLT faces there are some in which CLT and other mass timber products have a specific advantage and that they should push to exploit which will be detailed below.

17.1 Meeting lower emissions targets

CLT offers one way for governments to reach their carbon emissions reduction targets (Section 11.1). The manufacturing of timber products and harvesting of timber uses much lower energy consumption than traditional construction materials (Gerard *et al.,* 2013) and so potential savings can be had. Mass timber products now enables timber to be used in tall buildings, which previously had to be built from traditional materials, therefore increase the number of buildings in which carbon savings can be made. Studies have concluded, though, that “Climate change mitigation and energy policies aimed at a more sustainable development could more intensively aim at promoting innovative ways of using wood” (Gustavsson *et al.,* 2006, p.1122). This highlights the fact that greater promotion and education of the environmental benefits of timber construction are still required.

17.2 Greater site potential

CLT’s low mass means that it can be used for buildings on a wider range of sites unlocking more brownfield sites for development and being able to build taller. For instance, it can be used on sites which have weak soils and landfill sites due to the decreased weight of construction (Brandner et al., 2016). The same holds true for building over tunnels and pipework and brownfield sites where deeper foundations require prohibitive excavation and remedial works. One instance of this occurring is at Bridgeport House in the UK where the new CLT building was built over a storm relief sewer (Karakusevic Carson, 2018). Here, the new structure was twice the height of the previous one while only weighing a tenth more (Miller, 2012). Dalston Works was also able to be built taller that was thought possible on a brownfield site due to its lighter weight (Waugh Thistleton, 2018a). CLT can similarly be used to build on existing foundations of old sites (BM TRADA, 2015) where the foundations may have degraded to a point which they would no longer support the weight of traditional construction methods.

Also of interest, is CLT's potential to be used in the upgrading of existing properties (Brandner *et al.*, 2016), especially building up. Increasing urbanisation, which requires greater housing densities, means that building up is often the only solution. Being able to extend existing buildings without having to demolish and rebuild them not only saves resources but may be much more cost efficient.

Additionally, CLT is particularly good for building method for earthquake zones as the force exerted on a building in an earthquake is proportional to its mass (Ramage *et al.*, 2017). Timber has a high strength compared to its density (Ramage *et al.,* 2017), so is an ideal material to use in this instance. Current research shows that midrise mass timber buildings can be built to seismic standards and can perform to the same standards and better than steel and concrete (Pei et al., 2016). One controlled study found only relatively small deformations after a 7 story CLT building was subject to a magnitude 7.2 earthquake (Quenneville and Morris, 2007). There are encouraging signs that very tall Highrise CLT buildings could also be developed to be earthquake proof (Ceccotti *et al.*, 2013). One such study in Colorado is monitoring a CLT building with seismic sensors for 10 years (Devlin, 2017) although the results will not be available until 2027. Although the technical tests are encouraging, as with all new materials, it may take time for people to accept this new approach, especially as it involves their personal safety.

Overall CLT can be used in several nonstandard building sites which gives it an advantage of traditional materials and means that it may not even have to compete to be used for these sites in the future but instead is used as a go to method.

17.3 Utilising a wider range of timber

Panelised mass timber products, such as CLT, have an advantage that they can utilise smaller diameter timber (Mohammad *et al.,* 2012) and lower grade timber (Oregon BEST, 2017) in the manufacturing process. They can also utilise a greater portion of timber affected by disease and insects; meaning that standing deadwood, which would otherwise be a waste product, can be harvested and used (FPInnovations, 2013). UK studies show that CLT can be made from spruce sideboard material which is currently not structurally graded and is used in low value applications such as pallets and fencing (Crawford et al., 2013). Mass timber buildings can also use damaged timber such as that from trees killed by mountain pine beetles (McKnight, 2016). In addition, it is also possible to use low grade hardwood logs that are often a by-product of logging or urban tree removal. These otherwise often end up in low value products such as pallets or chips. Studies have shown that these logs can also be utilised for producing CLT and may offer an economical source of timber for CLT due to their low value although further research is needed to confirm their viability (Thomas and Buehlmann, 2017).

VII. The future of CLT usage and production

18.0 CLT market comparisons

18.1 Correlation to construction sector

As a building product the fate of CLT will inevitably be influenced by the health of the construction sector. Historically demand for traditional timber products has correlated well with the wider level of activity in the construction sector (Manninen, 2014). Mass timber has, however, not followed this trend. Despite the downturn in the construction industry post the global financial crisis in 2007/8 the consumption of mass timber products continued to rise and European producers increasing their capacity (Manninen, 2014). In the past 5 years CLT use in the UK has continued to increase at a rate of ~14% annually (IMARC, 2016) while construction output from the sector as a whole has remained steady and even declined (ONS, 2018). Growth has differed from that of GDP as well. This is in part since CLT is used as a substitute to other building materials (Hetemäki and Hurmekoski, 2016). So rather than adding extra capacity, in which case the industry would be growing, it can still grow market share without the market having to expand or even when the market is declining. It should, however, be noted that the health of the construction industry and rate of building will have a impact of CLT use (Brandner *et al.*, 2016). Moreover, as CLT use and market share increases it will be more affected by changes in the overall construction industry.

18.2 Market share of CLT vs. other OSM building products

OSM has been identified as a major growth sector within the construction industry (UNECE, 2016) and has a lot of pollical support (see Section 11.1.2). CLT and other mass timber products are not the only products which are utilising prefabrication. Other such products include precast concrete products which range from panels (20% of the precast concrete market) like those made from CLT to stairs and balconies (35% of the precast concrete market) and columns and frames much the way GluLam would be used (AMA Research, 2018). Overall the global precast and prefabricated construction market is predicted to be valued at US$208.79Bn by 2020 with a CAGR of 6.5% from 2015 to 2020. This growth will be driven by high demand for prefabricated housing in both developed and developing markets (Offsite Hub, 2015).

The main market difference between CLT and precast concrete is that precast concrete is used more widely for infrastructure projects and not just buildings. Resultantly the market for bricks, blocks and precast concrete products, which was valued at £2.1bn in the UK 2017, is split between buildings and infrastructure (AMA Research, 2018). Nevertheless, the market for these products is still considerable larger than that of CLT which had a global market value of $480m in 2016 (IMARC, 2016).

Although sales in precast concrete blocks declined from 2010 to 2012 they grew 50% from 2012-2017 (AMA Research, 2018). Recently, sales of precast concrete blocks grew 15% from 2015-2017 with much of this growth put down to the increase in housebuilding although it is important to observe that a large portion of sales are also derived from non-residential construction such as infrastructure and commercial sites (AMA Research, 2018). The supply issues surrounding the bricks and blocks sector being unable to keep up with recent demand (AMA Research, 2018) may have caused some of this increase in demand. Now growth is expected to slow to 2-3% from now until 2020 with small increases in growth expected after than (AMA Research, 2018). By comparison the growth of CLT compares favourably. In the past 5 years CLT use in the UK has continued to increase at a rate of ~14% annually (IMARC, 2016) and CLT production in Europe is forecast to increase 28% yearly up to 2020 (Ebner, 2017a). If this is kept up it will allow CLT to narrow the gap in-between itself and precast concrete panels, however, the size differences of the markets mean that this will still take many years.

19.0 CLT as a portion of the UK residential housing market

19.1 Current use

19.9.1 Number of residential properties

Figures show that timber frame houses currently make up just below 30% of all new houses (Egan Consulting, 2017), however, there are no similar figures for CLT or mass timber products. To aid with understanding how CLT fits into the construction industry and create realistic expectations for the product, it is important to work out what percentage of the market it currently has and what is possible to achieve.

There are currently 23.7 million households in the UK (MHCLG, 2018a). Over one million of these, approximately 4%, have some form of non-traditional construction (Hollington, 2011). However, there are only estimated to be 450-500 CLT buildings in the UK (Stora Enso UK 2018, personal communication, 28 March). Furthermore, there are no there is no information whether these are residential or non-residential or what size each of these buildings are. Judging from statistics from 2003-11 approximately 270 CLT buildings were constructed with most of buildings built being educational and civil and only ~20% being residential (Crawford, et al.,2013). Taking 20% of the 270 buildings built prior to 2011 (Crawford, et al.,2013) gives 54 residential buildings leaving 180-230 buildings that were built from 2011 to present. This assumes that there are very few residential CLT buildings built prior to 2003 in the UK, as 2005 is thought to be the first year that CLT was commercially used in Europe on a building larger than an individual home (Fourthdoor, 2018).

As no statistics were found on the ratio of the number residential to other CLT building for 2011-2018 volume comparisons will be used. By volume, over half of all CLT now produced is used in residential applications with the next largest sectors being educational institutes, commercial spaces, and government and public buildings (IMARC, 2016). If this ratio holds true for the UK, and CLT use, by volume, is the same for residential and non-residential buildings that would imply that roughly half of the remaining 180-230 buildings are residential giving 90-115 residential buildings.

However, educational buildings use a greater volume of timber than average residential buildings. Two UK examples are the Norwich Open Academy, built in 2010, which is 3 stories high and used 3,600 m3 of CLT (Crespell and Gagnon, 2018) and the William Perkin High School which was the largest CLT building in the UK on completion in 2014, at 4 stories tall and containing 3,800 m^3 of CLT. (Ramboll, 2018). These volumes are comparable to Dalson Works (Table 2) which is currently the largest CLT building in the world by volume. It is, however, not a traditional shaped building as it Is made up of several towers of different heights (5-10 stories) and shapes all joined on a single podium. More traditional cuboid shaped buildings such as Murray Grove, Bridgeport house, Via Cenni and Trafalgar Place all have much lower volumes of CLT ranging from 750 m^3, for a 4-story building, to 1525 m^3, for a 9-story building (Table 2). In addition, many smaller private homes will use far less CLT for construction of the building.

There are also other types of buildings to consider. Public and government buildings, the 4th largest category, are likely to use similar amounts of CLT in construction of educational buildings. The 3rd largest category, commercial spaces, are likely to either use large volumes of CLT when used in a warehouse setting or similar volumes to residential developments in an office setting. There are, however, fewer examples of CLT buildings that are purely offices as they are often combined with residential buildings and those that are, are very large voluminous structures such as the BskyB office building (Binderholz, 2018). With this considered, non-residential building types appear to use greater volumes of CLT to construct a building, mainly because they are larger buildings, which should be reflected in the proportion of residential CLT buildings that a 50% share of CLT volumes correlates to.

Table 2 – Volume of CLT used in mid-rise building case studies

Name	Total stories	% Residential	CLT Vol (m^3)	CLT Vol. for Resi. Area (m^3)	Resi. CLT Vol /floor (m^3)	Residential units	
						No. Units	CLT Vol/unit (m^3)
Dalston works	10	71%	3,852	2,735	273	121	22.6
Murray Grove	9	89%	950	844	94	29	29.1
Whitmore Road	6	50%	499	250	42	3	83.2
Bridgeport House	8	100%	1,576	1,576	197	41	38.4
Trafalgar Place	4	100%	750	750	188	30	25.0
Via Cenni	4 x 9 stories	100%	6100	6,100	169	124	49.2
Total	73	-	13,727	12,255	-	348	-
Average	8	85%	1525	1362	160	23	35

To be on the conservative side, even if the upper range value of CLT used in a residential building is taken, at approximately 1500 m^3, the volume used in the example schools is 2.5x greater than this. To create a more conservative estimate this figure will be decreased to 2x greater. This translates to an estimate of residential CLT buildings comprising 2/3rds of the number of buildings when 50% of CLT volume is used for residential buildings. This then equates to 120-153 of the remaining 180-230 buildings. Overall it can therefore be estimated that out of the 450-500 CLT buildings in the UK, 174-207 are residential.

It is, however, not straight forward to determine how many units 174-207 residential buildings equates to as buildings differ in height and shape and have different sized apartments. A selection of CLT buildings, shown in Table 3, presents an average of 35 units per buildings. When applied to the 174-207 residential CLT buildings this gives a total of 6090-7245 units. This range is, however, not representative of the actual number of CLT housing units in the UK. Table 3, which includes most the large CLT developments in the UK, and some from Europe as well, totals 973 housing units which is far below the estimate. What is unaccounted for is individual houses that use CLT. These houses would give an average of just 1 unit per building which would lower the average considerably.

As there are no statistics, it is hard to know how many individual homes have used CLT construction. As there are no more than 75 mid and high-rise residential CLT buildings in the UK known to this study, there must be, at least, 100-125 low-rise homes. If these all provide 1 housing unit and the remaining 75 use the average of 35 units per building this equates to 2725-2750 units. Although just a rough estimate it is more probable than the previous total. The total of 2750 is used in Table 4 to show the proportion of housing stock that residential CLT buildings comprise. It shows that although CLT buildings represent low overall percentages they are increasing their share.

Table 3 – Number of units in residential CLT buildings.

An overview of mid and high-rise residential CLT projects in the UK and Europe. They range from small private housing projects such as Whitmore Road to the largest CLT building, by volume, in the world which is Dalston Works. Those projects with a number after their name (e.g. 4x) show developments where multiple buildings of the same specification were built as part of a larger development.

Name	Total stories	% Residential	Build Type	Residential units	
				No. Units	Type
Dalston works	5 to 10	71%	CLT	121	
Murray Grove	9	89%	CLT	29	19 private, 9 affordable, 1 shared
Woodbery Down	5	100%	CLT	19	
Curtain Place	6	50%	Steel Hybrid	9	
Whitmore Road	6	50%		3	triple story flats/houses
Bridgeport House	8	100%	CLT	41	100% social housing
Pitfield Street	7	71%		19	(2x1 bed, 13 x 2 bed, 4 x 3 bed)
Wenlock Road	10	100%	Steel Hybrid	50	1-3 bed
WYNG Gardens	4	100%	Steel Hybrid	72	Student en-suite

Inre Hamnen (5x)	6	100%	CLT	20	apartments
Via Cenni (4x)	9	100%	CLT	31	1-3bed (50/75/100m2)
Limnologen (4x)	8	89%	Hybrid-Steel/Glulam	33.5	6 x1B, 40x2B, 44x3B, 28x4B, 16 2-storey apt 3–5B
Vallen	9	100%		60	1x1, 25x2, 27x7 7x4
Trafalgar Place	4	100%		30	1 and 2 Bed
Treet	14	100%	Timber Hybrid	62	luxury Apt 11x1B (43m2) 51x2B (65m2)
Average	7.6			34.9	

Table 4 – Residential CLT buildings as a percentage of UK residential housing stock.

The percentage of total housing stock that residential CLT buildings comprise is shown. Figures based on 2750 units of CLT housing in the UK (Calculated in Section 19.9.1 above). Figures for UK housing stock from MHCLG (2018a; 2018c). *The post 2003 high-rise flats estimate figure is based the ratio of high-rise to low-rise flats in the UK housing stock which is then applied to the post 2003 figure for all flats (MHCLG, 2018a; 2018c). This figure is, however, likely inaccurate there is probably a far higher percentage of high rise flats built relative to low rise more recently than the total average.

	% of UK Housing Stock		
	All Residential	All Flats	All High-rise Flats
Total Stock	0.01%	0.08%	0.67%
Built Post 2003*	0.15%	0.36%	3.20%

19.1.2 How many cubic meters of CLT is required to build one housing unit

Due to variances in buildings shapes and sizes and the differing sizes that apartments can be built to this makes it difficult to create a benchmark for the volume of CLT required for each unit of housing. Nevertheless, this section will attempt to reach a rough estimate of how much CLT is required to validate the feasibility of CLT production being able to meet potential demands of increased usage.

There are many metrics which could be used to try and determine a rough estimate. One is the amount of CLT required per building. Other research has estimated that approximately 120,000 m^3 of CLT is required to build 200 multi-storey buildings (Manninen, 2014) which equates to 600 m^3 per multi-storey building. However, this begs the question of how big is a building and how many housing units does it have in it? Table 2 shows that 600 m^3 would probably be for a small midrise building while other studies estimated that 125 m^3 of CLT would be required for a 3-story building (Lesprom, 2014) which seems conservative but may have been referring to an induvial home. Separately 35,000-40,000 m^3 of CLT has been estimated to build 700 housing units (Crawford *et al.*, 2015) which equates to 50-57 m^3 per housing unit. The figure reached in Table 2 is below this at 35 m^3 which would only require ~25,000 m^3 for 700 housing units. This may be the case as only the timber required for the residential section of the building is calculated. However, taking this into account would only increase the figure to ~40 m^3/unit leaving a difference of 10-17 m^3. This could be as the case studies used here are of taller/larger buildings which use timber more efficiently and include a lot of social housing units (Table 3) which are likely to be smaller in size than equivalent flats on the private markets and therefore fit more housing units into the same volume of timber. Separate studies, thought, have also found that 30–40 m^3 of timber would be used for a CLT apartment in a multi-storey cross-laminated timber building in the UK (Ramage et al., 2017). As it is unknown how the estimate 50-57 m^3 was calculated the figure of 35-40 m^3 will be used as a guideline for future calculations but the possibilities at all volumes per unit will be explored.

19.2 Number of potential units that could be constructed with CLT

This section will briefly look at the size and character of the housing market in the UK to determine how many available units have the possibility to be built with CLT. As each country within the UK is responsible for its own housing policy and statistics this section will focus on the housing market in England.

The current forecast is that an average of 210,000 new households to be built each year in England from 2014 and 2039. This is less than the estimated 240-250,000 new homes needed to keep pace with household formation with some saying that 300,000 homes a year are needed to meet demand (Wilson *et al.*, 2018). Current completions in England are around 160,000 per year which is below the average, but the number built each year is following an increasing trend so that by 2039 this average will be likely be met (MHCLG, 2018c).

When wanting to predict the potential for residential CLT buildings it is important to examine the typology of housing as CLT is commonly used for mid and high-rise homes. In this regard, as building heights are not normally found in building statistics, looking at the number of flats will be used as a proxy for buildings taller than 2 stories. The housing stock profile differs in England for pre and post 2005. Flats comprised roughly 18% of the housing stock built prior to 2005 (Wilson *et al.*, 2018) and in 2006 flats were recorded at 16.8% of all dwellings in England. Low-rise flats (less than 6 stories) were 15.1% of all housing and high-rise flats (more than 5 stories) were 1.7% or 408,000 units (MHCLG, 2018a). The housing stock built from 2005 onwards, however, had a much higher proportion of flats at 44% (Wilson *et al.*, 2018). Currently the proportion of housing stock that is built as flats is around 25% and it has been around this level for the past 3 years although prior to the financial crisis in 2008/9 the proportion was around 50% and has decreased since then (MHCLG, 2018c).

Tables 5a/b outline the possibilities of how many hosing units it is possible for CLT to be used in each year. The lowest figure, based on current rates and housing mix, is 4048 units for flats above 5 stories (Table 5a/b). It is, however, probable that CLT would not be able to be used for every one of these units due to technical restrainst. Nevertheless, this is still likely to be the very lowest posisble estimate as it does not include buildings below 6 stories. Additionally the current trends in residential construction means this coud be unduly conservative. The structural drivers which are supporting the building of flats in mid to high-rise buildings are the need for greater densification, shrinking houshold sizes and a doubling a private renters since 2000 (MHCLG, 2018a). With this taken into the low-end predictions of 5313- 9350 units (Table 5a/b) will be used as a conservative figure going forwards.

Table 5a/b - Number of housing units forecast to be constructed in the UK.

Table 5a is based on current potential construction rates and the housing mix from England and the potential number of new flats is calculated. Table 5b is based on a housing mix with a greater percentage of flats representative of the peak ratio between flats and other housing forms reached in 2005.Numbers shown are potential units that could be constructed and not number of buildings. Figures used in calculations sources from MHCLG (2018c)[1] and Wilson et al. (2018)[2].

		No. Units at Current Ratio[1]	No. Units at 2006 Flat Height Ratio[1]	
Construction rate/yr		Flats = 25%	**Flats >5 stories (10.12%)**	Flats <6 stories (89.88%)
Current[1]	160,000	40,000	4,048	35,952
Predicted[2]	210,000	52,500	**5,313**	47,188
Potential[2]	300,000	75,000	7,589	67,411

Table 5a

		No. Units at 2005-Present Average[2]	No. Units at 2006 Flat Height Ratio[1]	
Construction rate/yr		Flats = 44%	**Flats >5 stories (10.12%)**	Flats <6 stories (89.88%)
Current[1]	160,000	70,400	7,124	63,276
Predicted[2]	210,000	92,400	**9,350**	83,050
Potential[2]	300,000	132,000	13,357	118,643

Table 5b

19.3 Realistic expectations of market share

Currently in the UK for CLT to be used to build 5313 units a year, this would assume total market dominance and 100% market share in residential buildings above 5 stories. This is, however, nearly impossible in the short term due to material limitations for CLT use in very tall buildings, cost pressures and limited supply. The volume of CLT currently imported to the UK yearly used for residential projects, 20,000 m^3, at 40m^3/unit would only allow for 500 units to be built. Even over the long term complete market dominance is unlikely. A North American market study looking at the whole construction market including commercial properties and educational buildings estimated that CLT could achieve at 5 to 15% market penetration over the near to long term respectively (requiring 1.2 to 3.6 million m^3) (Crespell and Gaston, 2011). At this market penetration of 5-15% of total residential builds, this would give 10,500-31,500 units out of a possible total of 210,000. These figures are above the possible number of units built in flats above 5 stories both for the current ratio and an increased ratio of flats (Table 5a/b). The study, however, also includes buildings less than 6 stories in its analysis and it can be seen in Table 6 that there are several CLT buildings below this height. So, when comparing this range to the total number of flats, 10,500-31,500 units represents a 20-60% market share respectively within apartment construction.

Table 6 – Number of units and dates of completion for a selection of English CLT buildings.

In the field 'type' of residential unit B stands for Bedrooms

Name	Total stories	Build Type	Residential units		Date	Location
			No. Units	Type		
Dalston works	10	CLT	121		2017	Hackney
Murray Grove	9	CLT	29	19 Private, 9 Affordable, 1 Shared	2009	Hackney
Woodbery Down	5	CLT	19		2016	Hackney
Curtain Place	6	Steel Hybrid	9	Flats on upper floors	2015	Hackney
Whitmore Road	6		3	Triple story flats/houses	2012	Hackney
Bridgeport House	8	CLT	41	100% Social Housing	2011	Hackney
Pitfield Street	7	CLT Concrete Core	19	2x1B, 13 x 2B, 4 x 3B	2018	Hackney
Wenlock Road	10	Steel Hybrid	50	1-3B - 33 Private 17 Social	2015	Hackney
WYNG Gardens	4	Steel Hybrid	72	Student en-suite	2016	Cambridge
Whitmore Road	7	CLT	3	Triple height family apt.	2012	Hackney
106 Lewes Road	5	Hybrid	48	Student Housing	2017	Brighton
Spruce Apartments N16	5		6	2x3B maisonette 2x3B flats 1x1B	2016	Hackney
Lansdowne Drive	2	Concrete Hybrid	1	2 Bed House	2013	Hackney
Trafalgar Place	4		30	1 and 2 Bed	2015	Elephant & Castle
Hurst Ave	2	CLT	2	2 Family Homes	2013	Highgate
Total			453			
Average			30.2			

Current build rates for CLT are unavailable but just taking a few UK case studies (Table 6) it can be seen that, at least, 89, 97 and 169 units were built over 2015, 2016 and 2017 respectively. These are all less than half a percent of the total number of flats built in their respective years but show a meaningful increase year on year. The true number of units built with CLT can be estimated using approximate UK imports of CLT and the volume of CLT required per unit which is shown in Table 7**.** Here, the figures vary widely depending on which import volume and CLT volume per unit measurement is used. Taking the high and low value estimates it can be calculated than CLT currently has between 0.1-0.27% of the total residential market and 0.42-1.09% of the market share of flat construction. This shows that CLT has a long way to go before reaching its predicted 20-60% market share within flat construction.

Table 7 – Number of possible housing units from CLT imports at different volumes per apartment.

The number of units potentially built from different import volumes of CLT at different densities are displayed. 1figures are based on an estimate of 40,000m3 imported in 2017 and half of this used in residential construction (IMARC, 2016; Stora Enso UK 2018, personal communication, 28 March). 2figures based on EU trade figures of imports to the tune of €12 million in 2015 underestimated by 3-6% (CBI, 2017a), divided by the market price of €500/m3 (CBI, 2017a). 1,2 Both import volumes are halved to represent use in residential projects (IMARC, 2016) and the of 35-40 m3 required per unit is calculated in Section 19.1.2 and 50-57 m3 is used from Crawford et al. (2015).

No. of units from different volumes of CLT at different densities

CLT volume per unit (m^3)	35	40	50	57
[1]Number of units from 20000 m^3	571	500	400	351
[2]Number of units from 12500 m^3	357	313	250	219

20.0 Requirements for UK industry growth

20.1 Global supply and demand

From inception until 2012 global CLT production capacity grew quickly with growth rates of between 15 to 20% yearly with the slowdown in growth after this period attributed to a slowing of the construction sector (Brandner *et al.*, 2016). As industries get larger growth rates also naturally decrease so it is possible this may also be an influencing factor but is less likely as the industry is still relatively young. From 2010-2017 the global CLT market grew at a compound annual growth rate of 14% yearly with the majority of this centred in Europe (IMARC, 2016). Growth rates are forecast to remain elevated for some time due to the current market dynamics where demand outstrips supply (Ebner, 2017a). As demand outstrips supply, it will not be until production increases the available supply that the equilibrium between supply and demand will be found.

In 2017 demand outstripped supply with output in central Europe rising by 15% but it is estimated that market growth exceeded this (Ebner, 2017a). This suggests that the gap between supply and demand is widening. In response European producers are drastically increasing their production capacity which will be able to meet a yearly 28% increase in demand up to 2020 (Ebner, 2017a). The imbalance between demand and supply results in longer lead times between the ordering of CLT and its delivery. For example, in 2017, European manufacturers on average needed a lead time of 10-14 weeks from order to site delivery. This was, however, down to an average 8 weeks by the end of the year (Ebner, 2017a), however, delivery times of several months are not uncommon (Jauk, 2017). These long lead times may have a detrimental impact on demand as it negates some of the speed advantages of building with CLT. Yet, it the time frame of planning and constructing a mid or high-rise building 10-14 weeks is still a relatively short period of time. Longer delivery times do give producers extra leverage to increase prices. At current demand levels where supply is exceeded it is estimated that selling prices could be increased 5-7% (Ebner, 2017a). Higher costs reduce the competitiveness of CLT against other materials, but it is thought that many sales opportunities were lost due to undersupply (Ebner, 2017a) showing that even at elevated prices demand still exists.

Production capacity is not only determined by how many factories that suppliers open, but the ability of machine manufactures to supply the presses which are needed to make CLT. IT is estimated that these manufactures will have little spare capacity until 2019 (Jauk, 2017). Total production is also not currently smooth which affects the supply and demand imbalance. This is due to the nature of CLT production, requiring large factories and presses and considerable capital expenditure meaning that new production capacity will be lumpy, linked to when new factories come online. This is especially so when the total production Is low. For example, one new factory, such as the one built by L&G with a production of 120,000 m^3, will be 10% of Europe's current 1.2 million m^3 production volume (Ebner, 2017b). This could create temporary over supply until demand catches back up. This, however, has not been the case as new capacity has just catered for exciting demand (Stora Enso UK 2018, personal communication, 5 January)

Production estimates vary, but in Europe, from 2017 to 2020, market growth rates are assumed to continue at approximately 15% annually (Ebner, 2017b). Production of CLT globally is predicted to increase at an even faster rate with a tripling of production volume from 2016 to 2020 (Jauk, 2017). This will go some way to addressing the supply demand imbalance. However, as the true demand is not yet known and CLT buildings have only a low market share, the supply demand imbalance could persist for some time to come. Additionally, there is the conundrum of whether demand drives production or production facilitates demand. Without CLT production there cannot be demand for it, but suppliers will logically not increase production if there is no demand for CLT. It is thought that it is increased demand which will facilitate production to take place which will then keep pace with gently rising demand (Oregon BEST, 2017).

As CLT use is going through a period of rapid change it is hard to estimate, with certainty, what production volumes will be in the future. Previous estimates of 1 million m^3 of global production by 2016 (Espinoza et al., 2016) were slightly over optimistic with only 0.8 million m^3 achieved (EMR, 2017). However, future estimates of 1.4 million cubic metres by 2022 (EMR, 2017) now seem conservative. Other estimates made only last year (Ebner, 2017a;2017b), have already been increased to reflect the 1.78 million m^3 that is currently being produced and is in the production pipeline for 2020 in Europe alone (Ebner, 2017c). This has come from recent announcements of top producers to expand production at current and new factories. In Europe, 1.6 million m^3 will come from solely from the top 15 companies in 2020 (Ebner, 2017c). In addition, there is the Japanese governments goal to increase CLT production capacity to 500,000 m^3 by 2024 (FEA, 2017) and the impact of production starting to increase in North America (Ebner, 2017c). With this considered the forecasts of some researchers, estimating that global CLT production could reach 3 million m^3 within by 2025, with most of the growth expected to occur outside Western Europe (Plackner, 2015), seem reasonable.

20.2 Timber volume required at maximum market share

At 5-15% total market penetration, equivalent to a 20-60% market share within flat construction, CLT has the potential to construct 10,500-31,500 units (Section 19.3). It is important to determine what volume of CLT is required to produce this many units to discern whether it is possible to reach such a target. In Table 8, it shows that even the lowest range of the predicted market share, at the smallest CLT volume per unit, requires over 9 times the volume of CLT currently thought to be imported to the UK (40,000 m^3 in 2017 (Stora Enso UK 2018, personal communication, 28 March)). Imports have, however, increased considerably from the 24,700-25,4000 m^3 imported in 2015 (CBI, 2017a).

Table 8 - Volumes of CLT required at varying market shares and volumes per unit

	CLT Volume Required (m^3)			
Market Share of UK Flats	$35m^3$ /unit	$40m^3$ /unit	$50m^3$ /unit	$57m^3$ /unit
20% - 10,500 Units	367,500	420,000	525,000	598,500
30% - 15,750 Units	551,250	630,000	787,500	897,750
40% - 21,000 Units	735,000	840,000	1,050,000	1,197,000
50% - 26,250 Units	918,750	1,050,000	1,312,500	1,496,250
60% - 31,500 Units	1,102,500	1,260,000	1,575,000	1,795,500

Table 9 – European CLT volume required for UK imports to be sufficient to meet varying market shares.

Figures calculated for half of European CLT production being exported (CBI, 2017a) and the UK importing 10% of European exports.

	Total European CLT Volume Production Needed			
Market share & Units	@ $35m^3$ /unit	@ $40m^3$ /unit	@ $50m^3$ /unit	@ $57m^3$ /unit
20% - 10,500 units	7,350,000	8,400,000	10,500,000	11,970,000
30% - 15,750 Units	11,025,000	12,600,000	15,750,000	17,955,000
40% - 21,000 Units	14,700,000	16,800,000	21,000,000	23,940,000
50% - 26,250 Units	18,375,000	21,000,000	26,250,000	29,925,000
60% - 31,500 units	22,050,000	25,200,000	31,500,000	35,910,000

As well as the volume of CLT required, it is important to determine where the UK would source CLT from. Even though global production outside of Europe is set to increase rapidly (Jauk, 2017) it is unlikely that the UK would import CLT from outside of Europe. The same cost and transport issues which have encouraged domestic production outside of Europe are likely to apply when importing CLT into Europe. Moreover, the demand for CLT outside of Europe may also mean that there is no excess capacity to be exported to Europe anyway. Although, less exports from Europe to the rest of the world may mean that there is greater availability of CLT in Europe.

UK Imports will have to rise for CLT to increase market share. Out of a total of 166 million euros worth of CLT imports in the EU in 2014 the UK comprised 12 million of this (CBI, 2017a). As the UK had no domestic production then, this represents just over 7% of European exports. Based on statistics from the CBI (2017a) it can be calculated that in 2015 exports comprised ~49% of production. If this ratio has stayed the same, last year's 680,000 m^3 of production (Ebner, 2017b) equates to approximately 334,000 m^3 of exports. UK imports of 40,000 m^3 in 2017 (Stora Enso UK 2018, personal communication, 28 March) is ~12% of this suggesting that either, the UK now imports a greater proportion of all exports or that the share or CLT produced that is exported has risen. When using the mid figure of ~10% of European exports, Table 9 shows the European production needed.

European production is currently increasing at a growth rate of 28% per year up until 2020 (Ebner, 2017a). However, a predicted growth rate of 15% annually (Ebner, 2017b) appears more reasonable for the long term, especially as total capacity expands, and every new factory is a smaller percentage increase of total production. At growth rates of 15% annually from the predicted 1.78 million m^3 in

2020 it will be 2032 before there is enough production to reach 20% market share at 40m^3 /unit and 2034 for 30% (Figure 5). At a 10% growth rate, which is the high-end prediction for the mature timber frame industry whose growth range is 2-10% (Egan Consulting, 2017), European CLT production would not be able to support a market share above 20% before 2035 (Figure 5).

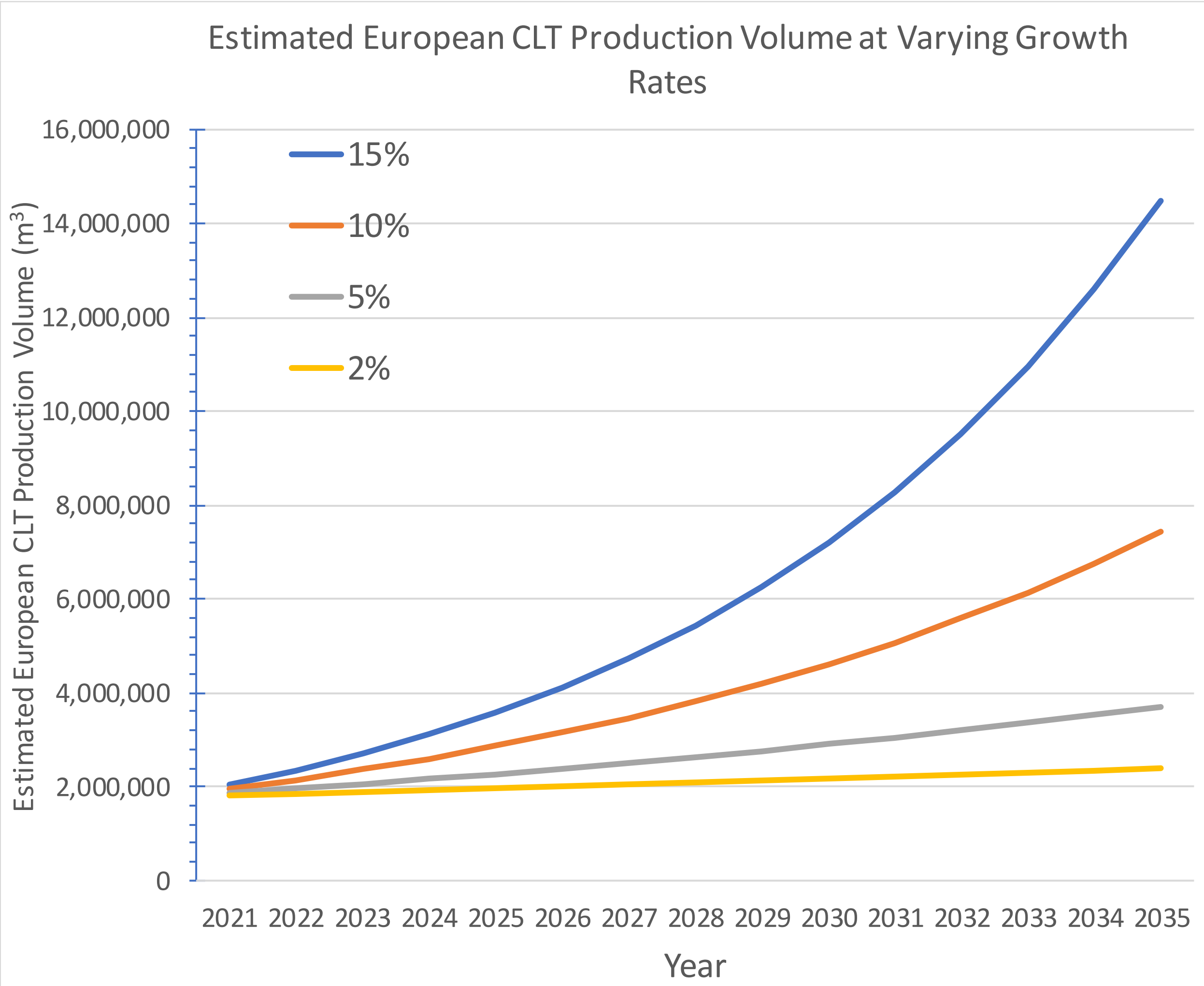

Figure 5 - Estimated European CLT production volumes under different growth scenarios

20.3 CLT production possibilities in the UK

Rather than relying on imports of CLT the UK could focus on domestic production. It is, however, uncertain if the UK production would be enough to provide a sufficient volume of CLT for it to reach its potential market share.

Also, in question is whether it is possible to make CLT from UK timber. The main timber found in the UK is Sitka spruce, which accounts for roughly 50% of the total UK softwood resource (Crawford et al., 2013). This timber is currently only dried to around 20%, rather than 12% required for CLT, as there is not the demand for timber dried further than this and it is expensive to do so (Crawford et al., 2013). Although small scale attempts at drying UK spruce to 12% moisture content have been successful there has not been any research into the viability of a largescale commercial kiln

(Crawford et al., 2013). This timber is also of a lower grade (C16) than its European equivalents (C24) which creates uncertainty about its use in CLT.

Practical studies have shown that it is possible to produce CLT in the UK by using C16 timber instead of C24 (Crawford et al., 2013). There has been an increase in the use of C16 timber to make CLT as areas without higher quality C24 timber have attempted domestic production (International Timber, 2016; CBI, 2017). Although C16 timber can be used to create CLT panels its inferior nature means that its load bearing capacity has been calculated as only 85% of current CLT meaning that panels may need to be made thicker, however, the difference for floor spans is minimal (Crawford et al., 2015). These studies (Crawford et al., 2013;2015) have also revealed though, that some of the timber currently harvested in the UK and generically labelled as C16, has the potential to be classified as a higher-grade material (Crawford et al., 2013). This would go some way to addressing the issue of creating an inferior product although more research is needed in this area.

Presently, although it is technically feasible to use different species of trees and grades of timber to manufacture CLT from, even those of inferior quality (Brandner et al., 2016), they each need their own specification which is time-consuming and costly and has discouraged established producers from manufacturing in the UK (Stora Enso UK 2018, personal communication, 5 January). This means that CLT therefore needs to be imported by countries which don't have a domestic production base. There are, however, sufficient timber resources in the UK, but greater confidence is needed in the future market and investment in the necessary manufacturing facilities (Hairstans, 2018).

There is the potential for CLT production in the UK as new companies, which do not have exciting CLT products, have already begun building manufacturing facilities. The largest of which was built by the wealth management company Legal & General under their L&G Homes brand. When fully operational it will be able to produce 120,000 m^3 of CLT a year (Ebner, 2017b). The L&G factory aims to make 3000 houses annually (GWMI, 2016) which would equate to $40m^3$ per unit and 29% of the 420,000 m^3 required to reach 20% market saturation at $40m^3$ per unit (Table 8). Although the factory is basically finished production is currently on hold indefinitely (Ebner, 2017c; Jauk, 2017). Another UK company, CCG, bought a site with the aim of establishing a CLT factory in the UK (The Herald, 2015). This has also not been completed and the company still imports CLT (Edmonds, 2017).

Regardless of when these factories start producing, the issue here is that they still import foreign timber to process in their facilities. Having to import timber to use in the production lines reduces the benefits of domestic production and some have argued that it is easier to manufacture abroad where you are close to high grade forests and have all the associated infrastructure and then ship the final product (Stora Enso UK 2018, personal communication, 5 January).

21.0 Based on timber production what is the maximum theoretical amount of CLT production that could be achieved

21.1 UK timber industry capacity

Current UK harvest volumes of soft wood are 8.75 million m^3 of standing softwood timber (Forestry Commission, 2017a). These are roughly split into 3.7 million m^3 of sawnwood, 3.0 million m^3 of wood-based panels and 3.7 million tonnes of paper and paperboard (Forestry Commission, 2017a).

The available harvest volumes from forest resources in the UK are predicted to rise over the next 25 years and present an average of 15.2 million m^3/yr up until 2061 (Forestry Commission, 2017a). This is considerably above current harvest volumes with capacity for an extra 6.45 million m^3 of harvest available. A conversion of 1:2.5 is required to convert this volume to that of softwood panels (Forestry Commission, 2017b) which equates to 2.58 million m^3 of CLT. This conversion of harvest volume is likely conservative as there is less wastage in CLT production as it can utilise smaller diameter timber (FPInnovations, 2013). It will, however, be used in the absence of an exact conversion figure to account for the likelihood that not all timber harvested will be suitable for CLT production.

At possible production volumes of 2.58 million m^3 of CLT this is equivalent to greater than the possible 60% market share for CLT in residential flat construction, even at 57 m^3/unit (Table 8). At 40 m^3/unit (Table 8) this volume of CLT is also greater than that required for 100% of flat construction. Therefore, this means that the forest resources in the UK are sufficient to support the expansion of CLT in the domestic building industry. As there is currently no domestic CLT production and the possible production facilities plan to use imported timber it is important to consider where this timber or CLT imports will come from.

21.2 Global timber possibilities

Global forest harvest volumes were at 5.481 billion m^3/yr in 2016 (FAO, 2018). This official figure is, however, thought to be about 20% under the actual total due to illegal logging (Sutton, 1999). Fuelwood makes up over half of all wood use with the remainder split between wood pulp (10.3%), wood-based panels (10%), sawnwood (23.7%) and other timber products (4.3%) (Ramage *et al.*, 2017). So out of the 1.11 billion m^3 of timber used solely in building and construction, the volume of timber currently used in CLT production is just 0.11% of this.

There are two ways to meet the shortfall in CLT production required for widespread CLT use in the UK. Increasing overall imports by utilising unharvested forest resources abroad could be pursued. Alternatively, areas of the timber market where use and therefore imports are declining, can be explored alongside the substitution of certain wood products for non-wood-based equivalents freeing up timber production for another use such as CLT.

21.2.1 Increasing production

There has been a structural decline of the forestry sectors in both Europe and North America (Hetemäki and Hurmekoski, 2016). This is a result of market share being taken by fast growing Asian and South American markets (Toppinen *et al.*, 2010), a declining demand for paper products and a long period of low general economic growth post the global financial crisis (Hetemäki and Hurmekoski, 2016). This has led to a lot of excess capacity in these markets. A U.S. study of CLT's impact on the timber market found that CLT use at 15% market penetration, across all build types from 1-10 stories, would lead to a 12% increase in timber demand (based on 2011 production levels). Traditional production levels in 2005 were 186% more than 2011 levels meaning that this increase would be easily covered it production were to return to traditional levels. Moreover, if all the additional capacity was used for CLT buildings then CLT could be used in over 100% of all new buildings (FPInnovations, 2013). Part of this fall in demand for timber in the U.S has come from decreased demand for traditional wood products for which demand has decreased over 45% from 2006 to 2012. This decrease in demand is equivalent to over 167 million m^3 of CLT (FPInnovations, 2013) and would be able to cover U.S. demand for CLT while having the excess capacity to also supply the UK.

Other European nations, regardless of demand for timber products, have excess capacity in their forests. Austrian forests, for example, produce 30 million m^3 of timber yearly but only 26 million of this is harvested leaving 4 million of extra capacity (CTI, 2017b). This extra capacity would be enough to double the current supply all of European CLT. Long term relying on other countries to increase their timber production may not be the best approach as if CLT gains market share across Europe this excess domestic capcity may be used to support this gorwth domestically and not be avalible for export.

21.2.2 Substituting Products

By focusing on substituting current end uses of timber for CLT production instead it is possible to meet timber demand without having to increase forest harvest volumes. This has, for example, been seen where the competition provided by mass timber products, such as CLT, has been responsible for a lack of growth in volumes of sawn softwood and other panel products to pre-crash levels (Forestry Commission, 2015). Here mass timber products have out competed them and therefore used timber which would have been previously used by them and is part of a trend where old industrial countries shift their focus to value added timber products (Manninen, 2014).

Another timber product which has been declining is paper products which are declining due to the shift to digital media (Hansen *et al.*, 2013). For example, North American production has nearly halved from 45 million tons in 2000 to 25 million in 2014. European production has declined less from 48 million tons to 36 million tons but over a shorter timescale of 2006 to 2014. The input for paper production, softwood pulp, has, however, shown a smaller decline of just 13% over the same period (Hetemäki and Hurmekoski, 2016). This offset is likely due to the increase in the packaging industry which also utilises pulp. In the UK 3.7 million tonnes of paper and paper board were still imported in 2016 although this was a decrease of 7% from the year before (Forestry Commission, 2017a). This 7% decrease represents 0.3 million m^3; as paper pulp and timber panels have the same conversion ratio from raw timber to end product 1 tonne of paper pulp roughly equals 1 m^3 of CLT (Forestry Commission, 2017b). This 300,000 m^3 of CLT is equivalent to ~15% of UK flat construction market share at 30-40 m^3/unit (Table 8). This shows that by using this volume of timber that was previously used for another product that most of the UK needs could be met.

In addition, a reduction in use of biomass and instead utilising the timber for a higher value product such as CLT could provide the necessary timber volume. Biomass is controversial as forestry practices also have a large influence on whether burning wood as biofuel actually leads to carbon reduction (Eriksson et al., 2011). Globally fuelwood makes up over half of all wood use (Ramage *et al.*, 2017) but the increase in use of round wood for wood fuel has decreased. Wood pellets have, however, increased 6% from 2015-2016 (29 million tonnes produced in 2016) (FAO, 2018). They are commonly used for biomass energy production and demand has increased due to bioenergy targets set by the European Commission (FAO, 2016). In particular, an increase in UK imports to 1.6 million tonnes (Forestry Commission, 2017a), is responsible for most of the growth in global consumption (FAO, 2016). If the energy produced from burning of this biomass was created instead from other renewable energy sources, such as wind or solar, then this would free up this volume of timber for other uses. The 1.6 million tonnes of wood chips available converts to 768,000 m^3 of CLT if using the same ratios from Section 21.1 (Forestry Commission, 2017b). This would allow for over 40% market share at $35m^3$/unit or over 35% at $40m^3$/unit.

After considering the possibilities of replacing timber products with CLT It is important to consider that timber used for one wood product may not be able to simply be reallocated to another. The different grades of timber and parts of the tree that are used for different purposes are not necessarily interchangeable (Gustavsson *et al.*, 2016). For example, the increase in timber used for fuel is said to not impact the wood supply used for construction due to it coming from short rotation forests or coppice which are small diameter timber (Fiala and Bacenetti, 2012). These timber products would ordinarily be too small to be used for traditional construction timber. However, as seen in Section 17.3 CLT can utilise smaller diameter and lower grade timber in its production meaning that it can use a broader range of timber sources.

22.0 The Sustainability of timber resources

One of CLT's main selling points is its sustainability and it is therefore important that the timber used in its production is sustainable, i.e. it must originate from sustainably managed forests. There have been concerns raised over the scalability of timber production and the impacts this will have on deforestation (Skog, 1993). Worldwide only 10% of forests are certified by sustainable forest standards with illegal logging common in developing countries (FPInnovations, 2013). Current timber demand is also outstripping supply grown each year which makes the need for plantation forests more pressing (Fenning and Gershenzon, 2002). Globally only 10% of global supply in the 1990s came from plantation wood (Buchanan and Honey, 1994) with that number only up to 12% in 2002 (Fenning and Gershenzon, 2002). Planted forests still comprise less than 10% of all forests yet now supply 35-40% of roundwood harvested (Jürgensen *et al.*, 2014). By continuing the growth of planted forests, it is estimated that they will provide 80% of global annual harvest by 2030 (Carle and Holmgren, 2008). This goes some way to allaying the fear of unsustainable logging, even though 2030 is a long way off.

As CLT is made predominantly from European softwoods illegal logging is not such a concern. Builders and manufactures adhere to the latest standards and ensure that timber is derived from well-managed forests (Abusow, 2018). Some manufactures guarantee that their CLT comes from sustainable forests (Doyle and Lewis, 2017) while others go a step further by sourcing timber from forests they manage themselves or are managed by a partner (CTI, 2017b). As well as corporate responsibility there are also sustainable forest management practices which ensure the sustainability of timber production. For example, in the U.S and Canada harvesting levels are restricted (FPInnovations, 2013) and in Sweden the Forestry Act requires that 3 new trees are planted for every one that is felled (Sveaskog, 2018). Such restrictions mean that timber that would be used in the production of CLT should be harvested from sustainable sources.

In addition, although some current incentives aim to offset emissions by storing carbon in forests, and thereby protecting them, this could be counterproductive if a reduced timber supply leads to a greater usage of concrete and steel (Oliver et al., 2014). These alternatives to wood are seen as even more damaging to the environment than deforestation would be (Buchanan and Honey, 1994). A further argument regarding the necessity of forests being managed and harvested can be found in Japan. Forest cover in Japan is roughly two thirds, much of it planted after the second world war. However, much of the current forested area is currently unmaintained and it is argued that greater harvesting will result in better maintenance and will encourage communities to ensure their sustainability (Marsh, 2018).

Regarding the total volume of timber used a study by Ramage *et al.* (2017) found that for a 3-bed apartment built from CLT, which is replace every 50 years, would require 0.15 to 0.2 ha of forest. Extrapolated to the whole of Europe living in 3 bed CLT apartments would require approximately 25-30% of European forests under current harvesting and management practices (Ramage *et al.*, 2017).

So far it is clear that the majority of forests in Europe are sustainably harvested and that the timber needed for largescale CLT production will not add demand sufficient to change this. Although not currently a concern but the use of wood for new innovative products.

Fibres for textiles and clothing made from wood are already in use in some clothing products (Allen, 2017b). Although this product is still in the early stages and only has a small market share, the total market potential is thought to be 140-150 million tons which is equivalent to half of the global pulp market (Mäntyranta, 2017). Glass substitutes have also been made from wood process to be optically transparent. This product is cheaper than traditional glass and new processes mean that it is well suited to mass production (Li et al., 2016). This new wood-based glass can also be combined with an epoxy to make it stronger then glass and a better insulator with other potential uses from solar panels to automobiles (Zhu et al., 2016). Although still largely in the development phase these products in the future could place extra demand on timber resources and cause the need for a revaluation of what is the best use of finite timber resources in the future, whether it be in structural construction elements or other consumer products.

23.0 The purpose of mass timber hybrid buildings

There is much contention over whether CLT buildings should incorporate other structural materials and create hybrid structures. From a physical resource standpoint, it has been shown that there are sufficient timber resources that it is not necessary to use other materials to substitute wood in CLT structures (Section 21). However, incorporating other structural materials such as steel and concrete can offer advantages and it would be ignorant to believe that timber is the best material for everything. Also, in a global perspective, e.g. including the building sectors in China and India, huge volumes of building materials are needed annually, and in combination with increased global energy conversion using forest biomass, may result in shortage of sawn timber. In the case, hybrid solutions may enable the best resource efficiency, i.e. using a minimum of building material for certain functions and building applications.

To start with, all mass timber buildings use concrete for the building foundations so from a basic viewpoint all CLT buildings could be considered as hybrids. For those buildings that are actually classified as hybrids there are two types that both offer many advantages. The first type is a timber hybrid building which uses many forms of mass timber and non-structural timber elements. In such cases CLT panels can create the load bearing structure with timber frame as infill for non-loadbearing walls. This results in reduced wall thickness as insulation can be used between the stud work. In other buildings glulam has been used in conjunction with CLT as structural beams to produce larger open spaces (BM TRADA, 2015). This form of timber hybrid building is preferred to the other form of hybrid building, where CLT is combined with traditional materials such as steel and concrete which also have load bearing functions. Examples of such buildings are when concrete is used to make a structural core for the building or used to make composite floors where the CLT acts as formwork for the poured concrete (BM TRADA, 2015).

Hybrid construction is currently necessary for very tall and irregular shaped buildings and can allow for more complex building forms (Ravenscroft, 2018). As CLT lacks mass, its lightweight nature could become counterproductive at higher altitudes due to wind loading (Institution of Structural Engineers, 2018). Reinforced concrete cores are, therefore, required for structural stability in CLT buildings up to 150 meters high (Kuilen *et al.*, 2011). There are, however, some structural issues with hybrid construction. Over time shrinkage, elastic deformation and creep will naturally occur in all buildings. When this happens in a building built from different materials the process will not be uniform, therefore careful consideration must be given to designing these hybrid buildings to account for this (Institution of Structural Engineers, 2018). In addition, combining traditional materials with CLT results in the air tightness of CLT being drastically reduced (Ravenscroft, 2018).

There have been concerns about hybrid buildings detracting from CLT buildings environmental credentials and carbon saving possibilities. However, even hybrid structures can bring CO_2 savings. A tall CLT building of 43 floors with a concrete core is estimated to still comprise greater than 80% timber products and could still lead to savings of 50,000 tonnes of CO_2, the equivalent to the emissions of 33,000 cars for a year (Kuilen *et al.*, 2011). This shows that, although there is a reduction, carbon negative buildings can still be made with hybrid methods. Furthermore, hybrid buildings may be the only way that some very tall CLT buildings will be built. One such building in London, 17-21 Wenlock road, found that, due to the unusual shape of the building, a pure CLT construction was too costly and so opted for a hybrid construction with a concrete core and steel frame (Ravenscroft, 2018). In this case the benefits of CLT construction were found through a hybrid structure where otherwise traditional construction methods would have been used.

Construction times of hybrid buildings may be slower than those of pure CLT buildings. The introduction of other trades on site is seen to erode the scheduling benefits of CLT (Ravenscroft, 2018). This may have a knock-on effect on cost, but as traditional materials are cheaper than CLT (Section 9.4) this is less likely, and it may be the case that hybrid buildings are actually cheaper to build. For taller buildings hybrid structures are also encouraged as mass timber is weaker than concrete and steel and so uses up more floor area at greater height (Institution of Structural Engineers, 2018). This means that there is a less saleable floor area available, increasing the cost per square meter.

Overall, some companies encourage the use of hybrid buildings and see this as a way to use the right materials for each purpose and play down the need for everything to be made from timber (Business

Vancouver, 2016). Hybrid buildings can also give confidence to using CLT which may then lead to moving away from the need for hybrid structures in the future. Other believe that only pure CLT structures will realise the full potential of the material (Ravenscroft, 2018) and that by creating hybrid structures that the emphasis is being removed from finding timber solutions to problems. Currently though fully timber and hybrid structures have their individual advantages and building contractors look to find the most appropriate, sustainable and economic solution for each problem such as building timber buildings taller than 20-40 stories (Ravenscroft, 2018). Even those venomously against non-timber structures realise that hybrids currently have a role to play under the current building regulation and knowledge frame work surrounding mass timber and view them as a stepping stone to all timber buildings in the future (Ravenscroft, 2018).

VIII. Conclusion

Overall, this study has found that, from a construction perspective, CLT construction can compete on cost with traditional forms of construction when used in mid-rise buildings. Moreover, quality is not compromised when using CLT. It is predicted that lifetimes of CLT buildings are comparable to other forms of construction, although there is still uncertainty in the insurance industry which is resulting in higher premiums for mass timber buildings.

The main opportunities for CLT construction lie in its carbon saving credentials, which, unlike traditional timber construction, can now be applied to mid and high-rise buildings. CLT can also be used on a greater range of sites due to its lightweight construction. These opportunities are compounded by the supportive general market conditions in which the densification of urban areas is a growing trend. The disadvantages of CLT construction include the need for further sound insulation and the addition of thermal insulation in some instances. Additionally, in very tall or non-standard buildings either steel or concrete is required to complement CLT as construction becomes technically challenging and cost prohibitive otherwise.

The main barriers CLT faces are uncertainties regarding fire safety and regulations and a lack of standardisation of building codes and products between countries and producers. Additionally, a lack of familiarity with building codes and the material creates prejudices towards CLT. Most prejudices are thought to derive from a lack of education in timber products in the construction industry. This also extends to the public who are unaware of mass timber buildings and associate prefabrication with poor quality post war homes. The public perception is, however, turning in favour of using timber in buildings as part of the growing sustainability movement.

Government policies generally support OSM and current governmental carbon reduction policies targets create a positive environment for timber construction. However, the UK government, unlike some other countries, do not directly promote the use of timber, instead focusing on biomass to energy and storing carbon in planted forest. A change to focusing on timber buildings as a major source of offsetting carbon and increasing building volumes could provide a large boost to CLT construction. CLT construction and production is currently being carried out by a few key specialised players. New entrants to the market are more common than incumbents switching to producing or using CLT, however, there is an increasing uptake among large contractors.

In the UK the lack of CLT production volumes are a very tangible barrier. Given a realistic possible market share of 20-60% of apartment construction, CLT has the possibility to competitively be used in 10,500-31,500 units annually which will require approximately 370,000 to 1.26 million cubic meters of CLT respectively. Under mid-range growth forecasts, European CLT production levels will not reach a level where they could support a UK market share of 20% before 2035 and even under ambitious growth forecasts production volumes would be unable to provide for a 40% market share.

Forest resources are, however, not a limiting factor. In UK forests alone, there is enough spare sustainable harvesting capacity to cater for a 60% market share in apartment construction. Domestic production using native timber has been proved viable but is yet to be tested on a large scale. There is also sufficient capacity for European and North American producers to increase harvest levels within sustainable limits to cater for UK demand. The future impact on demand for timber from new and existing sources should be considered though when relying on future imports.

IX. Recommendations & Future Work

From the study it is apparent that more work is required to tackle the problems faced by CLT construction methods and that there is still much work to be done.

A large scale conclusive study into the effects of fire on CLT and how CLT should be specified to deal with that would go a long way to providing reassurance to those wanting to use the material but currently unsure to do so. A report on this should be published later in the year now that the findings of The Hackett Review have been published in the UK and an overhaul of fire testing practices is being undertaken. If this does not prove conclusive then further research into the standardisation of CLT fire protection is recommended.

Other recommended future work could include an analysis of the future competition for timber resources both from exciting products such as biomass as it is used as a method for meeting carbon reduction targets and also from new products such as cellulose based glass products and textiles derived from timber products. With this considered a study into the possibilities for CLT to be made from non-traditional timber sources such as small diameter timber from plantation thinning, damaged timber from insect infestation and timber from urban tree removals. If technically possible on a large scale then a further study into the availability of these resources and if they decrease the timber input costs of CLT, leading to a cheaper product, could be carried out.

Now that the potential market share and volume of CLT required to reach this have been found, a further study into the capacity of the building industry to build this many CLT units is recommended. This study could find whether there the companies currently working with CLT buildings have sufficient capacity to build an increased number of homes, whether they will have to scale production or whether other players in the industry will have to start using CLT for a higher market share to be achieved.

Lastly, what would be extremely useful is an extensive database of CLT products, production and buildings. This would enable quick and easy comparisons between the volumes of CLT produced, used and in what form. This would aid in future research into the market potential for CLT and provide a free to access resource for academic uses. Although much of this information is already online, as it is scattered, and inconsistent such a database would rely on the cooperation of manufactures and developers providing information. This research will ultimately help those wanting to use greater amounts of CLT so there should be little resistance to providing such information, however, the costs of projects may be more difficult to procure due to businesses not wanting to share this with their competition.

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