An embodied carbon implications of home grown cross laminated timber, the Scottish case.

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2022

AN EMBODIED CARBON IMPLICATIONS OF HOME GROWN CROSS LAMINATED TIMBER, THE SCOTTISH CASE

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Abstract. Cross-Laminated Timber (CLT) is a carbon-efficient form of construction, but no UK manufacturers exist, therefore, it remains a product imported from mainland Europe, doing so significantly increases the associated carbon emissions. This paper presents an 'embodied carbon over life-cycle comparative analysis between Austrian CLT manufacturers and a hypothetical CLT supply chain in Scotland using Scottish homegrown timber.
The analysis uses an existing seven-story CLT construction project in Scotland as the unit of analysis, to test the following hypothesis: The amount of embodied carbon emissions would differ should a hypothetical Scottish Manufacturer also have supplied this construction. The predominant variables include the timber species, European grown Spruce, and homegrown Sitka Spruce, the different qualities, and the distances between forest, manufacture, and site. Calculations will be performed by analysing the embodied carbon within every stage of the building life cycle with a focus on the sequestered carbon in the timber products. The results will provide an approximate figure which can quantify the embodied carbon emission difference between imported CLT and homegrown CLT.
The study concludes that a Scottish CLT manufacturer would achieve lower carbon emissions exclusive of sequestered carbon. If including sequestered carbon, both manufacturers produce a net loss in carbon emissions, however, Austrian timber would sequester more carbon dioxide than Scottish timber.

Keywords. Cross laminated, timber, embodied carbon, supply chain, Scotland.

1. Introduction

There is a global climate emergency, and the construction industry is responsible for 49% of carbon emissions exasperating it (LETI 2019). A global housing shortage has coincided with record-high levels of atmospheric (greenhouse) gases (GHG) trapping heat and significantly increasing the global temperature. Greenhouse gases make up 0.03% of the Earth's atmosphere yet contribute vastly towards trapping Earth's radiant heat, warming the planet (Buis 2019). The majority of global greenhouse gases (94%) are carbon dioxide (CO2). An increasing population presents an increasing demand for housing construction as well as a decrease in global carbon emissions. There is presently an increasing movement towards reducing energy from the operation of buildings, but there is also a large inherent amount of carbon associated with the extraction, production, and construction of building materials. It is now possible to construct architecture using less carbon-intensive building materials, mass timber products like Cross Laminated Timber (CLT) being prime examples, materials that can sequester and store carbon from the atmosphere and reduce the carbon footprint of construction.

There is vast and tangible evidence that CLT can compete fairly with the structural properties of concrete and steel. Moreover, CLT provides numerous additional benefits throughout use, including healthy indoor living environments and speed of assembly. In the isolation of costs and business plans, there is an inherent reduction in carbon emissions achievable by building from mass timber over concrete and steel. Carbon emissions in Scotland account for 74.2% of the greenhouse gas emissions (Scottish Government 2020). Scotland is a country abundant in timber and trees, yet the majority of our construction timber is imported. Can Scotland further reduce carbon emissions by using homegrown timber in large construction projects as mass timber systems? Such innovation would contribute to the Scottish economy through local manufacturing and processing industries to benefit the country and the environment. With recent timber losses from natural disasters, there is an expectation that CLT importation into the UK is going to become more difficult and more expensive, therefore there is a motive and there is an opportunity for a homegrown mass timber supply chain. It is assumed that should a Scottish CLT manufacturer exist then there would be a vast carbon emission reduction, especially given shorter transportation distances.

2. Study Aim & Objectives

This paper aims to explore CLT as a suitably sustainable and well performing construction method for medium-high rise buildings in Scotland.

The study objectives are:

1. to review CLT as a suitably sustainable and well performing construction method for medium-high rise buildings. Research into CLT as it regards architecture in pattern and cultural movement.

To achieve this objective, a desk-based literature review will take place of existing documentation. The proposal will investigate the arguments advocating for designing with mass timber products with performance information somewhat comparative to concrete and steel.

2. To review current practices of CLT manufacture, production, distribution, and importation from mainland Europe with analysis of associated embodied carbon.

A desk-based literature review of existing methods of manufacture as well as published documentation surrounding the Environmental Performance of the production of CLT facilities will be conducted.

3. to test whether using homegrown (Scottish) CLT would produce tangible lifecycle emission savings compared to EU imported CLT.

Comparative calculation between Scottish timber and EU timber for a Scotland-based construction project would be worthwhile and would produce new and definitive insight into this area. An example construction project of a medium-high rise CLT housing project based in Scotland, will provide volumetric quantities of CLT and timber. Volumetric figures could be used to quantify the entire embodied carbon over life cycle emissions and to gauge the quantity of sequestered carbon stored in the CLT. Furthermore, it is necessary for the building to be placed at a literal site to analyse embodied carbon over the life cycle associated with travel to and from the forest, manufacturing facility, and construction site.

Comparisons would be drawn between the embodied carbon over the life cycle from building the structure from CLT from Scottish timber than with CLT imported from mainland Europe. It will be necessary for the model to define the use of CLT as per the definitions (alluded to in the literature review) of pure CLT, Pure Timber, or Hybrid CLT. The outcome of the calculation should be compatible with national life cycle assessment standards as far as possible. Comparisons would be drawn between the embodied carbon over the life cycle from building the structure from CLT from Scottish timber than with CLT imported from mainland Europe. It will be necessary for the model to define the use of CLT as per the definitions (alluded to in the literature review) of pure CLT, Pure Timber, or Hybrid CLT. The outcome of the calculation should be compatible with national life cycle assessment standards as far as possible.

3. LITERATURE REVIEW

Buildings produce approximately 35-45% of all global GHG emissions (World GBC 2018). Approximately 28% from Building Operations and 11% from Building Materials & Construction. The domestic construction industry alone in the UK is responsible for approximately 49% of GHG emissions in the UK (LETI 2019, Architecture 2030). Total GHG emissions from the construction sector equal 72% from Building Operations, this is
referred to as Operational (Energy). The remaining 28% is from Building Materials and Construction, this is referred to as Embodied (Carbon).

3.1. THE CASE FOR BUILDING IN TIMBER

"There is a global climate emergency, the evidence is undeniable, and the science is coherent" (Scottish Government 2019). A worldwide shortage of readily available houses is to be continually felt whilst there is migration to urban areas. Increased urban area demand should logically be met by the construction of medium to high rise housing and supporting infrastructure. The current drawbacks to this solution are that an increase in construction leads to an increase in atmospheric carbon emission levels. The carbon content within the current most common superstructure materials of concrete and steel continues to increase atmospheric carbon levels. For example, the extraction and utilisation of cement for concrete accounts for around 8% of global CO_2 emissions (Waugh & Thistleton 2018). The widespread use of concrete does not appear to be sustainable nor able to reduce carbon emissions to an acceptable level in the immediate future. As such, an ever-increasing number of Built Environment Professionals are advocating that building in timber could be our best and most readily available solution to climate change (Hairstans 2019; Build-in-Wood 2020; Smedley 2019).

Timber grows and can be grown, therefore can be classed as renewable and sustainable, and can be a mainstream structural material available for implementation in the built environment (Ramage 2017). Timber as a primary superstructural material produces fewer carbon emissions than concrete or steel. Trees absorb and store (sequester) atmospheric carbon through growth, ceasing once fully grown, therefore creating an abundance of fully-grown natural construction material. Cutting and re-planting would maintain the carbon cycle and produce a renewable stock of timber.

The cut timber can be utilised in construction, storing the sequestered carbon within the timber construction throughout the building's life cycle. Furthermore, should panellised mass timber such as CLT, be re-used or recycled after the building's life cycle, the sequestered carbon will remain stored and thus will achieve significant carbon emission reductions. Timber construction tends to absorb more CO2 than is emitted in producing timber construction products. Simply put, mainstreaming timber construction can reduce the greenhouse gas content that is causing the global warming effect (Build in Wood 2020). Building in timber would reduce atmospheric carbon content by approximately 40 tonnes of CO2 per home (Waugh & Thistleton 2018).

A form of timber construction perceived most suitable for medium-high rise construction is 'mass timber', a phrase that describes 'large slab' engineered timber construction components (Hairstans 2020). Recent innovations in mass timber have produced an unforeseen opportunity to compete with steel and concrete for the superstructure (Waugh & Thistleton 2018). There are a variety of mass timber products currently available, and CLT is perceived as the most competitive mass timber product in terms of performance for medium-high rise construction compared to concrete and steel, based upon results from extensive testing as well as practical implementation.

CLT was established in the 1960s and has been successfully used as the superstructure for multiple medium and high-rise construction projects (Waugh &Thistleton 2018). Timber boards of varying grades are glued adjacent to one another, each rotated at a full right angle from the adjacent board. This process is called cross lamination and it produces high-strength timber panels with many associated positive performance attributes (Laguarda 2015; Waugh &Thistleton 2018). CLT originated in Austria and it has been very prolific in the European market ever since its introduction (Lehmann 2012). CLT production increased by 315,000m3 between 1996 and 2016 (Crespell & Gagnon 2010). As of 2013, an analysis of Edinburgh Napier University showed that an estimated percentage of 74% of total CLT imported was from Austria.

CLT construction has been increasing in the United Kingdom, the legislative structure allows for a versatile and diverse range of CLT applications as superstructure and can be categorised as: Pure CLT (CLT only), Pure Timber (CLT Combined with other timber structural elements) and Hybrid (CLT combined with non-timber elements such as steel or concrete) (Waugh & Thistleton 2018).

As of 2020, The United Kingdom has approximately 500 completed construction projects which utilise CLT in the superstructure (Waugh 2021). All of these projects imported CLT from out of the UK, with none of the projects utilising CLT manufactured in the UK.

3.2. CLT PERFORMANCE

It is important to define how well CLT performs comparative with other structural types. 'Performance Characteristics' are attributed to CLT to measure this. The following performance characteristics of CLT are highlighted by Laguardia Mallo & Espinoza (2015) study and others:

3.2.1 Environmental Performance and Sustainability:

CLT sequesters carbon over time (Lehmann 2012). CLT panels are suitable for reuse for a reduced carbon footprint and increased lifespan. However, increased CLT production would decrease fossil fuel emissions through the manufacturing process (FPInnovations 2013). CLT buildings embodied carbon emissions are less than half in comparison to concrete or steel (Hammond and Jones 2008). This results in net loss in Global Warming Potential (GWP) comparative to concrete or steel (John et al 2009). CLT buildings require less energy to operate (Chen 2012), and they have smaller environmental impacts and can thus produce 18% less emissions from non-renewable energy compared to reinforced concrete buildings (Robertson et al. 2012).

3.2.2 Installation Simplicity and Cost Effectiveness:
CLT construction can be easier to construct than timber frame through fewer but larger components (Waugh, Thistleton 2018). Construction per storey can take no more than 4 days, a whole 17 days less than with concrete (WoodWorks 2013). Construction time with CLT can be reduced by up to 30%, making vast economic reductions in on-site labour (Silva et al. 2013).

3.2.3 Structural Performance:
Hybrid CLT and concrete construction could produce designs as high as 150m (Van de Kuilen et al. 2011). All CLT elements have an inherent structure that is stable and resistant to two directions of force (Popovski et al. 2010). The cross laminating of panels enables good performance as shear panels and load bearing plates (Steiger and Gülzow 2010), in addition CLT provides a competitive and viable competitor to steel and concrete for medium and high-rise construction (Fountain 2012).

3.2.4 Design Flexibility:
200mm thick CLT panels can produce spans of 7.5m not too dissimilar to spans achieved by concrete (Malczyk 2011). Wall structures utilized as deep beams and columns can produce long uninterrupted spans (Silva et al. 2013). Techniques known as “cassette” and “folded” can achieve spans as large as 19m (Fountain 2012).

3.2.5 Fire Performance:
Airtight seal between elements prevents the spread of smoke and fire, thereby limiting fire damage to specific areas (Frangi et al. 2009). CLT panels under testing could withstand 180m of fire before collapsing (AWC 2012). Internalised metal plates contribute to good performance in fire. (FPInnovations 2013).

3.2.6 Seismic Performance:
CLT structures withstand no lasting deformation from earthquake simulations (Popovski and Karacabeyli 2012). CLT construction offers strength and ductability which improves seismic performance of panels (Winter et al. 2010). CLT fastening systems aid dissipation of seismic energy (Hristovski et al. 2012).

3.2.7 Thermal Performance:
CLT construction creates opportunity of airtight construction. Reduced air leakage therefore producing improved thermal performance (Skogstad et al. 2011). CLT offers a substantial quantity of thermal inertia from being a large mass, improving the building’s thermal performance (Cambiaso and Pietrasanta 2014).

It is apparent through the summary of the performance characteristics of CLT that the product offers many construction benefits in addition to the significant carbon emission savings to be had. There does not appear to be a significant performance flaw which advocates for the specification of concrete or steel over CLT in buildings under 150m tall. CLT use in building of over 150m tall becomes more complicated and requires deeper research and detailed scrutiny at this time.

3.3. THE PERCEPTION OF CLT

Given the well-established performance characteristics of CLT it is necessary to understand the awareness, willingness, and perception of CLT in the construction sector and in the UK market. The results of Laguaradia's (2015) study upon the US architecture community discovered that awareness of CLT was low in the U.S firms, it is expected that similar results would have been experienced at the time in the UK. Whilst this study was taken six years ago and awareness of CLT should by now have improved, it is the case that a lack of knowledge of CLT was perceived as a threat to the industry by 38% of industry professionals who undertook a survey in 2020. (CSIC 2020). Therefore, it is paramount that CLT be publicised and taught, with information upon its use in construction advised to be open source and accessible to all. Results from a webinar poll (CSIC 2020) concluded that CLT is perceived as the most suitable of all mass timber systems in a UK / Scottish context. The primary market for mass timber was divided: Health/Education (30%) Commercial/Office (26%) 1-4 storey housing (26%) and 5-9 storey housing (13%). Of industry professionals who are aware of CLT, there is a perception that CLT is applicable across multiple sectors.
The emergence of mass timber and CLT resembles the patterns of the architectural movement and innovation associated with steel in the 19th and 20th century. It can therefore be perceived that we are in the midst of a new architectural movement and a paradigm shift towards mass timber perpetuated by innovation and climate emergency.
The adoption of mass timber may be hindered by multiple factors. A perpetual love affair of the architectural steel movement, or perhaps association of timber being a historical and therefore a superseded or redundant construction material, and many in the industry hold firm to the erroneous perception of timber being a flammable and combustible material. Furthermore, some in the industry with conflicting interests will rally against the use of CLT in the spirit of economic competition and may spread deceptive information to curry perception in favour of alternative construction products. Equally, there may be bias on the side of CLT advocates with conflicting interests, though it cannot be denied that the offering from CLT of fewer carbon emissions questions the validity of a perpetual endorsement of steel and concrete. Mass timber should be perceived as a new form of construction material distinct from timber frame, and one with the potential to spark widespread industrial change and opportunity for architectural space, quality and ultimately, a much lower carbon footprint. In the contemporary age we refer to concrete and steel as 'traditional' methods of construction. Traditional, to mean 'existing in, long-standing'. Concrete and steel were a product of the 20th century, and it could be argued that timber frame which predates steel, is the traditional method of construction. Albeit timber frame is different to mass timber construction, but it can be perceived as a challenge to the contemporary ideal of traditional construction.

Based upon a recent survey by Construction Scotland Innovation centre (2020) from UK Architects and Engineers, Figure 1. Precision manufacture was identified as the top motivational driver. Offsite manufactured products such as CLT allow for increased precision of manufacture and design, enabling airtight and correct detailing. Mass timber products being inherently machined and manufactured offsite enable repetitive changes based upon constraints, a noticeable advantage from a highly engineered mass timber product. The sustainability and the life cycle benefits including recycling, ease of maintenance and re-use after life and carbon sequestration differential compared with alternative structural materials were deemed approximately as important by designers. The eco-conscious architect and specifiers with a long, whole life product view would have appreciated the sustainability of mass timber products. 49% of specifiers felt that faster construction was a motivational driver, a figure which was deemed the most important driver by Building Contractors. Fast construction benefits architects by product of simplified construction detailing, requiring fewer design consultations.

Key motivational drivers for investors, specifiers and contractors:

Investors	Specifiers (architect, engineer)	Building contractors
Reduced on site labour (59)	1. Precision manufacture (59)	1. Reduced on site labour (71)
Carbon sequestration (58)	2. Parametric design flexibility (57)	2. Speed of construction (70)
Sustainability (56)	3. Life cycle benefits (57)	3. Ease of construction (63)
Speed of construction (54)	4. Sustainability (56)	4. Reduced wastage (55)
Life cycle benefits (53)	5. Speed of construction (49)	5. Reduced H&S risks (53)

Figure 1.0. Motivational Drivers for Built Environment Professionals. (Construction Scotland Innovation Centre 2020)

In another section of the survey (2020), the primary threats to CLT implementation in the UK were identified as follows: Building Regulations (50%), Lack of Knowledge (38%), Traditional Construction Materials (38%) and Perception of poor performance (25%). Regulations which may erroneously prohibit CLT, or which may incite upside to more carbon intensive building materials. A lack of comprehension regarding CLT was deemed to be a threat to it as an industry. This is perceived to stem from a lack of education from obtaining an architectural qualification, coupled with a dis-interest or an inability to readily accept and access information about CLT sufficient to overhaul an architecture practice understanding of construction.

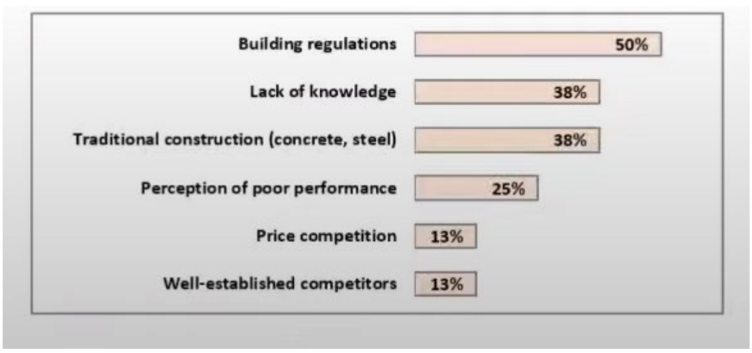

Figure 2.0. Primary Threats to Mass Timber in the UK (CSIC 2020)

CLT requires implementation from the Initial Design Stage, it would be understandable to suggest that some find it more efficient use of their time to utilise structural forms more known, such as concrete and steel, which also gained 38% of the survey votes (CSIC 2020). A perception of poor performance received a quarter of the votes. There will remain voices within the industry that lobby against mass timber products for they provide direct competition to traditional forms of construction.

3.4. THE PROCESS OF CLT PRODUCTION FROM TREE TO SITE

As already alluded to, mature softwood trees cease to absorb atmospheric carbon. The embodied carbon calculations begin in the felling of trees from sustainable and managed forests. Trees are replaced and re-planted. An expectation of minimal carbon emissions is to come from the use of tools in order to fell trees. For CLT this normally takes place in mainland Europe, not in UK forests. Felled trees must be transported to a CLT manufacturing base.

CLT is one of many examples of off-site manufacture (OSM). OSM it is the manufacture and pre-assembly of construction components, elements, or modules in a factory before installation into their final location (Abosaod et al, 2010; BuildOffsite 2013). manufacturing construction products in a factory support efficiency and design quality precision and control. A direct benefit of OSM techniques can result in fewer days spent upon the construction site. OSM can be considered to be a “Modern Method of Construction (MMC),” A UK Government phrase for house building innovations (Hairstans 2014).

The vehicles used in transportation of the trees would emit carbon and add to the embodied carbon calculation. Manufacturing machinery requires energy to convert felled lumber into cross-laminated panels. Approximately 40% of the timber is lost through machining sawdust, capable of use in biomass and animal bedding. Further energy is required for heat to kiln dry CLT. Logistics, which concerns the organisation of transportation tools, routes, and sequence is of increased significance to the carbon emissions control for the product and construction stage**.** Efficient planning of prefabricated construction components will aid in the reduction within the logistics stage (Dong et al 2018).

Once dried, energy is required to cut and plane CLT into usable construction components, and subsequent sawdust can be added to the existing stock for transportation and use. Once prepared off site, panels need transportation to the construction site. CLT requires significantly less deliveries to site than a concrete frame would require (Waugh & Thistleton 2018). Common practice dictates that panels are transported from mainland European manufacturing facilities to United Kingdom construction sites. Construction and

building assembly may require vehicular assistance requiring fuel and energy, a final contributor to the total sum of embodied carbon emissions for a single construction. In absence of any major fluctuations in vehicle efficiency it is an undisputable fact that CLT transportation from a UK manufacturing facility to a UK construction site would emit less carbon. Timber would therefore be transported from either UK or mainland European forests, and conclusively it can be said that timber from a UK forest would travel a smaller distance and thus emit less carbon. The largest carbon emission reduction stands to be made through reduced transportation distances of CLT panels from manufacturing base to the construction site, though carbon associated with sequestered biogenic carbon also provides large potential savings.

3.5. MEASURING & REDUCING EMBODIED CARBON

3.5.1 Reducing Operational Energy

Operational Energy is the largest carbon emission contributor in the Built Environment. Current UK construction recommendations for reducing Operational Energy are firstly for buildings to be 100% electric with no fossil fuels such as gas involved in heating. As the grid becomes carbon free, building operations will also become carbon free. The Electricity grid is increasing in carbon-free energy generation, renewable energy (such as wind & solar energy.) Furthermore, we can increase the energy efficiency of buildings and reduce the Operational Energy demand, therefore requiring less electricity from the grid.

3.5.2 Reducing Embodied Carbon

Whilst reducing operational energy from Buildings should be a priority, it is important to not neglect the embodied carbon emissions. There is a large inherent amount of carbon associated from material extraction through to the construction of buildings. Constructing architecture using less carbon intensive building materials like CLT which remove carbon from the atmosphere can therefore reduce the embodied carbon of a construction.

The following Diagram, Figure 3, is from a European Standard which defines each stage of the construction cycle using a letter and a number e.g. A1. Operational Energy accounts only for stages B6 & B7, every other stage is classed as Embodied Energy. European Standard 15978:2011 is utilized in a professional statement by the United Kingdom Royal Institute of Chartered Surveyors (RICS). All members of RICS must abide by this European Standard and thus it is mandatory to use these terms in the United Kingdom (RICS 2017). Therefore, any professional calculation in the United Kingdom of the Operational Energy or Embodied Carbon must adhere to EN15978:2011. This RICS Statement upon Embodied Carbon Calculation is the most accepted methodology.

Embodied Carbon measurements can be termed differently based upon the amount of EN 15978:2011 stages included within the calculation.

- Stages A1-A3 (Cradle to Gate)
- Stages A1-A4 (Cradle to Site)
- Stages A1-A5 Embodied Carbon to Practical Completion (Cradle to Practical Completion)
- Stages A1-A5 & B1-B5 & C1-C4 Embodied Carbon over Life Cycle, (Cradle to Grave)
- Stages A, B, C & D reported separately = Whole Life Carbon (WLC)

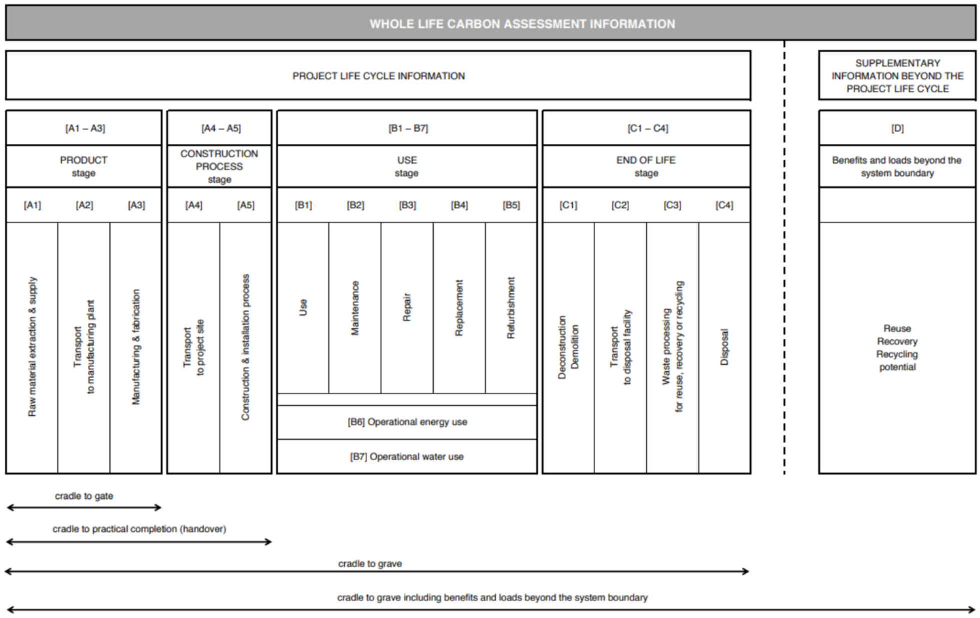

Figure. 3.0 EN 15978 introduces a modular approach to a built asset's life cycle, breaking it down into different stages. (RICS 2017). Life cycle stages from BS EN 15978: [B6-B7] = Operational Energy.

3.5.3 Sequestered Carbon

None of these Embodied Carbon Measurements consider the value of sequestered atmospheric carbon stored in timber as biogenic carbon. The largest carbon saving achievable in mass timber is in biogenic carbon and therefore it's place in the embodied carbon calculation would have a large impact upon its use in construction. "The carbon sequestered in timber or other bio-based materials (biogenic carbon) being repurposed should be considered in module [D], where applicable." sequestered carbon should though only be considered a benefit in the scope of whole life carbon assessment when the timber is sustainably sourced – certified by FSC, PEFC or equivalent. This is to ensure that any trees felled are being substituted with a minimum of the same number of trees planted and therefore not contributing to deforestation and not compromising the overall carbon absorbing capacity of woodlands (RICS 2017). Therefore, Carbon sequestration figure should be reported separately but can be included in the total product stage figures [A1–A3] provided the specified conditions are met.

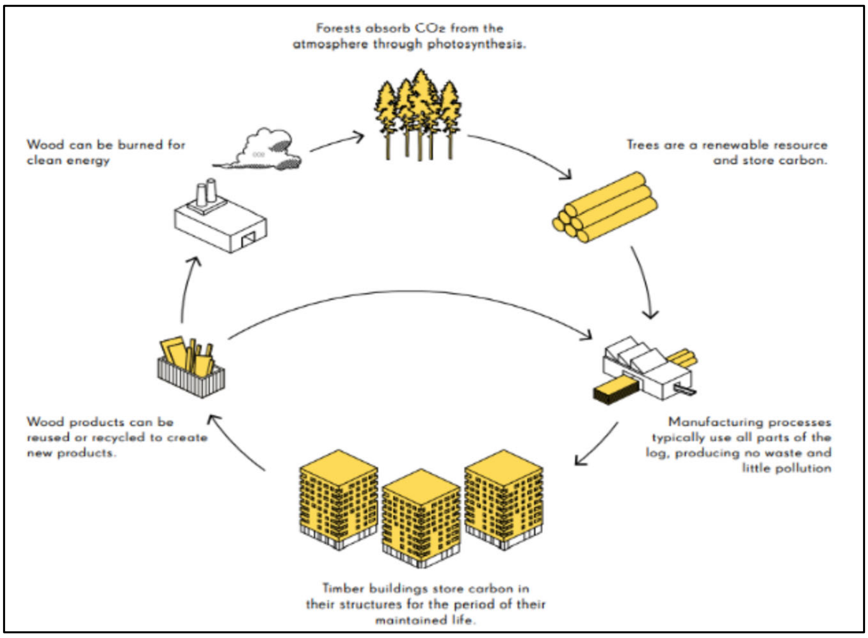

Figure 4.0. Cross Laminated Timber Life Cycle (Waugh; Thistleton 2018).

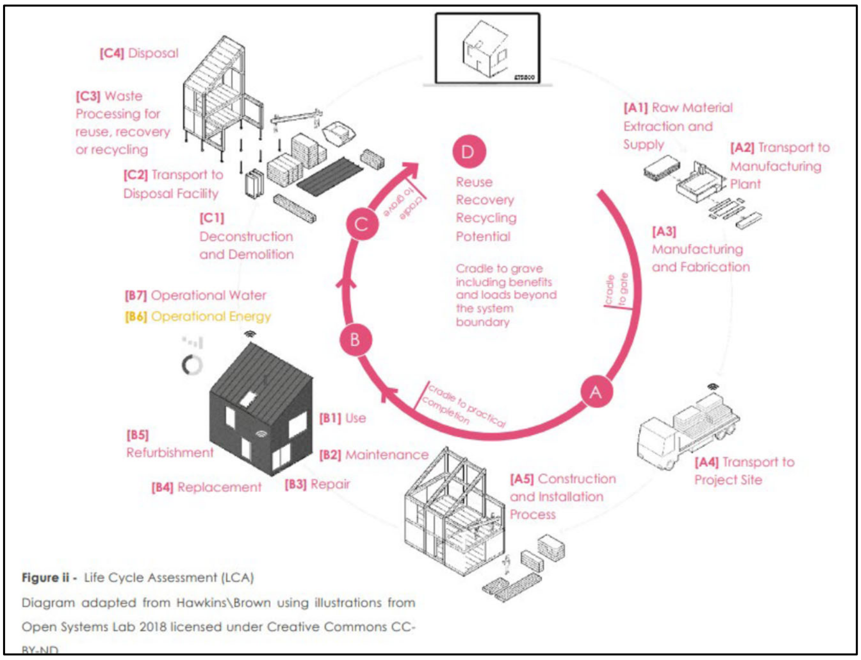

Figure 5.0. Circular Life Cycle (LETI 2018).

3.5.4 Alternative carbon measurement standards

The Measurement of embodied carbon through LCA or WLC is being widely considered across Europe, leading to many alternative developments to the existing assessment methods.

France have implemented requirements for new buildings and renovation through voluntary carbon-related labels. In 2020 the French Government implemented a carbon footprint calculation method which favours the use of wood and biogenic products more than the standard Life Cycle Analysis, described as Dynamic Life Cycle Assessment. Furthermore, they are due to release an energy and carbon regulation for new buildings with LCA based carbon thresholds in 2021. The Nordic Council of Ministers are initiating a plan for harmonization of building regulations concerning climate emissions (Nordic co-operation 2020). Finland is preparing new legislation to promote low-carbon building. The target is that life-cycle-based carbon footprint regulations are applicable by 2025. The Carbon Handprint concept in Finland aims to approach the carbon footprint from a positive standpoint, the climate benefit offered by a service or a product which people can use to reduce their own climate load. This encourages people to strive for a carbon handprint which is greater than their carbon footprint. Construction projects should strive to produce better than bad for the climate. Häkkinen (2021) concluded that the definition of a carbon handprint is equal to Stage [D] Benefits beyond the system boundary. Both terms should be used interchangeably dependent upon the context.

3.6. CLT IN THE UK & SCOTLAND

The pursuit of low carbon construction materials has produced a rise in timber usage in the UK built environment, yet the majority of timber used in these construction projects has been imported. UK Timber stock grown in, and ultimately used in the UK should be more sustainable long term and hopefully prove to be economically beneficial. If timber from Scottish resources is effectively produced through silvicultural practices, the resultant economic and environmental cost due to transportation would be much less comparative with current imported timber (Hairstans and Sanna). CLT panels produced from UK sourced Sitka Spruce have shown encouraging performance for strength and stiffness (Hairstans 2014). CLT can be manufactured with UK Sitka spruce, resulting in a structural performance similar to products manufactured and imported from central Europe (Hairstans 2014). Scotland Construction Innovation Centre are actively promoting the advantages of CLT with particular focus upon the economic potential CLT could be homegrown and mainstreamed in Scotland (MacDonald 2020). Prior research and innovation have tested and approved the potential for UK grown timber for successful CLT performance. It can be understood that there would be reduced embodied carbon from CLT transport should the product be mass manufactured in Scotland.

The most pioneering approach to a UK CLT facility comes from the financial institution Legal & General, they have established a subsidiary company and invested in a 51,000m2 offsite manufacturing facility for CLT and module assembly, based in Leeds (Wilson 2017). They are yet to produce any mass timber products for construction. In Scotland, the construction firm CCG has invested over £4m for a Lanarkshire based 'massive' timber production plant at 11,300m2 with a view to producing Cross Laminated Timber (Ridley-Ellis 2015). The Construction Scotland

Innovation Centre’s 3,250m2 factory in Hamilton currently contains the only CLT vacuum press in the UK. It is expected that a hydraulic press would be preferred for a mainstream CLT manufacturer. Innovate UK have provided them with funding to produce a viable business model for the use of Scottish Timber in Construction (CSIC 2020). Timber strength classes are categorized in a range from C16 to C24. The most common class for CLT is C24, but it is expected that if/when production facility(ies) start operating in the UK, C16 strength class is likely to be used as it is the most common strength class available in the UK.” Furthermore, recent European experience in CLT production forecast that £15-50 million would be required alongside a lead-in time of 3+ years before a UK CLT Production plant would be able to be fully operational (Wilson 2020). Large upfront costs to establish a CLT manufacturing base become an obstacle of progress towards a homegrown supply chain.

Existing research has provided irrefutable evidence that CLT is a competitive structural material which offers a sustainable new future for medium to high rise construction. CLT demonstrates beneficial performance qualities in addition to lower carbon emissions and sequestration. Transport carbon emissions would be reduced from using homegrown CLT, and there is sufficient research to conclude that UK grown timber would be suitable as CLT. In amidst a housing crisis and a timber import crisis, there is opportunity, albeit one with large upfront costs. UK CLT manufacture is seen as necessary and is viable, though there remains to be seen an embodied carbon comparison between import and homegrown to fully quantify what environmental advantages could be achieved from a homegrown CLT supply chain.

4. MATERIALS AND METHODS

The methodology of this study uses a case study approach to test The calculation method bears closely with RICS framework (2017) for embodied carbon testing.

4.1. CASE STUDY

Ellerslie Crescent is Scotland’s tallest CLT construction project. For details https://mastarchitects.co.uk/our-projects/ellerslie-crescent-yoker/ . The CLT was imported from Austria. The design aimed for maximum efficiency of the CLT as structural material. Three 7-storey blocks of accommodation, 42 flats in total, arranged around a stair core. The superstructure is 100% CLT including the lift shaft and the common areas. This construction project saw noticeable advantages in construction time, reduced material waste, inherent air tightness, excellent acoustic, and thermal properties and as an exemplar project of CLT in Scotland (MAST 2019), more details in table 1 & 2.

TABLE 1. Case Study Details

Client:	CCG (Scotland) Ltd / Sanctuary Homes	Timber Engineer:	Smith and Wallwork	Completion Date: January 2018
contract:	Design and Build	Structural Engineer:	Scott Bennet Associates	Project value: £4.5m
Main Contractor:	CCG (Scotland)	CLT Installer:	Eurban	
Architect:	MAST Architects	CLT Manufacturer:	Stora Enso	

TABLE 2. Case Study Quoted Values

CLT Volume: 1240 m3 (Stora Enso; CCG 2019).
Timber Volume: 1170 m3 - 94.3% timber and 5.7% glue (MAST 2019).
(Stated) Embodied CO2: 936,000 kg (CCG; MAST 2019).
(Stated) Sequestered Carbon: 757,000 kg (Stora Enso; CCG 2019).

According to MAST Architects, 936,000 kg of embodied CO2 is calculated, however, the EN:15978.2011 stages are not included in the calculation. Therefore, this figure of 936,000 kg CO2 embodied carbon (in 1240 m3 of CLT) without further detail to the formula or stages would be a hinderance to consider the stated value as accurate.

4.2. LIFE CYCLE STAGES

The life cycle stages as established in EN 15978, is shown in Figure 3.2, depicts a graphical representation of the life cycle stages.

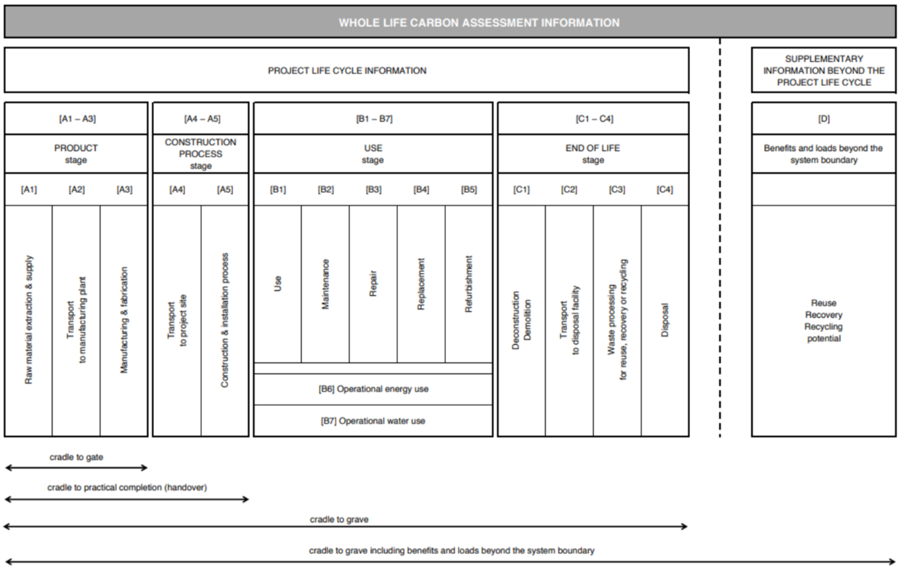

Figure 6.0. Embodied Carbon Over Life Cycle (RICS 2017).

The embodied carbon within the CLT superstructure can be obtained from the following methodology. The structure is in accordance with EN 15978. The intent is to produce a Life Cycle Assessment of the Embodied Carbon over Life Cycle, [A, B1-B5, C] based upon typical end of life scenarios. Furthermore, sequestered carbon will be emphasised for its significant carbon emission reduction which should not be neglected, for doing so would be to disregard all applicable embodied carbon information. The values used for the methodologies have been sourced using information readily available online by the Ellerslie Crescent Design Team, as well as any other applicable and readily available online sources.

The CLT used for Ellerslie Crescent is manufactured in Austria by Stora Enso. Stora Enso released an environmental product declaration (EPD) on the 11th of May 2020 for its CLT products. This EPD is in accordance with International Standard (ISO) 14025 and EN 15804 and based off of the International EPD System’s core product category rules for the assessment. The EPD has been independently verified by an external party. This study utilises the values stated within this EPD for Austrian CLT. This study also assumes some Scottish homegrown CLT would be equal or similar to values stated in this EPD. The EPD covers stages A, B1-B5, C & D covering the biogenic carbon sequestered in the product.

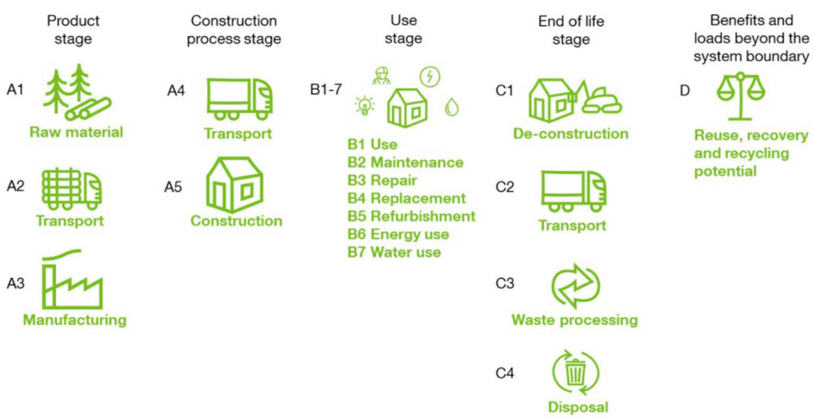

Figure 7.0. Embodied Carbon Over Life Cycle (Stora Enso 2020).

For this study, the data in this EPD is used by default, except in cases where more accurate information has been obtained.
[A] Product and Construction Stage
[A1] Extraction of Timber:

Stage A1 should regard the carbon emissions related to felling the Spruce trees and through extracting the glue for the CLT. The average GWP for Stage A1 is provided by the Stora Enso 2020 EPD for Austrian CLT. It is to be assumed that Scottish Timber extraction for CLT manufacture would have a similar carbon emission output.

[A2] Transport (From Forest to Manufacture)

Stage A2 concerns the carbon emissions associated with the transport of the timber from forest to factory and the glue from source to factory. Transport could be calculated should I be able to identify PEFC sustainable forests, the quantity of timber / deliveries and the fuel efficiency of the transports. The average GWP for Stage A2 is provided by the Stora Enso 2020 EPD for Austrian CLT. It is to be assumed that Scottish Timber and glue transportation from source to manufacture would have a similar carbon emission output.

[A3] Manufacture:
As per Stora Enso EPD 2017, The GWP is provided for stages A1-A3. The processes in stage A3 comprise:
Kiln Dried Sawn Timber > Strength Grading > Trimming > Finger Jointing > Planing > Edge Bonding > Surface Bonding > Laying > Pressing > Finishing > Machining > Surface Treatments. The average GWP for Stage A3 is provided by the Stora Enso 2020 EPD for Austrian CLT. It is to be assumed that Scottish Timber CLT manufacture will have a similar carbon emission output. A logical assumption would imply Austrian Manufacturers would be more energy efficient than a start-up Scottish Manufacturer, however there is no current way to quantify to what extent this may be.

[A4] Transportation to Site:
I will utilise a transportation method utilised within 100 CLT Projects UK (2018).
https://www.distancecalculator.net to calculate distance.
Number of deliveries x distance between manufacturer to site
d = Number of Deliveries (25 deliveries).
Z = Distance from Forest to manufacture I will determine: Number of deliveries x distance forest to site
Fuel Consumption = 0.44 L/km
(Department of the Environment, Food and Rural Affairs (DEFRA) 2007 qtd in 100 UK CLT Projects).
Carbon impact of fuel = 2.63kg CO_2 /L (DEFRA 2007).
$d \times (0.44(Z) \times 2.63))$

[A5] Construction: TBC
Ellerslie Crescent took 16 weeks to assemble (Stora Enso, 2018). The carbon emissions associated with the construction of Ellerslie Crescent should be equal for both Scottish and Austrian sourced CLT.
[B1-B5] Use Phase: Use, Maintenance, Repair, Refurbishment & Replacement
According to the same Stora Enso 2020 EPD; "Use stage: B1–B7: There are no environmental impacts expected in the use phase, and at least no harmful substances are released to air, water or ground during the use of the product". Therefore, as per the Stora Enso EPD of 2020 there is expected to be no emissions from these stages during the buildings use and occupation for sections B1 – B5 = 0.

Operational energy [B6-B7]
Operational Energy is not applicable for determining the embodied energy over life cycle. A Whole Life Carbon Assessment would include the Operational Energy.
[C1-C4] End of Life

The end-of-life scenarios varies in carbon emissions depending upon which occurs. Re-use, Recycling, Landfill, and Incineration. It is hoped that CLT structures are Re-used or recycled, retaining the biogenic carbon, and minimising resource usage. The four End of Life scenarios for this model (Stora Enso 2020) are as follows with details about what would occur for each stage:

Reused: CLT is reused in built form. C1: demolition of the building, C2: transportation to be sorted; 50 km, C3: preparation for reuse, C4: product for reuse, D: reuse of product, substituting virgin material.

Recycled: CLT chipping for recycling. C1: demolition of the building, C2: transportation to be sorted, 50 km, C3: preparation for recycling, C4: chipped for recycling, D: recovery of wood chips, substituting virgin material.

Incinerated: CLT incineration for energy recovery C1: demolition of the building, C2: transportation to be sorted, 50 km, C3: preparation, chipped for incineration, C4: chips to incineration (75% efficiency), D: substitution of natural gas in heat production.

Landfill: CLT is landfilled. C1: demolition of the building, C2: transportation to the sorting 50 km, C3: preparing for landfilling, C4: arrives and placed at landfill.

[D] Re-Use Recovery Recycling

[D] Sequestered Carbon

The carbon sequestered in timber or other bio-based materials (biogenic carbon) being repurposed should be considered in module [D], where applicable.

BS EN 16449 provides an equation for calculating the amount of carbon dioxide sequestered by a growing tree, carbon dioxide which is stored as biogenic carbon in wood products until the end of their life. Oven-dry timber contains approximately 50% carbon. Although this is only a measure of carbon in the timber, it can be translated into the equivalent amount of atmospheric CO2 using a calculation based on the atomic weights of carbon (12) and CO2 (44) (Forestry Scotland 2015). The biogenic carbon stored (sequestered) in timber elements must be calculated based on the formula provided in EN 16449:

The formula is:

$$P_{co2} = \frac{44}{12} \times cf \times \frac{P_{\omega} \times V_{\omega}}{1 + \frac{\omega}{100}} \quad (1)$$

Where:

PCO2 is the biogenic carbon (kg) oxidised as CO2 at the end of the timber component's service life, cf is the carbon fraction of the woody biomass when oven dry, ω is the moisture content of the product, ρ is the density (kg/m3) of woody biomass at that moisture content and V is the solid wood volume (m3) at that moisture content. In this study this formula is used to test one CLT Project.

5. FINDINGS

The exemplar building is intended to represent the superstructure of a potential new build medium-high rise residential but should not be taken as representative for all of the current building stock or all new buildings.

The main variables within the calculation occur within Stage [A] Product and Construction Stage. The two main variables, alongside logically assumed hypothetical variables are:

• Carbon sequestration

• Transport from manufacture to construction site

• (Potential variable) Density differences, harder timber to work is more energy intensive?

• (Potential variable) Energy inefficiency of a more inexperienced Scottish supply chain?

Considering only the Embodied Carbon to Practical Completion inclusive of sequestered carbon, Scottish CLT = -518 kg CO_2/m^3, Austria CLT = -588kg CO_2/m^3.
[A1] Scottish trees may require marginally more energy load to fell due to being more difficult to work. Otherwise, values are close to identical.
[A2] Transport between forest and manufacture is deemed to be similar across both methods. Scottish forest to the CCG manufacturing site should be similar in carbon emissions to the carbon emissions of an Austrian forest to the Austrian Stora Enso manufacturing site.
[A3] Stora Enso's EPD from 2020 has provided average values. Scottish timber is harder to work than Austrian Timber. Scottish timber has a lower density than Austrian Timber by approximately 70kg/m^3. It therefore may require greater energy load, though this dissertation has no way to quantity this statement. The density would the main variable.
Scottish timber, due to density, is harder to work and that means more energy required to machine, therefore, density = greater energy load.
Machine energy load should be similar across both models, for the same quantity of timber is required to be machined. A marginal variable is the estimated more efficient machines of Stora Enso against the newly created machines within the hypothetical Scottish manufacturer.
[A4] The transport from CCG manufacturing to Ellerslie Crescent is 1% of the emissions from Stora Enso Wood products Austria to Ellerslie Crescent. 25 deliveries would take place from either country.
[A5] The construction would produce similar-to-identical carbon emissions. Drilling holes into the Scottish timber may require marginally more energy.
[D] According to the EN 16449 biogenic carbon calculation, European timber absorbs more carbon than Scottish Sitka Spruce due to the higher density. Ellerslie Crescent constructed with Austrian CLT over Scottish CLT would store an additional 107 kg CO2/m3.

TABLE 3 Summary of calculation totals. Red highlights extreme highs, green highlights extreme lows. Demonstrates clear carbon emission reductions from re-use and from recycle.

Region of CLT Origin	Cradle to Grave / Embodied Carbon over Life Cycle (kg CO_2 / m^3)	[D] Benefits & loads beyond System Boundary. (kg CO_2 / m^3)	Whole Life Embodied Carbon (kg CO_2 / m^3)	End of Life Scenarios
Scottish	139.55	-706.20	-652	Re-Use
	145.20	-713.20	-654	Recycling
	934.55	-365.03	569	Incineration
	1153	-3.92	1149	Landfill
Austrian	175.60	-820.20	-637	Re-Use
	181.25	-827.20	-639	Recycling
	970.60970	-365.03	605	Incineration
	1185.60	-3.92	1185.68	Landfill

With estimated tolerances created using the difference in density, the four values are as follows:

TABLE 4 Scottish Homegrown CLT Manufacture estimated to produce 15-20kg CO2 per m3 less than Austrian CLT.

6. Scottish Timber: Cradle – Practical Completion	7. 136.97 kg CO_2 / m^3
8. Austrian Timber: Cradle – Practical Completion	9. 173.0 kg CO_2 / m^3

WITH Sequestration:

TABLE 5 Denser Austrian CLT sequesters more carbon and produces lower embodied energy when considered.

Scottish Timber: Cradle – Practical Completion	-518 kg CO_2 / m^3
Austrian Timber: Cradle – Practical Completion	-588.9 kg CO_2 / m^3

TABLE 6 Scottish Homegrown CLT Manufacture estimated to produce 15-20kg CO2 per m3 less than Austrian

Scottish Timber: Embodied Carbon over Life Cycle (re-use)	139 kg CO_2 / m^3
Austrian Timber: Embodied Carbon over Life Cycle (re-use)	175 kg CO_2 / m^3

TOTAL:

TABLE 7. Total Emissions from the structure of Ellerslie Crescent, sees a difference of 44700kg CO2.

Scottish Timber: Embodied Carbon over Life Cycle (re-use)	173048 kg CO_2
Austrian Timber: Embodied Carbon over Life Cycle (re-use)	217748 kg CO_2

Scottish CLT would produce equivalent to 21 average UK home's annual energy emissions, or the annual carbon footprint of 40 cars.

Austrian CLT would produce equivalent to 26.4 average UK home's annual energy emissions, or the annual carbon footprint of 47 cars.

A difference equivalent to annual emissions from 5.4 average UK home's or 7 cars.

6. Conclusion and Recommendations

The results of this embodied carbon calculation shall be used with care as the uncertainties on these results are high or as there is limited scope within available values, therefore the calculation has some degree of tolerance through multiple possible variables. The paper aimed to assess the carbon emission savings over the life cycle from a hypothetical Scottish CLT supply chain for a Scottish construction project, the likes of which could be used to demonstrate an environmental advantage to the establishment of a Scottish CLT supply chain. Specifically, an existing medium-high rise residential construction project was utilised to obtain accurate data regarding the Embodied Carbon over the Life Cycle. For this purpose, an Embodied Carbon Calculation was utilised as per the RICS 2017 Statement upon Embodied Carbon. The results displayed carbon emission savings of 7% based on the current RICS measurement strategies from a Scottish CLT supply chain. The results also found that CLT from Austria would store 15% more CO2 than Scottish CLT. Inclusive of sequestered CO2, this investigation would conclude that the use of Austrian timber offers more upside.

This study advocates that both Scottish and Austrian CLT produce net negative atmospheric carbon emissions, which is ultimately a good thing for the planet. CLT should be championed and encouraged as specified structural materials in the built environment.

5.1 RECOMMENDATIONS AND FURTHER RESEARCH

- This paper attempted to quantify the carbon emission savings achievable from using a Scottish CLT supply chain taken in isolation from economic variables. Further studies should explore the possible business case and economic standpoint of a potential Scottish CLT manufacturer.
- A business case could work in tandem with an environmental case to propose the extent of possible benefits that a Scottish CLT manufacturing base could provide to Scotland and the UK market.
- Further research could explore possible ways for Scottish Timber to absorb more carbon should we wish to further reduce the atmospheric carbon content from Scottish sources. Given the results of this study, it would be useful to explore ways in which Scottish timber may be able to absorb as much carbon as Austrian trees do.
- There is expected to be more demand for medium-high rise housing in urban areas of England than in Scotland, but it would be logical to assume that Scottish timber would be more commonly used and more widely available.

- There are two scopes for discussion: UK CLT manufacturing enhancement and the more regional Scottish CLT. There will be more demand for urban CLT development in England whilst Scotland maintains the forestry suitable for CLT. This paper focuses on Scotland, and it applies to the whole UK for CLT implementation, such as from the L&G Offsite Manufacturing base in Leeds.
- This paper concludes that architects and recent graduates should embrace CLT as a new pattern of architecture that can contribute significant characteristics aesthetically and spatially in addition to the carbon savings. Offsite construction provides the opportunity for precision engineering and efficient designs. Mass timber should be perceived as an opportunity and therefore be an exciting driver for future change.
- Further research into this area should investigate whether there is a significant amount of additional energy required to work Scottish timber into CLT relative to the energy load required of Austrian CLT, quantifying the amount of difference this would cause. Such investigation would aid with the increased accuracy of an embodied carbon comparison.

References

ABOSAOD, H., UNDERWOOD, J., ISIKDAG, U. AND BARONY, S. (2010) A classification system for representation of off-site manufacturing concepts through virtual prototyping, 9th International Detail Design in Architecture Conference

A.B. ROBERTSON, F.C. LAM, R.J. COLE. (2012). A comparative cradle-to-gate life cycle assessment of mid- rise office building construction alternatives: laminated timber or reinforced Concrete Buildings, 2 (3) (2012), pp. 245-270

ADAS Dundee (2021) INNOVATION IN TIMBER CONSTRUCTION - Lecture by Andrew Waugh from Waugh Thistleton [online video] Available at: https://www.youtube.com/watch?v=qrjHXBJpdEA

Architecture 2030, WHY THE BUILDING SECTOR? Architecture 2030, [Accessed 20.04.21] https://architecture2030.org/buildings_problem_why/

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

BSI, 2016. BS EN 350 Durability of wood and wood-based products. Testing and classification of the durability to biological agents of wood and wood-based materials . Online: BSI.

BUILD IN WOOD 2020 Why building in wood is the future - Project: Build-in-Wood . 2020. Directed by Build in Wood H2020. -: Build in Wood H2020.

BUIS, A., 2019. The atmosphere: Getting a handle on carbon dioxide . [online] USA: NASA. Available from: https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/ [Accessed 11/02 2021]

Construction Scotland Innovation Centre (2020) i-Con webinar: Mass Timber Alliance. [online video] Available at: https://www.youtube.com/watch?v=FXg6BUG-geM

Construction Scotland Innovation Centre Building a Sustainable Future: Timber Innovation [Interviews] .
2020. Directed by F. MacDonald, R. Hairstans and A. Chalmers. Online: Youtube.

CSIC, 2020. Scottish timber initiative plants seed of sustainability for UK construction. [online] Online: Available from: https://www.cs-ic.org/news/2020/november/23-november/scottish-timber-initiative-plants- seed-of-sustainability-for-uk-construction/ [Accessed 04.20 2021]

CRAWFORD, D., HAIRSTANS, R. & SMITH, R. E. (2013). Feasibility of cross-laminated timber production from UK Sitka Spruce. ISBN 1 85790 181 9

CAMBIASO AND PIETRASANTA, 2014 F. Cambiaso, M. Pietrasanta Innovative timber construction: sustainability and high-performance building skin IACSIT Int. J. Eng. Technol., 6 (1) (2014), pp. 47-54

CCG, 2019. Ellerslie road, Glasgow. Online: CCG Glasgow. Available from: http://c-c-g.co.uk/project/ellerslie- road-glasgow/ [Accessed 04.20 2021]

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

CHEN, C., PIEROBON, F. & GANGULY, I., 2019. Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix. Sustainability, 11(5), p.1278. Available at: http://dx.doi.org/10.3390/su11051278.

Construction (2013) WoodWorks Presentation. Retrieved 2014 from: http://www.woodworks.org/wp- content/uploads/2013-14-Q4-Introducing-CLT.pd

CUNNINGHAM, R., 2019. The Global Climate Emergency - Scotland's Response: Climate Change Secretary Roseanna Cunningham's statement. Edinburgh: The Scottish Government.

C.V. SILVA, J.M. BRANCO, P.B. LOURENÇO. (2013). A Project Contribution to the Development of Sustainable Multi-storey Timber Buildings Report Department of Civil Engineering. University of Minho, Guimarães, Portugal.

DAVIES, I. (2016). Sustainable construction timber: sourcing and specifying local timber. Forestry Commission Research Report Forestry Commission, Edinburgh. i-vi + 1-54 pp.

Dong et al., 2018 C. Dong, R. Boute, A. McKinnon, M. Verelst Investigating synchromodality from a supply chain perspective Transport. Res. Part D: Transport Environ., 61 (2018), pp. 42-57, 10.1016/j.trd. 2021.04.20

Ellerslie road [online] Online: Stora Enso. Available from: https://references.buildingsolutions.storaenso.com/en/projects/flats/uk/yoker-clyde [Accessed 04.20 2021]

EN 16449, 2014. Wood and wood-based products - Calculation of the biogenic carbon content of wood and conversion to carbon dioxide.

Fowler, 2014 FPInnovations CLT Handbook FPInnovations, Montreal, Canada (2013)

Frangi et al., 2009 A. Frangi, M. Fontana, E. Hugi, R. Joebstl Experimental analysis of cross-laminated timber panels in fire Fire Saf. J., 44 (2009), pp. 1078-1087

GARDINER, J., 2020. How is the CLT industry responding to the combustibles ban?. [online] Online: Building.co.uk. Available from: https://www.building.co.uk/focus/how-is-the-clt-industry-responding-to- the-combustibles-ban/5097651.article [Accessed 04.20 2021]

HÄKKINEN, T., 2020. Definition and methods for the carbon handprint of buildings. Danish Housing and Planning Authority.

Hairstans, R. (2014). Building offsite: an introduction. Edinburgh, Scotland: UK Commission for Employment and Skills (UKCES)

HAIRSTANS, R. and SANNA, F., 2017. A Scottish perspective on timber offsite construction. 1st ed. Online: Routledge.

Hairstans, R. (2019). Off-site and industrialised timber construction. (2nd). BMTRADA

Harvard GSD (2020) Mass Timber and the Scandinavian Effect [online video] Available at: https://www.youtube.com/watch?v=w2STKPvELD0

H. Fountain Wood that Reaches New Heights The New York Times (2012) Retrieved 2014 from: http://www.nytimes.com/2012/06/05/science/lofty-ambitions-for-cross-laminated-timber- panels.html?pagewanted=all&_r=0

Hristovski et al., 2012 V. Hristovski, B. Dujic, M. Stojmanovska, V. Mircevska Full-scale shaking- table tests of XLam panel systems and numerical verification: specimen 1 J. Struct. Eng., 139 (11) (2012), pp. 2010-2018

IBC, 2012 IECC, 2012 Jaksch et al., 2012 John et al., 2009 S. John, B. Nebel, N. Perez, A.H. Buchanan Environmental Impacts of Multi-storey Buildings Using Different Construction Materials Report Department of Civil and Natural Resources Engineering. University of Canterbury, Christchurch, New Zealand (2009)

Krug, D. and Miles, J. (2013) Offsite Construction; Sustainability Characteristics, BuildOffsite, www.buildoffsite.com

LEHMANN STEFFEN, 2012. "Sustainable Construction for Urban Infill Development Using Engineered Massive Wood Panel Systems," Sustainability, MDPI, Open Access Journal, vol. 4(10), pages 1-36, [Accessed 20.04.2021.]

MALIK, C., Construction cycle and waste. [online] Available from: https://ciaranmalik.org/portfolio/construction-cycle-and-waste/ [Accessed 20.04 2021]

Passivhaus: the route to zero carbon? London: Passivhaus Trust (2019)

LAGUARDA MALLO, M.F. and ESPINOZA, O., 2015. Awareness, perceptions and willingness to adopt Cross-Laminated Timber by the architecture community in the United States, Journal of Cleaner Production, Volume 94, pp. 198-199-210

LETI., 2018. LETI Embodied Carbon Primer.

LETI., 2019. LETI Climate Emergency Design Guide.

MAST, 2019. Ellerslie crescent, yoker. [online] Online: MAST Architects. Available from: https://mastarchitects.co.uk/our-projects/ellerslie-crescent-yoker/ [Accessed 04.20 2021]

MALCZYK, R., (2011) Cross-laminated timber in British Columbia Presentation. CLT Symposium. February 8–9 (2011)

H. SKOGSTAD, L. GULLBREKKEN, K. NORE (2011). Air leakages through cross laminated timber (CLT) constructions 9th Nordic Symposium on Building Physics (2011) Retrieved 2014 from: http://www.treteknisk.com/fullstory.aspx?m=1585&amid=14888

Michael Green, The Case for Tall Wood Buildings, Blurb, 2018

MONAHAN, J. and POWELL, J.C., 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Buildings, 43(1), pp. 179-188

Nordic co-operation, 2020. Declaration from the Nordic Ministerial meeting concerning buildings and construction on the 29th of May 2018, Stockholm. Available at: https://www.norden.org/en/declaration/declaration-nordic-ministerial-meeting-concerning-buildings-and- construction-29th-may [Accessed 4 20 2021].

POPOVSKI AND KARACABEYLI, (2012) M. Popovski, E. Karacabeyli Seismic behaviour of cross-laminated timber structures World, 15 (2012), p. 19

Popovski et al., 2010 M. Popovski, J. Schneider, M. Schweinsteiger Lateral load resistance of cross-laminated wood panels World Conference on Timber Engineering (2010), pp. 20-24

PLOWAS, W., 2019. COCIS Research into Mass Timber Systems – Cross Laminated Timber. Online: Centre for Offsite Construction + Innovative Structures.

RAMAGE, M.H. et al., 2017. The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews, 68, pp. 333-359

RICS, 2017. Whole life carbon assessment for the built environment. (1st Edition). London: Royal Institute of Chartered Surveyors (RICS).

RIDLEY-ELLIS, D., 2020. What's known about home grown? [online] Online: Centre for Wood Science and Technology. Available from: https://blogs.napier.ac.uk/cwst/clt-production-uk/ [Accessed 04.20 2021]

SMEDLEY, T., 2019. Could wooden buildings be a solution to climate change? [online] BBC Future. Available from: https://www.bbc.com/future/article/20190717-climate-change-wooden-architecture-concrete-global-warming [Accessed 14/12 2020]

R. Steiger, Gülzow, R. A. Validity of bending tests on strip-shaped specimens to derive bending strength and stiffness properties of cross-laminated solid timber (X-lam) The Future of Quality Control for Wood and Wood Products (2010), pp. 4-7

R. Steiger, Gulzow, R. A. Gsell, D. Non-destructive evaluation of elastic material properties of cross-laminated timber Conference COST E53. 29–30 October 2008, Delft, The Netherlands (2008), pp. 171-182 Retrieved 2013 from: http://www.coste53.net/downloads/Delft/Presentations/COSTE53-Conference_Delft_Steiger_Guelzow_Gsell.pdf

Scottish Government., 2020. Greenhouse gas emissions 2018: estimates. (Estimates of greenhouse gas emissions in Scotland for the years 1990 to 2018.). Scotland: gov.scot.

Scottish Government., 2019. Global climate emergency Scotland’s response climate change. [online] Online: gov.scot. Available from: https://www.gov.scot/publications/global-climate-emergency-scotlands- response-climate-change-secretary-roseanna-cunninghams-statement/#:~:text=Publication%20%2D%20Speech%2FstatementThe%20Global%20Climate %20Emergency%20%2D%20Scotland's%20Response%3A%20Climate,Change%20Secretary %20Roseanna%20Cunningham's%20statement&text=There%20is%20a%20global%20cli mate,The%20science%20is%20clear. [Accessed 04.20 2021]

STORA ENSO., 2020. Environmental Product Declaration CLT (Cross Laminated Timber). Online: The International EPD System.

STORA ENSO, 2019. Ellerslie road. [online] Online: Stora Enso. Available from: https://references.buildingsolutions.storaenso.com/en/projects/flats/uk/yoker-clyde [Accessed 04.20 2021]

Sutherland, N. qtd. in Riverside Sunderland: University Design Challenge (2021): RSUC VIDEO CALL 7 #RSUDC21 Desirable Homes & Communities [online video] Available at: https://www.youtube.com/channel/UClE63Emi7rx4M5dIngVy0ZA

S. Pei, M. Popovski, J.W. van de Lindt Seismic design of a multi-story cross laminated timber building based on component level testing World, 15 (2012), p. 19

Van de Kuilen et al., 2011 J.W.G. Van de Kuilen, A. Ceccotti, Z. Xia, M. HeVery tall wooden buildings with cross laminated timber Various, Cross-laminated timber, Design and Performance, Exova BM TRADA, 2017

WAUGH, A. and THISTLETON, A., 2018. 100 UK Projects CLT 1st ed. Canada: Waugh Thistleton Architects. https://www.cs-ic.org/news/2020/november/23-november/scottish-timber-initiative-plants-seed-of- sustainability-for-uk-construction/ STORA ENSO EPD 2020

WILSON, P., 2017. The Modern Timber House in the UK: New Paradigms and Technologies. 1st ed. Arcamedia Ltd.

WILSON, P., 2020. The butterfly effect on Scottish-grown timber. [online] Timber Design Initiatives. Available from: https://www.build-back-rural.com/post/the-butterfly-effect-on-scottish-grown-timber [Accessed 14/12 2020]

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

WoodWorks, 2013 WoodWorks Introducing Cross-laminated Timber. New Opportunities for Timber Wold GBC., 2018. Global Alliance for Buildings and Construction 2018 Global Status Report. Available Online. [Accessed 20/04/2021]