博士論文

The value of CLT: a multidimensional approach for building implementation inside Japanese context

（CLTの価値観　ー日本における建築物実現に関する多元的アプローチ）

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THE VALUE OF CLT: A MULTIDIMENSIONAL APPROACH FOR BUILDING IMPLEMENTATION INSIDE JAPANESE CONTEXT

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O VALOR DO CLT: UMA ABORDAGEM MULTIDIMENSIONAL PARA IMPLANTAÇÃO DE EDIFICAÇÕES NO CONTEXTO JAPONÊS

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Rafael Novais Passarelli
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Abstract

In Japan, high domestic demand for construction requires an equally large supply of building products, of which timber products have a significant share. Hence, local CLT producers see the Japanese building industry as an opportunity for further market expansion. However, despite efforts by local authorities and non-governmental associations, only a modest expansion of domestic CLT could be seen after almost five years of commercialisation. This thesis investigated what improvements are necessary to forward Japanese CLT implementation process from the manufacturing and utilisation points of view. The proposed measures aim to improve value generation possibilities of CLT-based building systems inside the local context by using a multidimensional approach. The approach includes the simultaneous assessment of dimensions from technical, function economic and environmental aspects of construction. The results showed the leading valuation strategy for CLT panels and buildings is focused on stressing technical and environmental subjects. However, at the time of this research, Japanese CLT is still not able to generate the same values. Firstly, the lower properties of the currently available Japanese Cedar supply limits the technical value of domestic CLT. Furthermore, finite forest resources in Japan cannot guarantee the provision of quality material in the long range. Second, building industry regulations and general public awareness about environmental issues are still in an initial stage of development in the country. Therefore, Japanese CLT cannot generate value from the environmental point of view either. Under these circumstances, the study concluded that to forward the implementation process of domestic CLT in Japan and improve its value generation possibilities three tasks need to be accomplished. 1) To reach a consensus and communicate the value generation possibilities of domestic CLT through the chain of production. 2) To increase social awareness about environmental issues and forward the idea of environmental impact evaluation into the building industry. 3) To promote the forestry sector to guarantee an abundant supply of quality material in the long range and increase the technical performance of domestic CLT panels and assemblies.

Key-words: forest resources, Cross Laminated Timber, multi-storey timber, mass timber buildings, Lifecycle Assessment.

Resumo

No Japão, alta demanda doméstica por construções requer uma oferta igualmente grande de materiais construtivos, dos quais os produtos madeireiros têm uma participação significativa. Tese contexto, produtores locais de CLT vêem no setor da construção como uma oportunidade para expansão da comercialização do produto. No entanto, apesar de esforços das autoridades locais e associações não governamentais, apenas uma modesta expansão do CLT no mercado doméstico pode ser vista após quase cinco anos de comercialização. Esta tese investigou quais as melhorias necessárias para avançar com o processo de implementação do CLT japonês dos pontos de vista da fabricação e da utilização. As medidas propostas visam melhorar as possibilidades de geração de valor dos sistemas de construção baseados em CLT dentro do contexto local, usando uma abordagem multidimensional. A abordagem inclui a avaliação simultânea de dimensões dos aspectos técnicos, funcionais econômicos e ambientais da construção. Os resultados mostraram que a estratégia principal de valorização para painéis e prédios da CLT, consisti em enfatizar qualidades técnicas e ambientais do material. No entanto, até o final deste trabalho, o CLT japonês não é capaz de gerar os mesmos valores. Primeiramente, as relativamente baixas propriedades físicas do cedro japonês disponível limitam o valor técnico do CLT doméstico. Além disso, os recursos florestais finitos no Japão não podem garantir o fornecimento de material de qualidade a longo prazo. Em segundo lugar, regulamentos no setor da construção e a conscientização pública em geral sobre questões ambientais no país encontram-se em uma fase inicial de desenvolvimento. Portanto, o CLT japonês também não pode gerar valor do ponto de vista ambiental. Nessas circunstâncias, o estudo concluiu que para avançar o processo de implementação do CLT doméstico no Japão e melhorar suas possibilidades de geração de valor, três tarefas precisam ser realizadas. 1) Definir um consenso e comunicar as possibilidades de geração de valor do CLT doméstico ao longo da cadeia de produção. 2) Aumentar a conscientização social sobre questões ambientais e promover a idéia de métodos de avaliação de impacto ambiental no setor de construção. 3) Promover o setor florestal para garantir fornecimento abundante de material de qualidade a longo prazo e aumentar as propriedades estáticas dos painéis e elementos construtivos constituídos por CLT doméstico.

Palavras-chave: recursos florestais, Cross Laminated Timber, construções multi-pavimentos em madeira, construções em CLT, Análise de ciclo de vida.

概要

現在、日本の建設需要は大きく、木造建築が大きなシェアを持つ建築生産には大きな供給体制が要求されている。そのため、CLTを生産している主体は、日本の建築市場がCLT生産に適していると考えている。しかし、各自治体やNGOなどの普及への活動はされているものの、日本での生産開始から5年ほど経過した現在でも、未だCLTの国内生産拡大は少量にすぎない。そこで、本研究では生産から使用までの観点から、日本のCLT普及にむけた課題を明らかにすることを目的とした。多元的なアプローチにより、CLT本来の価値を含んだCLT建築の価値観の拡大の可能性を提案する。多元的なアプローチとは、建設における技術、経済への効果、環境への配慮による研究を示す。結果として、CLTパネルと建築の評価の戦略は技術と環境の課題を強調することであることが明らかとなった。本研究を行っている現在、日本のCLTは先行している欧州などの他の国と同じ価値を生み出すことができていない。まず、国産材によるCLTの技術的価値はスギの生産量により限定されている。具体的に言えば、日本の森林資源では、長い期間、質の良い木材を供給し続けることは保証されていない。次に、環境問題に関する建築基準と公共の認識は成熟している社会と比較すると初期の段階である。それゆえに、日本のＣＬＴは環境の観点から見た価値を生成することが出来ていない。このような状況下であるため、結論として日本で今後行うべき実施プロセスを以下の3点に要約した。1.国産材CLTの価値を生成するため、生産プロセスにおいて、総意を決定すること。2.環境問題に対する一般的な意識を高め、建設業界における環境に対する影響に関する意見を増やしていくこと。3.林業セクターが質の良い材料を長い期間十分な供給を保証し、国産材CLTパネルとの技術的な性能の。

キーワード：森林資源、CLT、高層木造、マスティンバー、ライフサイクルアセスメント

Contents

0.0 Introduction

Abstract: this section introduces the theme and scope of this study. The section is divided into three chapters. The first one presents the background studies that provide the theoretical basis for the delimitation of the theme of this study. The second chapter describes the research strategy adopted to achieve the goal set by this study. Finally, the third chapter presents and defines main timber construction concepts used through the thesis.

0.1 Background studies

0.1.1 The concept of value in construction

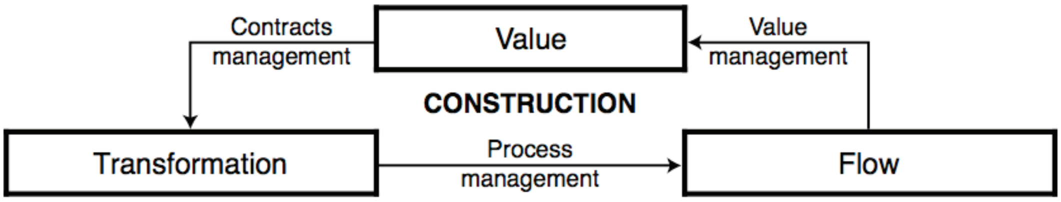
Based on "Lean construction" theory, production processes are defined as a transformation of inputs into outputs (Bertelsen and Koskela 2002). Hence, to perform the production task efficiently, improving the process as to reduce waste and minimise non-productive stages are important goals for most manufacturing industries. Likewise, the construction process can be added to the above definition, as it is also a transformation of inputs (building materials) to outputs (buildings). However, Bertelsen and Koskela (2004) warn of the fact construction presents its specific characteristics, such as the delivery of one-of-a-kind products by the cooperation of a multi-skilled team. For this reason, they suggest (Bertelsen and Koskela 2002) a holistic approach to understanding construction by three complementary concepts: "Transformation", "Flow" and "Value", defined as the TFV theory of production. The first concept (T) relates to the transformation of inputs into outputs; the second concept (F) is composed of transformation, inspection, moving and waiting; the last concept (V) accounts for the process where the value is created for the client. According to the authors of TFV Theory, its main contribution would consist of providing a method for modelling, designing, controlling and improving production from these three different points of view. Table 0.1.1 presents an overview of these concepts as well as their most important principles and practices.

Table 0.1.1 The TFV theory of production (Koskela 2000)

	Transformation view	**Flow view**	**Value generation view**
Conceptualisation of production	As a transformation of inputs into outputs	As a flow of material, composed of transformation, inspection, moving and waiting	As a process where value for the customer is created through fulfilment of his requirements
Main principle	Getting production realised efficiently	Elimination of waste (non-value-adding activities)	Elimination of value loss (achieved value in relation to best possible value)
Associated principles	Decompose the production task; Minimise the costs of all decomposed tasks	Compress lead time; Reduce variability; Simplify; Increase transparency Increase flexibility	Ensure that all requirements get captured; Ensure the flow-down of customer requirements; Take requirements for all deliverables into account; Ensure the capability of the production system Measure value
Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible	Taking care that customer requirements are met in the best possible manner

Bertelsen and Koskela (2002) then propose the organisation of TFV main concepts into a three-part management system, arranged in a loop and focusing mainly on generating value for the client (Figure 0.1.1). Furthermore, three different management types should derive from the interaction between each set of two concepts. First, "Contract Management" is the most formal type of management, mostly executed indoors and aiming to deal with all contract arrangements associated with construction. Second, "Process Management" is often executed at the work site, defined as a soft type of management that aims at a high efficiency production flow. Finally, "Value Management" assures the value required by the client is achieved at the end of the process by understanding and fulfilling their explicit and tacit needs (Bertelsen and Koskela 2002).

Figure 0.1.1. Three part management in construction (Bertelsen and Koskela 2002)



Nevertheless, looking at TFV theory's management model, one can observe that the "Value" of the building has to be generated by improving the transformation process and complying with the client's requirements. Despite its crucial role in the success of the production process, because "Value" can often be subject to a rather personal perception, even the creators of the TFV theory agree that among the three concepts, this is the most difficult one to approach (Bertelsen and Koskela 2004). Hence, addressing more precise attributes of what may constitute "Value" in the construction process has been a recurrent research theme inside the "Lean Construction" field.

Erikshammar et al. (2010) consider a consensus definition of the term "Value" among the different actors involved in the construction is necessary for a successful project. However, the ambiguity and vague characteristics of the concept act as an obstacle to that goal. The same author identifies five elements that contribute to comprehend and generate "Value" in construction: 1) waste reduction, that has been the focus in the past; 2) quality, understood as defect reduction and variation elimination or reduction; 3) price, defined as risk reduction that in turn, reduces costs thus achieving value; 4) function, understood as uncertainty reduction by providing a clear definition of the object's functionality; finally, 5) design, playing a central role in generating value, as the designer should be responsible for interpreting the client's needs into a set of concepts and plans (2010).

In contrast, because the concept of "value" has been mostly focused on answering the client's need, Pasquirre and Salvatierra-Garrido (2011) consider that it is overly associated with objective parameters such as waste reduction, cost, quality, time, function and etc. Contrary to this approach, the authors above suggest a wider notion for "Client" including the society in this definition, as the construction field usually has a large impact on the built environment that transcends the inner circle of the stakeholders. As a result, Pasquirre and Salvatierra-Garrido (2011) propose to divide the concept of "Value" into two different concepts: 1) "First Value", which is a wider concept that considers the impact of construction on society and thus should include a contribution to both environmental and social issues; 2) "Last Value", defined as the value delivered through the transformation activities, associated to market and utility values.

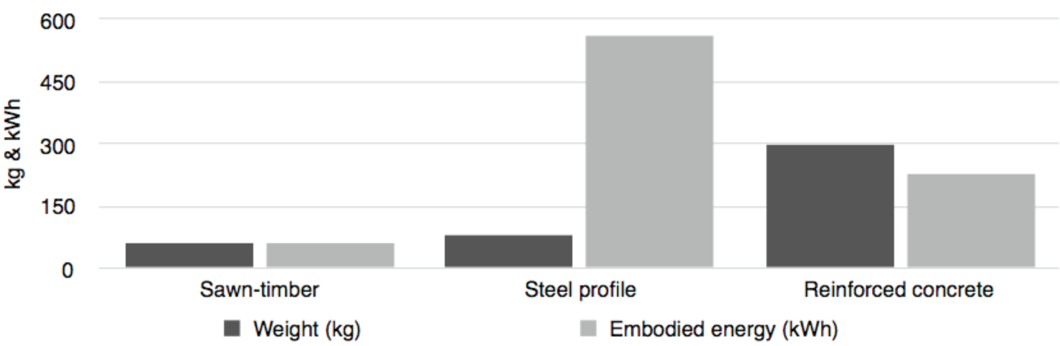
Novak (2012) also points out that value generation inside current construction industry is often restricted by the relationship between time, cost and quality, claiming for a paradigm shift from that view, owing to the potential contribution that the building stock can have to sustainability. However, the above author advises that just superimposing parameters commonly attributed to sustainable construction such as waste reduction and carbon footprint minimisation on traditional methods could instead result in cost increase (Novak 2012). Hence, in order to generate value in the new context of sustainability, without incurring in cost loss, Novak (2012) suggests a collaborative design approach, by including the owner along the process in a shared risk and reward mechanism. Miron et al. (2015) also support the importance of including the client in the design process, to maximise value generation, but also emphasise the need for all the actors involved in the construction to collaborate and seek a consensus on the concept of "Value". Likewise, Fernández-Sánchez and Rodíguez-López (2010) claim sustainable features of buildings have to be approached from environmental, social and economic views while keeping time, cost and quality at satisfactory levels. Additionally, the authors discuss that identifying and selecting relevant indicators to assess the sustainability of constructions is crucial to establish a solid methodological approach (Fernández-Sánchez and Rodríguez-López 2010).

0.1.2 Timber construction resurgence

0.1.2.1 WOOD FOR CLIMATE CHANGE MITIGATION

In the recent decades, the growing debate on environmental issues encouraged the use of more sustainable materials with low embodied energy and from renewable sources as a way to reduce the impacts of the construction industry on the environment. Consequently, studies comparing timber with other mineral-based materials regarding energy consumption and GHG emissions have been a field of increasing body of knowledge over the past two decades. An early study by Buchanan and Honey (1994) investigated different building types in New Zealand using concrete, steel or timber structures and concluded that even a moderate substitution from concrete and steel to timber could lead to significant CO_2 emissions reduction. Borjesson and Gustavsson (2000) found the primary energy and GHG emission shall be smaller for wood-framed buildings than for concrete-famed ones, as long as proper energy recovery of timber products is used for replacing fossil fuels during the waste management phase. Similarly, Gustavsson and Sathre (2006) found wood-framed buildings have smaller CO_2 emissions, owing to the effective ways of energy recovery in wood by-products. Furthermore, comparing the most common materials used in construction, Bribián et. all (2011) found wood-based building materials can have a neutral or negative CO_2 balance, depending on the end-of-life management and recommended the promotion of timber buildings instead of conventional concrete structures. Based on a comparison between concrete and wood-framed buildings regarding CO_2 emissions, Nässen et. al. (Nässén et al. 2012) endorse the promotion of the latter ones as a strategy to mitigate the current environmental impacts of the construction sector.

Figure 0.1.2. Comparison of the energy requirements for producing a 3 m high column carrying the same load. Source: Kolb, 2008.



In summary, timber construction has once more became an attractive possibility, for it usually requires fewer fossil fuels than other mineral-based building products during manufacturing stages. Also, wood by-products can have a high feedstock energy, meaning they can be used as biofuels. Finally, during its growth period, the photosynthesis process withdraws CO_2 (the main greenhouse gas) from the atmosphere, storing it in the derived timber products during their lifetime and releasing O_2 in exchange. It is estimated that nearly half of a tree's mass consists of carbon withdrawn from the atmosphere (Herzog et al. 2004). Even though this is not a permanent carbon reduction, the longer the lifetime of the timber product, more efficient it is as a countermeasure to global warming.

$$(1)\quad \text{Energy (sun)} + 6H_{2}0 + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$

$$(2)\quad \text{Energy (fire)} + C_6H_{12}O_6 + O_2 \rightarrow 6H_2O + 6CO_2$$

Figure 0.1.3. Timber products' carbon cycle equation: 1) photosynthesis; 2) Decay or fire. Source: FPL, 2010.

For this reason, with the aid of regulations or subsidies, spreading the use of timber in construction and increasing its share over conventional materials has become a goal pursued by many developed countries as a way to reduce CO_2 emissions. An example of successfully increasing the use of timber in construction is Austria, a country with a mineral-based building tradition (stone and masonry), in which timber construction accounted for no more than 25% of the building stock in 1998, but have reached 39% in 2008. That is an increase of 14% in just ten years (Teischinger 2011). Moreover, a study from Sathre and Gustavsson (2007) showed that timber products are not only less sensitive to carbon taxation regimes but that these could, in fact, increase the competitiveness of timber against concrete or steel, thus holding a significant potential to disseminate the use of timber in construction further.

0.1.2.2 CROSS LAMINATED TIMBER (CLT) OUTLINE

Concurrently with the environmental debate, timber construction technology has undergone substantial changes in the last two decades, with the development of new materials and a better understanding of timber properties. It is possible to say that one of the most symbolic products of this re-evaluation of timber construction is the material known as Cross Laminated Timber (CLT). CLT consists of a large mass timber panel made from perpendicular layers of timber lamellae, most of the times glued by their wider faces and pressed. Kiln dried, machine graded, softwood timber lamellae are utilised as the main raw material, with dimensions varying around 10 to 40 mm thick by 60 to 240 mm wide. Moreover, CLT panels are made from 3 to 9 layers of lamellae and up to 3 meters wide by 16 meters long, dimensions limited by transportation restrictions.

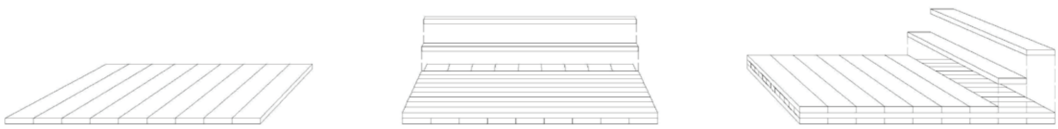


Figure 0.1.4. 3-layered CLT panel exploded perspective.

CLT was originally developed during the 1990s in the German speaking area formed by Austria, Switzerland and Germany. The original demand came from the Austrian Sawmill Association that at the time was facing problems selling smaller sectioned sawn-timber pieces from the outer part of the log, as a by-product of the log processing for more robust pieces. CLT was then idealised to make use of these and emerged from a joint research effort between university and industry. As an outcome of the research, CLT's earliest manufacturer, KLH was founded and a three storeys multi-family building employing CLT structure was erected at Alchach, Germany in 1995 (Brandner et al. 2016). The first standard for CLT would come three years later in 1998, and after that, an increasing number of buildings started to take shape in Europe and more recently in other parts of the world, such as North-America, Oceania and Asia. Due to the perception of CLT as a mass construction type material, such as masonry or concrete, it was first employed in residential construction. However, it was also utilised in a wide variety of public and commercial buildings, ranging from kindergartens to shopping centres. Nevertheless, CLT's biggest contribution to the expansion of timber construction arguably lies in the multi-storey multi-family housing application.

Some of the main features of CLT that led to a successful buildings implementation, especially in Europe and North America, include large planar and thickness dimensions that provide high load transfer capabilities in and out—of-plane, thus enabling it to be used as a stand-alone structural element; dimensional stability in case of moisture content variation due to cross-wise arrangement, thus attenuating some flaws related to the natural anisotropic behaviour of timber products; thermo-acoustic resistance properties, owing to the timber properties and mass timber construction; prefabrication possibilities due to highly automated manufacturing process which reduces construction time and increases building quality.

From the environmental point of view, due to the extremely fast market expansion of CLT, some studies started to include the assessment of timber building systems employing CLT elements in comparison to other timber or non-timber building systems (Robertson, Lam, and Cole 2012);(Takano et al. 2015). In one of the first LCA studies dealing with a non-residential mid-storey timber building using of CLT and Glued Laminated Timber (Glulam) elements, Robertson et. al. (2012) discovered that heavy timber building option has a greater embodied energy than the reinforced concrete equivalent version, as a result of the large volume of energy intensive CLT elements employed. However, the same authors claim the heavy timber option would result in lesser GWP than the reinforced

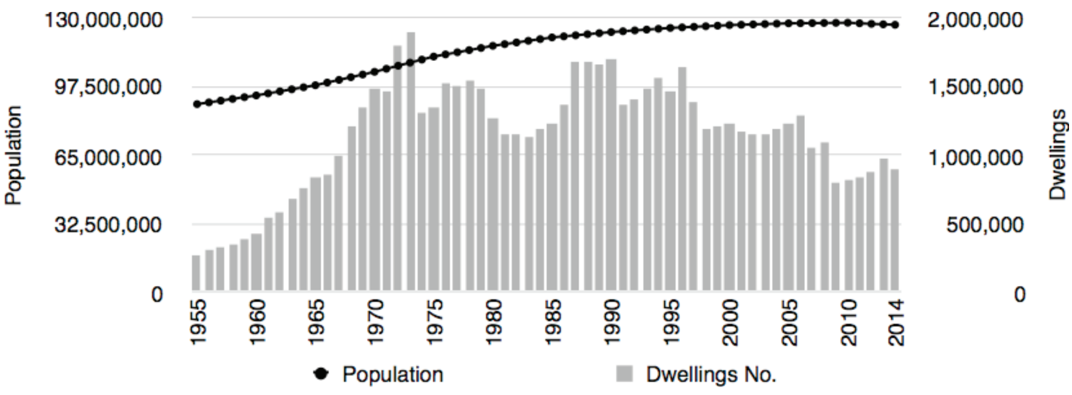
Figure 0.1.5. Murray-Groove Apartments, London.

concrete option, as a result of its predominant renewable-sourced energy consumed during the manufacture of CLT elements, together with the higher feedstock energy content present in the timber based materials. Takano et. al. (2015) also highlighted the higher primary energy demand for a hypothetical mass timber building in Finland when compared to other options that included reinforced concrete, steel, brick and lightweight timber, mainly due to CLT's energy intensive manufacturing phase. Nevertheless, the author highlighted the net energy benefits from the energy recovery of CLT elements during the end-of-life phase. On the other hand, analysing the lifecycle carbon implications of a multi-storey CLT building in comparison with two other timber building systems, namely Post & Beam and Light-frame modular system, Dodoo et. al (2014) showed CLT building has the smallest lifecycle carbon emission of all alternatives due to the lower use of concrete and steel in addition to a high energy recovery potential from the recycling of the panels.

0.1.2.3 JAPANESE HOUSING CONTEXT

New dwellings start in Japan have been increasing during the post-war period in a much faster pace than the population growth, reaching its historical maximum of 1,9 million units in 1973. After some ups and downs in the following decades, the housing industry achieved its second maximum dwellings start number in 1990, with 1.7 million units, just before Japanese bubble burst in 1991. After that, dwellings start have been decreasing, reaching its historical minimum value of 788 thousand units in 2009, after the global financial crisis in 2008. Meanwhile, Japanese population that was growing at a rather slow pace reached its maximum of 128 million in 2010 when it started to decline. In spite of Japan's depopulation phenomenon, new dwellings start have been increasing again from 2009 to 2013, showing once more figures close to 1 million units.

Figure 0.1.6. Population and number of dwellings in Japan by year. Source: retrieved from Statistics Bureau on April 2016 and compiled by the author.



According to Koo and Sasaki (2008), the high amount of new dwellings start seen in Japan can be explained by a conceptual difference regarding houses in other developed countries, such as the USA or UK and houses in Japan. In the former countries houses are a considered a "capital good", meaning that houses will not only keep their market value if properly maintained but will increase their prices with age under normal situation. On the other hand, in the latter one, houses are no different than a "consumer good", hence its market value will rapidly decrease, reaching zero after only 15 years. (Koo and Sasaki 2008)

The same authors also point out that due to the sharp rise in the land prices during the bubble period, less amount of money was left to be spent in the building itself, resulting in poorly constructed houses. The high prices of the terrain are considered one of the main reasons for the short average lifetime of Japanese houses, around 30 years (Koo and Sasaki 2008). Besides, the already known short lifespan and rapid market value depreciation of the houses would once more engender the construction of low-quality buildings, thus creating a wasteful vicious circle from the economic point of view, accounting for 4% waste of the national GDP yearly. (Koo and Sasaki 2008). Additionally, the performance of some vital functions, such as air-tightness, thermal and sound insulation are neglected, as there seems to make no sense investing money in a house that will be torn down after few decades.

Moreover, the somehow still contemporary Japanese belief, already expressed in 1330 in Yoshida Kenko's famous book - Tsurezuregusa - that a house should be designed for the summer worsens the situation. According to Sawachi (2013), even though housing and buildings account for about one-third of all annual energy consumption in Japan, the total average amount per household is relatively small if compared to other developed countries in Europe and the USA. Additionally, no more than 1/4 of all annual energy for heating spent in these same countries is spent in Japan (Sawachi 2013).

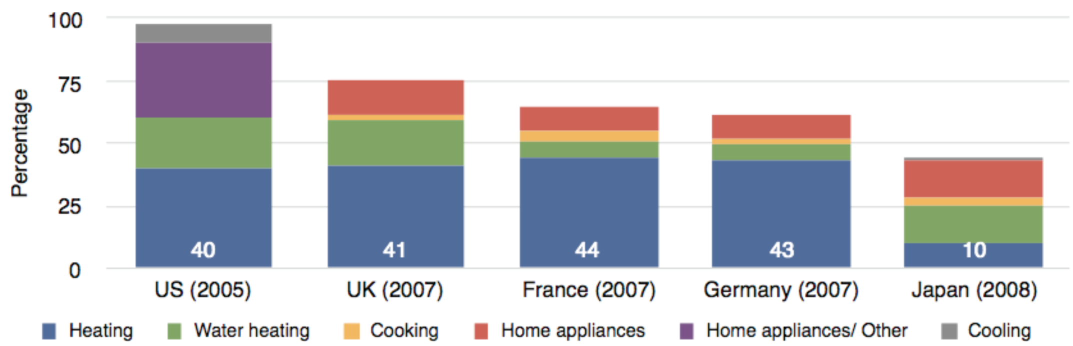
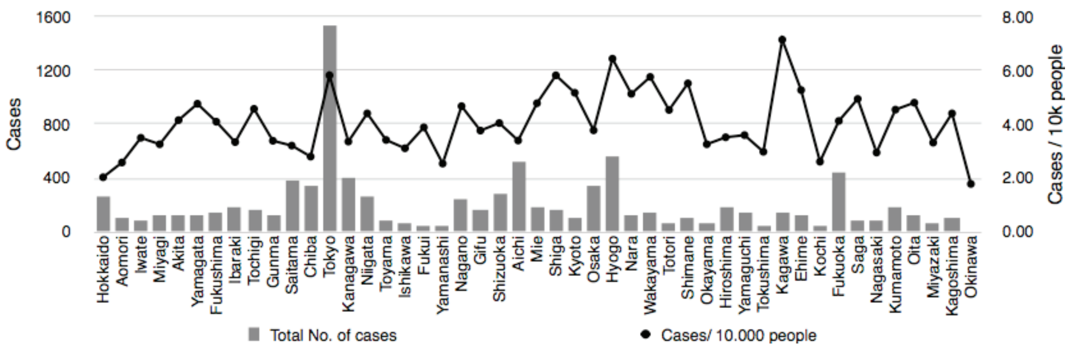


Figure 0.1.7. Household energy consumption by country (GJ). Source: (Sawachi 2013).

The lack of proper heating in the houses will have a significant influence on the health of the dwellers, especially the elderly ones, causing or worsening health problems such as sleep disorder, allergy, blood pressure and in extreme cases even leading to death. According to Tokyo Metropolitan Institute of Gerontology (Takahashi et al. 2014), during 2011 in Japan, more than 14 thousand deaths by cardiopulmonary arrest (CPA) were registered due to heat shock when getting out of the bath tube. The majority of the victims (over 9 thousand) were men and women over 65 years old, which is of particular concern in an ageing society like the Japanese one. Furthermore, looking at Figure 0.1.8, northern prefectures known for its harsh weather and lower average temperatures, such as Hokkaido or Aomori registered fewer cases of CPA than regions with more mild weather conditions, though still presenting a cold winter, such as Tokyo or Kagawa. The reason for this difference lies in the fact that in the former regions, common counter-measures against cold weather such as double-glazed window and wall insulation are more widespread than in the latter regions, owing to their higher self-awareness regarding climate conditions.

Figure 0.1.8. CPA cases in seniors by prefecture in Japan, 2011. Source: (Takahashi et al. 2014).



To break the vicious circle and give the people living in Japan a more affluent and comfortable lifestyle Koo and Sasaki (2008) would suggest promoting the construction of durable, good-quality houses, in order to increase the value of the housing stock and create a different domestic demand. Timber construction and specially CLT will benefit if such paradigm shift takes place in Japan, as it can provide durable and high-quality housing from the building physics point of view. Particularly, CLT's excelling airtightness values when compared to other timber systems, associated with timber low thermal conductivity properties, would have a direct impact on the thermal performance of the construction, thus creating an opportunity for increasing the value of the property and, most important, the life-quality of its dwellers.

However, research shows that depending on which building's feature is emphasised to potential buyers the effect might be the opposite. Yoshida and Sugiura (2015) have gathered a sample of over 40 thousand residential transactions inside Tokyo's 23 Wards in a period stretching from 2002 to 2009, aiming to comprehend how 4 different properties in green labeled buildings, namely long-life design, energy-efficient, resource-efficient and greenery, would affect the transaction price of the dwellings. The referred authors have found that overall green labelled buildings were traded with a discount price up to 10% lower than similar non-green labelled buildings. Nevertheless, the same authors point out that owing to the slower depreciation of value found in green labelled buildings, they were sold at a premium price after two years when compared to non-green buildings. Moreover, Yoshida and Sugiura (2015) found that long-life design features, which are likely to result in a longer economic life of the building, have a positive effect on the price. Conversely, energy-efficient and resource-efficient properties show a negative influence on prices, while greenery impact is insignificant. The explanation provided by the authors is that, because energy and resource-efficient features are associated with water recycling, eco-friendly materials and renewable energy, buyers anticipate the risk of an increased lifetime cost due to a presumably high demand for maintenance and replacement of those technologies (Yoshida and Sugiura 2015). On the other hand, Fuerst and Shimizu (2016) found a slightly different result by analysing a large residential transaction data from 2001 to 2011 in Tokyo's metropolitan area. The mentioned authors found a premium of 1% for the transaction prices of green labelled buildings when compared to non-green labelled ones and consider the small premium price may be because Tokyo labelling system is just a hypothetical environmental performance, thus making buyers reluctant to pay a higher price unless the announced performance is proven. That may be one of the reasons why after about two years of use, green labelled buildings are traded with a premium price as noted by Yoshida and Sugiura (2015).

Official efforts aiming to develop a national energy efficient policy that could have a positive impact on the quality of the built environment were made since 1979 when the "Energy Conservation Act" was enacted. Major revisions were performed in 1993, 1998, 2002, 2005, 2008 and 2013, expanding the scope of the energy conservation policies to all the main sectors in Japan, such as industrial, residential, commercial, and transportation. However, it was only after the 2005 review that the housing sector started to figure in the act. At that time, owners of residential buildings larger than 2000 m2 that were applying for a renovation permit or contractors planning new constructions of the same size were required to undertake energy conservation measures and submit a notification report.

After the 2008 revision, this requirement was extended to residential buildings from 300 m2 on, although as a recommendation only (Sawachi 2013) which attests the still limited influence of such area in the Japanese construction industry.

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0.2 Research Strategy

0.2.1 Goal

The high domestic demand for construction in Japan requires an equally large supply of building products, of which timber products have a significant share. In 2015, a total of 130 million m² of new constructions were built inside the Japanese archipelago. Furthermore, about 40% of this built floor area was defined as wooden buildings, predominantly aimed for residential use and concentrated near large urbanised areas in Tokyo and Osaka Prefectures (Ministry of Land, Infrastructure, Transport and Tourism 2016). Despite a gradual improvement in past years, the timber self-sufficiency rate in Japan is still relatively small, meaning that a great deal of domestic timber demand has to be supplied from imported products (Forestry Agency 2016). Nonetheless, both European and local CLT producers see the Japanese building industry as an opportunity for further market expansion. Hence, it is crucial to provide information demonstrating to what extent a local approach can be beneficial and, thus, contribute to more informed choices for the use of domestic CLT inside Japan instead of the imported version.

The thesis investigates how a multidimensional analysis can be used to understand and improve the value generation possibilities for CLT buildings implementation employing Japanese domestic CLT inside the local context from the manufacturing and utilisation points of view. The results aims to provide information to decision-makers, indicating primary issues to address through policies, product development, architectural design and education strategies. The study contributes to the field of domestic CLT construction: 1) Proposing an original method to evaluate the chain of production of Japanese CLT from the forest to the finished building. 2) Demonstrating the potential of combining various dimensions from different subjects to comprehend and facilitate the development of measures that can be beneficial considering the whole chain of production of CLT. 3) Proposing and detailing an action plan that, if followed by the leading actors from CLT chain of production, will be able to revert the threats and weaknesses identified throughout the research.

0.2.2 Method

The research scope includes the main stages of CLT production chain from the forest resources to the finished buildings to investigate Japanese CLT implementation process.

The reason for defining a comprehensive scope lies in the concept of "mass timber", frequently associated with CLT building elements and construction. In fact, mass timber panels category, in which CLT is arguably the most representative product, are the only wood-based engineered products that can simultaneously constitute structural and enclosure systems, without the addition of other products. Hence, mass timber systems show an intense use of timber per area unit of construction. Owing to the timber intensive characteristic of mass timber systems and therefore higher burden for the supply of raw material, it requires an in-depth examination of the forest situation. Furthermore, timber intensive characteristic acts as a multiplier of the employed mass timber panels main features, meaning both of its strengths and weaknesses are magnified when utilised. Therefore, it is crucial to evaluate how different options and rates in which CLT panels could be utilised in construction impacts final value generation possibilities and threats.

Next, taking into account Lean Construction literature reviewed during the "Background Studies" chapter, two primary production activities contained in the defined research scope were identified, and an analytical model for mass timber chain of production was proposed (Figure 0.2.1). The model allocated four main fields of study into two blocks, "Technology" to the left and "Execution" to the right. The first refers to "Timber resources" turning into "CLT panels" by the industrial manufacturing process, while the second presents a "Building demand" being translated into a "CLT building" by the act of designers and builders. The "Implementation" of a mass timber system is situated in between these two blocks and defined as a result of the interaction between them. A successful implementation consists essentially on maximising value generation in each side and communicating this value throughout each block, in other words, the whole chain of production. Furthermore, at the top are situated the general inputs for any timber building system (timber resources and building demand) and at the bottom are placed the specific outputs for CLT and mass timber systems (CLT manufacturing and CLT building). Finally, good communication should be established inside each knowledge block (vertical knowledge transfer), as well as between the two blocks (horizontal knowledge transfer) to ensure a successful implementation process. For instance, if the vertical transfer fails, the result may be an inefficient or even defective production process, thus unable to generate the "Value" foreseen. On the other hand, if the horizontal transfer fails, products created on the left block may be unable fulfil real needs, or current needs may not yet find products to satisfy the market request. Either way, the "Value" produced in one block will not be fully transferred to the next one, thus hindering the implementation possibilities.

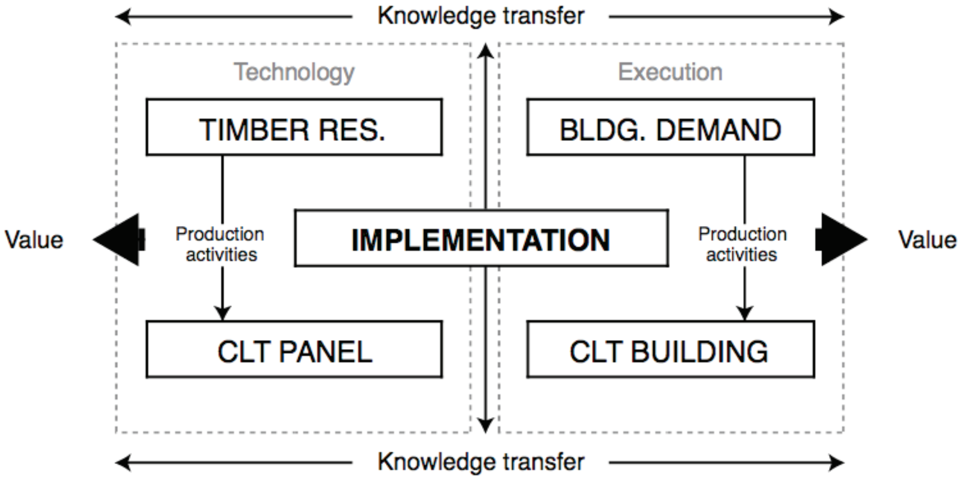

Figure 0.2.1. Analytical model for mass timber building system implementation.

This thesis focus on the output fields showed on the bottom of the analytical model, namely "CLT" manufacturing and "CLT buildings", as well as their value generation possibilities. Nevertheless, general fields at the top were briefly analysed by statical data aiming to provide a context in which the output fields are understood. In contrast, the specific fields at the bottom were analysed in depth by related literature, case studies, questionnaires and interviews. Next, value generation possibilities were hierarchically categorised into a set of "Concepts", "Subjects", "Dimensions" and "Indicators" (Figure 0.2.3) to evaluate the results of the analysed fields. First, "Direct Value" concept, meaning subjects directly related to the construction itself and including widely spread "Subjects", such as the technical, functional and economic performance of buildings, covering "Dimensions" such as statics, thermo-acoustics and costs. Second, "Indirect Value" concept, including subjects which have an impact that extends beyond the physical body of construction, such as environmental and social "Subjects", covering "Dimensions" like health and impact on the surroundings. Unlike the "Subjects" in the "Direct Value", "Indirect Value Subjects", are sometimes neglected, particularly in the present Japanese society. Furthermore, each of the "Value Dimensions" contains countless "Indicators" that are used for the assessment of the performance of parent "Dimensions" and "Subjects".

Each "Subject" represents vast areas of knowledge that contain "Dimensions" leading to several fields of expertise with their particular literature and know-how. As much as possible, this study tried to outline some of the main "Indicators" related with CLT manufacturing and construction and how they could impact value generation strategy inside Japanese context. Nevertheless, after a general understanding of some of the "Indicators" involved in the implementation of CLT and aiming to achieve scientifically

Figure 0.2.2. Value hierarchy: concepts, subjects, dimensions and indicators.

Concepts	**Subjects**	**Dimensions**	**Indicators**
Direct	Technical	Statics	bending, shear, tension, (…)
		Fire	combustibility, flammability, (…)
		Seismic	ductility, pushover, (…)
		(…)	
	Functional	Thermics	thermal conductivity, U-value, (…)
		Acoustics	air-borne sound, structure borne sound, (…)
		Durability	building services, condensation, (…)
		(…)	
	Economic	Material cost	raw-material, manufacturing, freight, (…)
		Construct. cost	labour wage, energy, machine, (…)
		Life-span cost	service energy, maintenance, etc.
		(…)	
Indirect	Environmental	Atmosphere	global warming potential, Ozone depletion, (…)
		Waste	hazardous, non-hazardous waste, (…)
		Resource use	primary energy, use of fresh water, (…)
		(…)	
	Social	Health/ Comfort	low toxicity, user satisfaction, (…)
		Safety	user and community security, (…)
		Surroundings	heritage, public utility, shade, noise, (…)
		(…)	

relevant results, this study focused on the analyses of two “Indicators”, one from the “Economic” and one from the “Environmental Subject”. The reason for this delimitation lies in the fact that “Technical” and “Functional Value Dimensions” can be adjusted through the material and the design solutions. However, according to the choice that is made, consequences to economic, environmental and social subjects will vary. For this reason, “Indicators” from four dimensions in “Technical” and “Functional Subjects” were assessed and fixed to obtain a comparable model for the evaluation of value generation possibilities. Then, the impacts of different manufacturing situations and design possibilities on “Indicators” from “Economic” and “Environmental Subjects” were analysed. It is worth note that “Dimensions” from “Social Subject” were no investigated in-depth, as they are strongly related to the forest resources and building demand fields, and thus situated out of the main scope of this thesis. However, they are also of crucial importance for the implementation of CLT and should be investigated in detail during a further study.

Sections	Chapters	Topics
0.0 Introduction	0.1 Background studies 0.2 Research strategy 0.3 Concepts and definitions	
1.0 CLT technology	1.1 Forest and timber industry	1.1.1 Austrian forest resources 1.1.2 Japanese forest resources 1.1.3 Forest resources comparison
	1.2 CLT manufacturing	1.2.1 Austrian CLT manufacturing 1.2.2 Japanese CLT manufacturing 1.2.3 CLT manufacturing
	1.3 Section 1 conclusions	
2.0 CLT bldg. execution	2.1 Building demand	2.1.1 Austrian building demand 2.1.2 Japanese building demand 2.1.3 Building demand comparison
	2.2 CLT utilisation	2.2.1 Austrian CLT utilisation 2.2.2 Japanese CLT utilisation 2.2.3 CLT utilisation comparison
	2.3 Section 2 conclusions	
3.0 CLT implementation	3.1 General recommendations	3.1.1 Forest resources 3.1.2 CLT manufacturing 3.1.3 Building demand 3.1.4 CLT building
	3.2 Action plan	3.2.1 Short-term 3.2.2 Mid-term 3.2.3 Long-term
	3.3 Multidimensional evaluation	3.3.1 Techonology view 3.3.2 Execution view
4.0 Conclusions	4.1 Discussion 4.2 The future of CLT 4.3 Topics for further research	

Figure 0.2.3. Research flow chart.

0.2.3 Research outline (plan)

The analytical model applied to divide the thesis into three main sections. The first two sections, "CLT technology" and "CLT buildings execution", cover the two knowledge blocks (left and right) production processes. Nevertheless, to understand the results of the Japanese context concerning the world-wide situation, similar studies were realised for Austrian CLT. The choice of Austria over other countries producing CLT was made considering its present stable situation and wealthy available information, owing to its original development of CLT and leading role from production and technology points of view. The third section, "CLT implementation", presents two multidimensional analyses, one from the technology block and one from the execution block, aiming to evaluate some of the possibilities for CLT panels and buildings' value generation in Japan following the results of the previous chapters. Figure 0.2.4 presents the research's flow chart, followed by a more detailed description of each section.

0.2.3.1 SECTION 1.0: CLT MANUFACTURING TECHNOLOGY

Description: This section is divided into two chapters. The first analyses forest resources and timber industry situation, while the second focus on CLT manufacturing process. Furthermore, both chapters present three topics, the first two analyse the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place.

Objective: to understand the relationship between Japanese forest resources and CLT manufacturing for panel's value generation.

0.2.3.2 SECTION 2.0: CLT BUILDINGS EXECUTION

Description: This section is divided into two chapters. The first analyse the building demand and the second focus on CLT utilisation in construction. Furthermore, both chapters present three topics, the first two investigate the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place.

Objective: to understand the relationship between building demand and CLT utilisation in Japan for CLT buildings' value generation.

0.2.3.3 SECTION 3.0: CLT BUILDINGS IMPLEMENTATION

Description: This section is divided into three chapters. The first discuss general recommendations for domestic CLT implementation in Japan based on the results from the previous chapters. The second chapter proposes an action plan towards a favourable scenario for CLT buildings in Japan, describing measures to be implemented over 50 years from the time. Finally, the third chapter presents two multidimensional analyses aiming to evaluate some of the possibilities to increase CLT value generation in Japan from both "Technology" and "Execution" points of view.

Objective: to propose and evaluate a favourable scenario for Japanese CLT value generation from a multidimensional point of view.

0.2.4 References

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0.3 Fundamental Concepts

0.3.1 General concepts

The general concepts regarding timber construction have been divided into four parts: load-bearing structure (load patterns and building components), building physics (thermal and acoustics), fire resistance and durability.

0.3.1.1 LOAD-BEARING STRUCTURE

Building components are defined as parts of the structure that cannot be further divided without impairing their function. Additionally, when properly joined, components will generate building elements, that will form a building system. According to Baurmann et al. (2014), components are grouped by their shape into four types: 1) point components that refer to the smallest components, such as nodes; 2) linear components that extend mainly in one direction, such as beams and girders; 3) area components that extend in two direction and can be divided into plates (force within the plane) or slabs (force perpendicular to the plane); 4) space components that occur in three dimensions and are used for instance in foundations.

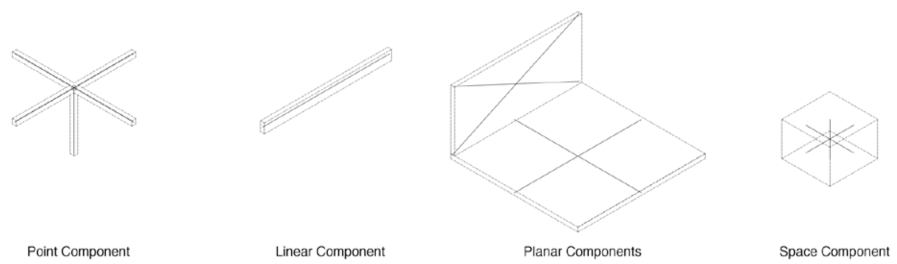
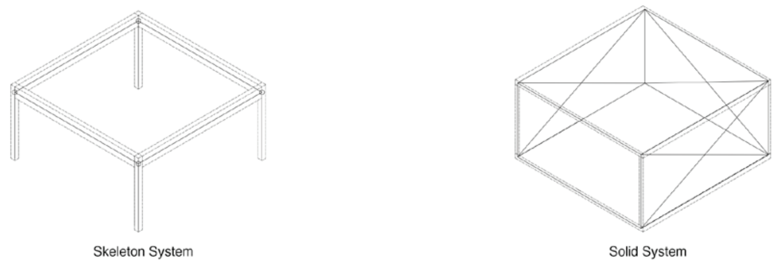


Figure 0.3.1. Types of building components.

Building components are subjected to compression, tension, bending, torsion and shearing forces, often seen in combination. Forces burdening building components and elements are called loads and occur in vertical, horizontal or diagonal directions. The loads can be divided into point, linear or area patterns and are transferred, depending on the building components, along one, two or three axes.

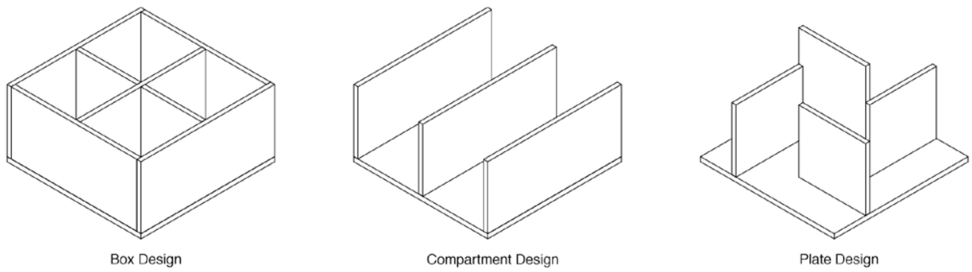
Hence, taking into account building components and loading patterns combinations, two primary building systems can be differentiated: Skeleton and Mass Construction. The former will mainly employ linear components in point load patterns, resulting in different elements for load-bearing and room enclosing functions. The latter employs area components in a linear load pattern, where the same components fulfil both load-bearing and room enclosing functions.

Figure 0.3.2. Types of building systems.



Furthermore, Mass Construction can be divided into 3 main design types: 1) box design, characterised as an enclosed cube-like volume surrounded by rooms; 2) compartment design, characterised by a sequence of transverse walls, enabling longitudinal faces to be as open as possible; 3) plate design, characterised by a free arrangement of angled or linear plates in different directions. (Baurmann et al. 2014)

Figure 0.3.3. Design types of Mass Construction.



0.3.1.2 BUILDING PHYSICS

Thermal insulation:
Materials with low thermal conductivity are utilised as thermal insulation in the building envelope; they can be inorganic based mineral materials, such as glass wool and rock wool or organic cellulose-based materials, such as wood fibreboards, cellulose flakes and mats (Kolb 2008). Usually, insulating materials are installed on roof, wall and suspended floor elements to reduce the building's heat transfer. The properties of the insulating materials define to what extent energy is transported through these elements between the inside and outside of the building, which is called the "U-value" of the element. Hence, the goal of thermal insulation would be to providing maximum comfort with minimum energy expenditure.

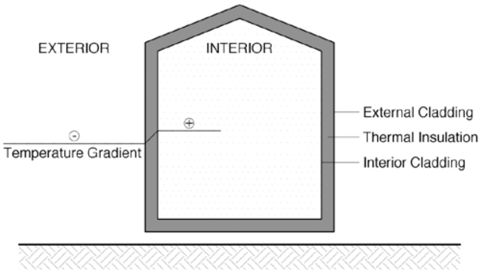


Figure 0.3.4. Diagram of building thermal insulation concept.

The so-called thermal (or cold) bridges happens when some non-insulating component such as a stud is placed continuously from the outside to the inside. Timber thermal bridges do not pose a problem from the surface condensation point of view (explained on the durability topic), but from an energy perspective, because the performance rises (and the u-value decreases), heat losses from thermal bridges become increasingly significant and the use of insulating material becomes necessary.

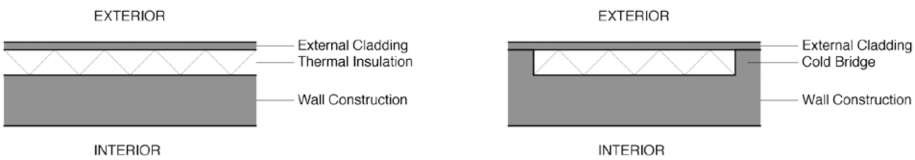
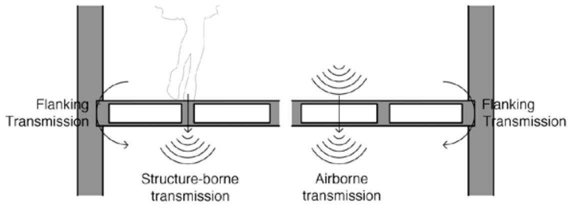


Figure 0.3.5. Building element without thermal bridges (left); building element with thermal bridges (right).

Sound insulation:
Acoustic insulation in a building is used to safeguard the building's occupants from unacceptable noise levels according to building codes or comfort parameters. It aims not only to shield the ingress of sound from external sources but also to prevent the transmission of noise from internal sources to different rooms or even to the exterior of construction. Two basic forms of sound transmission should be distinguished: airborne sound and structure-borne sound. The former refers to the sound that is transmitted through the air, while the latter relates to the sound transmitted through solid (or liquid) materials such as ribs or beams, that in turn induces vibrations in the air as well (Kolb 2008). Airborne sound insulation from single skin elements, such as the ones made from concrete or masonry depends mainly on area density, i.e., the heavier the element is, the better sound resistance value it can achieve. As timber elements cannot compete with concrete or masonry regarding mass, a multiple layer component is used to achieve the desired sound insulation. In this case, the element's insulating properties depends on each layer and the way components and elements are connected, so to avoid air breaches in which airborne sound could propagate, also known as acoustic bridges. Hence, for an

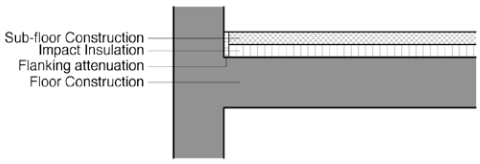
adequate acoustic performance, it is important to have sufficient airtightness properties in the connections between elements. On the other hand, to minimise structure-borne transmission, flexible impact insulation layer has to be added at some point to discontinue the sound transmission path.

Figure 0.3.6. Sound transmission concepts diagram: airborne, structure and flanking.



Finally, three basic sound insulation situations can be identified: 1) attenuation of noise from the external sources, achieved by insulating the building's envelope elements, such as external walls, roof and windows; 2) attenuation of noise propagation within the building, obtained by insulating the building's interior elements, such as party walls and suspended floors, assuring good detailing on the connections between different elements in order to minimise flanking transmission; 3) situations where sound insulation is necessary in order to reduce the noise level at the internal source, which is particularly important for applications such as schools, concert halls, gymnasiums, etc.

Figure 0.3.7. Details for attenuation of flanking transmission.



0.3.1.3 FIRE RESISTANCE

No building, whichever system or materials are utilised can be entirely exempt from the risk of fire. In fact, according to Kolb (2008), every building is subject to fire once every 100 years on average. Therefore, the role of fire safety is not only to avoid the fire itself, but also to prevent the building or parts of it from collapsing shortly in the event of a fire and prevent the spreading of fire to other areas of the same building or other buildings (compartmentation). Finally, it should also enable firefighting measures to be employed in the worst case scenario (Herzog et al. 2004). Three different fire safety purposes can be identified regarding building materials or components: load-bearing only, fire compartment only and materials or elements fulfilling both uses. Then, two distinct concepts in fire safety can be clarified: 'fire behaviour' and 'fire resistance'. The first defines whether the materials are incombustible or combustible and how flammable the last type of materials are (how easily they ignite and how much smoke they produce when burning). The second concept defines how long building components or constructions remain functional and fulfil their roles (load-bearing/ compartmentation) when exposed to fire.

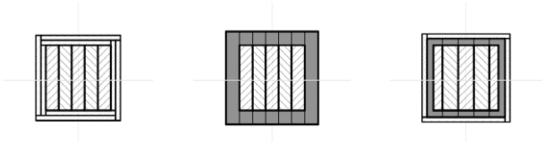


Figure 0.3.8. Fire resistance methods: encapsulation (left); charring (middle); both (right).

From the fire behaviour point of view, timber is a combustible material. Depending on the wood species and type of products its flammability varies from not readily flammable to highly flammable (Kolb 2008). However, the combustible property of timber can be used from the fire resistance point of view as well. As a timber piece burns, the outer layer chars and acts as a fire retardant layer, burning slowly and steadily, at a speed that can be estimated accurately. Hence, required fire resistance in timber constructions can be satisfied by two different methods. The first method is the encapsulation of the timber components by incombustible or virtually inflammable materials so that the inner timber structural components will not ignite in the case of a fire. The second method is called charring and consists on achieving the fire resistance requirements by using timber combustible nature. That means extra thickness would be added to the structural timber component so that there is no harm to the structural integrity of the construction during the estimated time. This extra thickness is sometimes referred as sacrifice wood layer. Additionally, both methods can be combined to achieve the required fire resistance.

0.3.1.4 DURABILITY:

Most of the durability issues concerning timber constructions are related to the moisture content of the load-bearing frame, as wood decays and rotten when exposed to higher moisture than recommended. Moisture can infiltrate timber building components in two different times: 1) before the building is completed, meaning during the manufacturing, transportation, storage and construction phases, or 2) after the building is completed, due to condensation, penetrations on the building envelope or leakage from the hydraulic installations.

In order to prevent infiltration of moisture through precipitation or diffusion on “1” adequate protection measures have to be taken during the manufacturing at the factory (controlling relative humidity inside the facilities), transport to the site, storing and installation of the elements (keeping the elements wrapped until they are ready to be installed, and protecting elements from precipitation during installation, especially on end grain of the pieces in which the capillary effect is considerably greater than the perpendicular to the grain direction). In “2”, the condensation of water in finished timber buildings can be prevented by the adequate detailing of the layers that compose the construction, carefully considering the movement of vapour water from inside to the outside. Best practices in cold climates dictate diffusion resistance should decrease from inside to outside to avoid condensation in the inner layers of construction (interstitial condensation). Particular attention has to be given at the place where timber meets steel components, for these are spots where surface condensation may happen. Finally, no building may be entirely exempt from hydraulic installations leakage. Therefore, it is important to be able to notice the leakage as earlier as possible before damage to the timber load-bearing frame becomes too severe. One option is to arrange the wet areas of the building around a reinforced concrete core, thus enabling the pipelines to run through a concealed zone (Ringhofer and Schickhofer 2013).

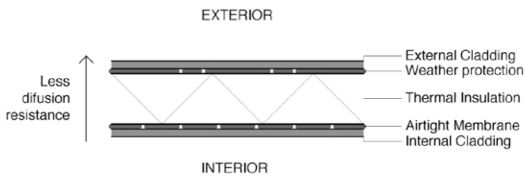


Figure 0.3.9. Diffusion resistance layer arrangement in external elements.

0.3.2 Timber building systems

According to (Kolb 2008), timber building systems can be categorised into six types. The first two types would include the traditional building systems of Log Construction and Timber Frame, while the remaining four types would cover the modern and contemporary building systems, namely Balloon/ Platform, Frame, Panel and Solid (Mass) Timber Construction. The first three types are briefly introduced bellow, whereas the following three types are explained in detail in the following topic.

0.3.2.1 TRADITIONAL AND MODERN SYSTEMS

Log Construction has a long tradition in many European countries, especially in the Nordic countries of Finland, Sweden, Norway and in Central Europe's mountain areas of Switzerland and Austria. Traditionally, logs are stacked on top of each other in a single layer wall that fulfils the functions of load-bearing, enclosure and cladding. However, because vertical loads are transferred downwards linearly in a perpendicular to the grain direction, a high amount of settling allowance has to be attributed to the construction.

Figure 0.3.10. Log-house construction at the Open-air Museum in Oslo, Norway.

Timber Frame is also a traditional building system, nevertheless utilising much less timber than log construction. According to (Kolb 2008) this type of construction has spread in regions where the availability of wood would not be enough for Log Construction. Shorter length squared elements of hardwood are employed as vertical studs, horizontal rails or plates and diagonal braces. The space in between the load-bearing frame is then filled with insulating material leaving the former exposed. From the structural point of view, the bottom plates connect the construction with the foundations, and on top of it timber studs are fixed, to direct the vertical loads downwards. Horizontal rails are placed in the openings, mainly providing a place to fix the frames for doors and windows but may sometimes also be used to prevent buckling of the studs. The diagonal braces provide stiffness to the construction, while the top plates hold the studs in position and act as a support for the suspended floors or roof structure. As there is a big amount of perpendicular to the grain loading, especially in the area of the plate, settling of the structure is to be expected.

Figure 0.3.11. Timber Frame construction in Hannover downtown, Germany.

Balloon/Platform construction was developed during the end of the 19th century in the dawn of new machine based means of production, such as the mass production of nails and first plywood boards (Kolb 2008). Balloon/Platform construction comprises closely spaced timber studs stiffened by planks or boards nailed to them. In Balloon Construction, wall studs extend for two or more storeys; on the other hand, in Platform Construction, each storey is built on top of the previous one which is then used as a working platform, hence the name of platform construction. In both cases, studs carry the vertical loads all the way downwards up to the foundations (balloon) or suspended floors (next platform). The load-bearing frame is braced by a sheeting layer (planks or boards) attached to the studs.

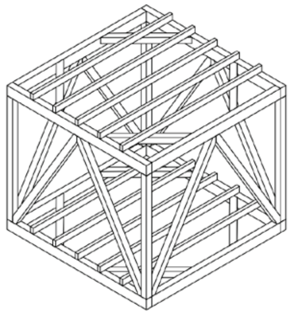
Figure 0.3.12. Balloon Frame Construction: Serpentine Pavilion 2011 by Peter Zumthor in London, England.

0.3.2.2 FRAME CONSTRUCTION

Structure

Frame construction is a concentrated point load system, that is to say, the function of load-bearing and room enclosing are entirely separated. Consequently, the load-bearing frame can be placed anywhere from the outside to the inside of the building envelope. However, depending on the position, problems regarding building physics, fire-safety and durability may occur (as explained bellow). Nevertheless, because walls do not carry the vertical loads, they can sometimes be installed independently, enabling the creation of large openings without necessarily weakening the load-bearing frame, thus providing more flexible layouts and overall freedom of design. The load-bearing frame is divided into a primary and secondary structure. The former is composed of columns, beams and braces, usually placed on a regular grid and responsible for carrying the main loads of the construction. The latter consists of the suspended floor components, made of floor joists or planar prefabricated elements. Glued laminated timber (class GL24h) is preferred for the primary structure, but sawn timber (class C24) can also be utilised if available on the required dimensions. Timber girders, wood-based sheathing or steel can be used for the stiffening of the structure on both horizontal (floors and roof) and vertical (walls) directions. (Kolb 2008)

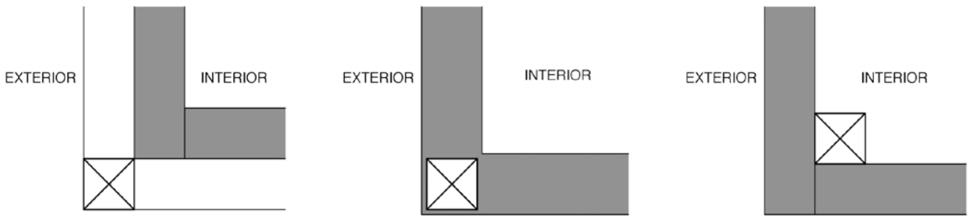
Figure 0.3.13. Basic diagram of Frame Construction.



Building physics

Because of the clear distinction between the load-bearing frame and building envelope or party walls, there are three different possibilities of structural arrangement. The load-bearing frame can be placed 1) on the outside, 2) integrated with, or 3) on the inside of the building envelope. The first option is the worst possible arrangement as the load-bearing structure would not only act as a thermal bridge but would also penetrate the building envelope all the way from the outside of the construction. In these joints, complete sealing would be a challenge owing timber's swell-shrinking behaviour, thus posing a threat to the building's airtightness and overall physical performance. If the second option is chosen, the load-bearing frame would still penetrate the building envelope, therefore thermal bridges and air leakage could happen, though probably in a smaller amount than the first option. The last option is the most advantageous one from the building physics point of view, for there would be no thermal bridges and the building envelope could run along the construction seamlessly (Kolb 2008).

Figure 0.3.14. The positioning of the load-bearing frame and building envelope in Frame Construction.



Sound insulation properties in Frame Construction depends on other material layer's arrangement. Conventional solutions to achieve adequate sound insulation include at least a layer of sound insulation material and impact sound insulation. Nevertheless, because Frame Construction slabs have a little mass per area unit, it is not unusual to use a concrete or cement screed layer to achieve better airborne sound insulation. Also, if more insulation is necessary, the bottom of the slab construction can be covered by sheathing components fixed by flexible connectors.

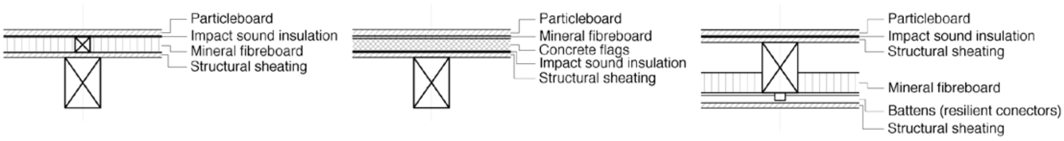


Figure 0.3.15. Suspended floor elements in Frame Construction.

Fire resistance

If the load-bearing frame is placed in between the building envelope and party wall elements, the fire resistance of the building would depend on the lining material properties (encapsulation method). If the load-bearing frame is exposed, i.e., not in the same plane as the building envelope and party wall elements, it would also be possible to cover the structure components with incombustible materials to achieve the desired fire resistance. However, owing to the common idea of exposing the timber load-bearing frame as an architectural feature an extra thickness can be added to the exposed faces of the load-bearing frame, (charring method).

Durability

If the load-bearing frame is placed on the external face of the building envelope, protection of the timber load-bearing frame against the weather should be given priority. However, because providing adequate permanent protection in such a disadvantageous situation is difficult, this would be the worst case concerning the durability of the load-bearing frame. If the load-bearing frame is placed either in between or on the internal face of the building envelope, it would be protected from the bigger weather changes outside. Nevertheless, the last option is preferred as the load-bearing frame is placed entirely on the warm side of the construction.

0.3.2.3 PANEL CONSTRUCTION

Structure

Panel Construction employs closely spaced slender studs covered by a sheathing layer. The former is responsible for carrying the vertical loads from roofs or suspended floors downwards to the foundations, whereas the later provides horizontal stiffness and sometimes fulfil the roles of weather protection layer and airtight membrane. The studs are fixed on a bottom plate on top of each floor or directly on the foundation of the construction, and the sheathing is placed on the inside face of the wall due to advantages for building physics.

Figure 0.3.16. Basic diagram of Panel Construction.

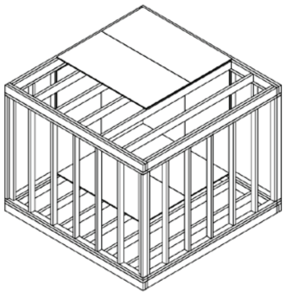


Figure 0.3.17. Factory of Panel Construction wall elements in Lower Austria, Austria.

However, Panel Construction differs from Platform Construction regarding the degree of pre-fabrication: all building elements such as walls, floors and roof are expected to be manufactured in the factory. Therefore, inside a controlled environment that offers optimum working conditions, resulting in higher quality elements, due to the greater degree of mechanisation and automation (Herzog et al. 2004). The completed elements are transported to the construction site where, with the aid of a mechanical crane, large elements can be easily installed, assembling the building in less time than a conventional Platform Construction. Panel Construction's main components are load-bearing timber studs or ribs (class C24), with a moisture content of 12% (± 2%), sheathing components such as 3-layered plywood, veneer plywood, OSB, fibreboard, etc. and thermal insulation materials such as mineral or glass wool, cellulose fibre, etc. In general, the load-bearing frame is completely concealed between the internal lining and the external cladding material (Kolb 2008). As seen in Platform Construction, due to the perpendicular to the grain loading in every floor at the bottom and top plates, some amount of settling allowances have to be attributed to the construction.

Building physics

Wall construction will vary depending on the desired building performance. The choice is made taking into account the use of the building, thermal insulation and energy requirements. If more insulation is necessary, studs can be made deeper to provide more space for insulation. Also, a second continuous layer of insulation can be added continuously to the external face of the wall construction, even at the junctions between floors and corners, which in turn would reduce to a minimum the thermal bridges. In some cases when rigid insulation such as wood fibre is used, the external cladding can be directly fixed to it without the need to install battens.

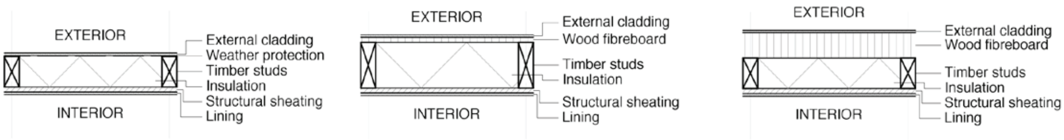


Figure 0.3.18. Wall elements in Panel Construction.

Sound insulation properties in Panel Construction depends on the arrangement of the other materials. Standard solutions to ensure adequate sound insulation include at least a layer of sound insulation material and impact sound insulation. Nevertheless, because Panel Construction slabs have little area density, it is not unusual to use a concrete or cement screed layer to achieve higher airborne sound insulation. When more insulation is necessary, the bottom lining can be fixed by flexible connectors.

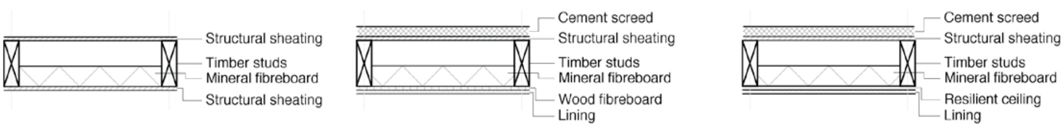


Figure 0.3.19. Suspended floor elements in Panel construction.

Fire resistance

As the components are very slender (usually ranging from about 45 to 60 mm thick) the concept of “charring” cannot be utilised. On the other hand, as the load-bearing frame is concealed between the lining, the standard practice would be covering it with fire resistance materials such as gypsum board (encapsulation method).

Durability

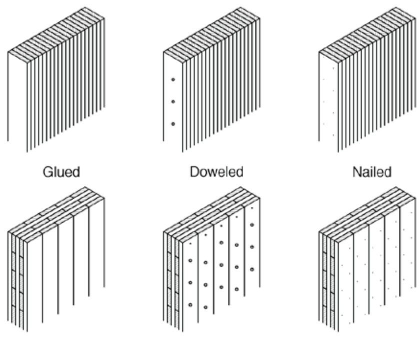
As mentioned in the durability topic, in cold climates diffusion resistance should decrease from inside to outside to avoid interstitial condensation. In Panel construction, that means the airtight membrane should be placed on the warm side of the thermal insulation and the weather protection layer on the cold side. Ideally, the building should be completely airtight when all ventilation openings or mechanical ventilation systems are closed or turned off because leaks in the envelope could lead to moisture penetration that in turn could result in damage to the load-bearing frame due to decay or rot and also decrease thermo-acoustic insulation.

0.3.2.4 MASS TIMBER CONSTRUCTION

Structure

Mass Timber Construction employs two-dimensional components loaded as plate or slab elements, fulfilling both the role of the load-bearing frame and room enclosing walls. Hence, it is a linear load-bearing system. However, frequently the elements of Mass Timber Construction have no voids. Roughly, mass timber elements can be divided into two distinct categories: single direction laminated timber and cross wisely laminated timber. Each category can be divided into three types, according to to how the layers are bonded together (glued, dowelled or nailed). Additionally, glued cross laminated timber can be further divided into edge + face glued or only face glued CLT.

Figure 0.3.20. Different types of mass timber panels.



CLT elements have an advantage over SLT ones regarding dimensional stability and loading capacities in both directions, owing to the cross-layer arrangement. Nevertheless, a distinction should be made between primary and secondary load direction in CLT, according to the layer arrangement. Hence, dimensional changes due to moisture induced deformation, especially in the tangential direction, have to taken into account when designing with SLT using expansion/contraction joints at the connections between elements. On the other hand, though SLT can carry loads mainly in one direction, they are usually more efficient in this direction than CLT.

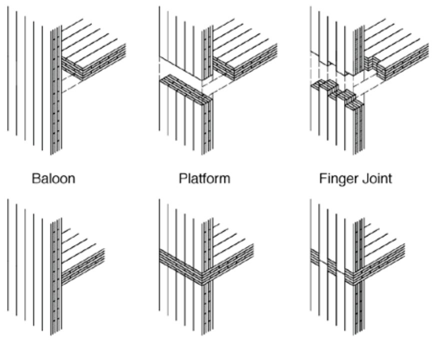


Figure 0.3.21. Connection of CLT Construction wall-slab elements: balloon (left); platform (middle); finger-joint (right).

CLT components are produced in large dimension panels from which smaller building elements are cut out, usually by computer controlled cutting machines, thus freeing Mass Timber Construction from a rigid grid or module. The finished elements are then transported to the site and fixed to its assigned place. As in Platform Construction, CLT buildings are usually assembled laying one storey on top of the previous one. However, this arrangement requires the settling of the structure to be taken into account, especially in mid-to-high-rise building. Continuous wall arrangement, such as in Balloon Frame is also possible but mostly utilised for shorter buildings. A second option would be the execution of finger joints on the edges of the wall and floor panels, reducing about 30% of the perpendicular to the grain loading.

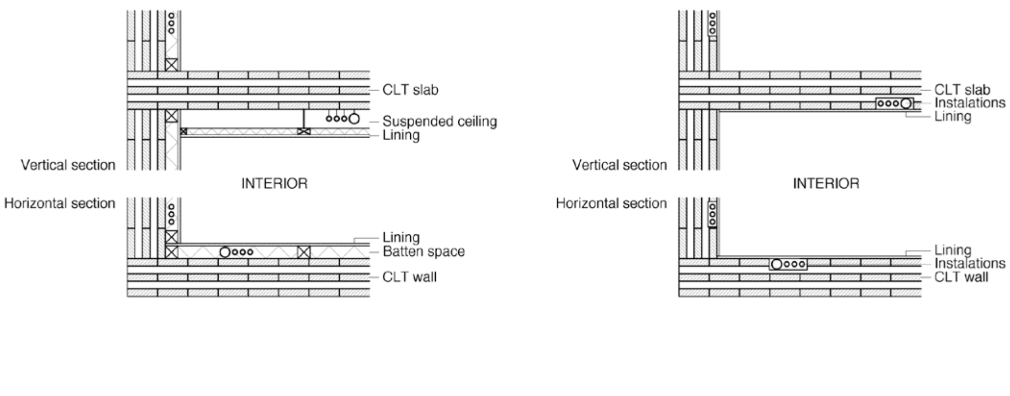


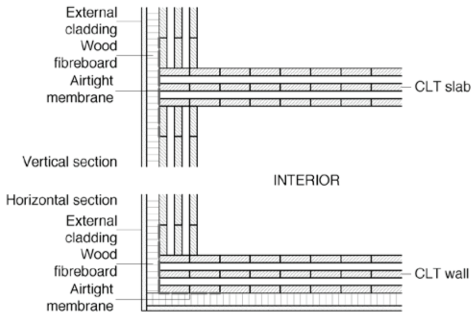
Figure 0.3.22. Diagram of CLT construction installations: extra layer (left); embedded (right).

Because there are no voids in the elements, installations have to be placed in between an additional layer of battens, fixed on the internal face of the mass timber element or inside cut-out grooves on the inner face of the panel.

Building physics

Mass timber construction, especially when employing glued CLT elements, may present slightly fewer layers than the previous systems, owing to the fact CLT panels can also fulfil the roles of weather protection and airtight membrane. The former is justified by the moisture buffering behaviour of timber, which absorbs or releases the moisture from the surrounding environment trying to reach an equilibrium point (moisture buffering). The latter requires proper detailing of connections between elements with additional pieces of an air-tight membrane for ideal sealing of the joints between different elements, to fill the small gaps between the elements (Boye Skogstad, Gullbrekken, and Nore 2011).

Figure 0.3.23. Sealing detail of CLT construction wall-slab joints.



Also, as there is no void inside mass timber elements, thermal insulation is usually placed on the external face of walls, thus eliminating thermal bridges.

Figure 0.3.24. Wall elements in CLT construction.

Mass Timber Construction has the biggest ratio of mass per area unit among the timber building systems, and as a consequence, it also has the best airborne sound insulations properties. However, it is not enough to assure acceptable noise levels for most uses alone. Hence, standard solutions to achieve adequate sound insulation include at least a layer of sound insulation material and impact sound insulation. If more sound insulation is necessary, a concrete topping can be added, and a bottom lining can be fixed by flexible connectors.

Figure 0.3.25. Suspended floor elements in CLT construction.

Fire resistance

As mentioned above, because the installations usually require an additional layer over the internal face of the Mass timber elements, encapsulation concept is utilised mainly as a fire resistance method. However, if the internal surface of the element is left exposed, charring method can also be utilised.

Durability

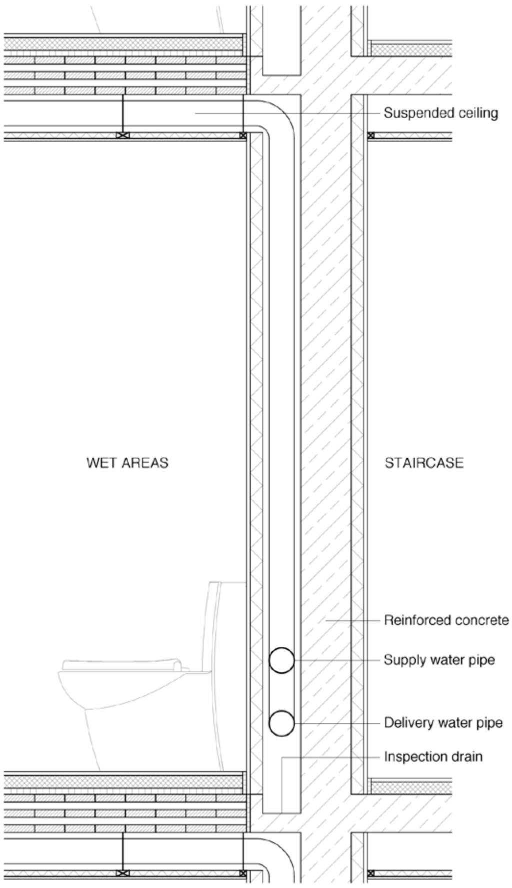


Figure 0.3.26. Hydraulic shaft detailing for CLT Construction

As Mass Timber Construction elements are capable of absorbing large quantities of water, if the elements get wet they would need an extended period to get dry. Therefore, avoiding the infiltration of moisture has to be a priority during manufacturing, transportation and installation of the elements, taking adequate protection measures (as mentioned on the durability topic). Additionally, when using mass timber elements, particular attention has to be given to the placement of hydraulic installations. If there is a leakage in water pipes are running close to the timber elements, this might lead to uncontrollable moisture infiltration in the load-bearing structure that may only be noticed in advanced stages of damage, due to the nature of mass timber construction concealed walls (Ringhofer and Schickhofer 2013). In order to prevent the infiltration of moisture because of leakage and increase the durability of the load-bearing frame, wet rooms can be designed around a reinforced concrete core, thus enabling the pipes to run between the transition zone (Ringhofer and Schickhofer 2013). Additionally, the design of an accessible inspection drain would help to address the leakage problem quickly and accurately.

1.3.1.5 REFERENCES

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1.0 CLT technology

Abstract: This section investigates the relationship between forest resources and manufacturing for the value generation of CLT panels. This section is divided into two chapters: the first analyses the forest resources and timber industry situation, while the second focus on CLT manufacturing process. Furthermore, both chapters present at first two topics which analyse the situation in Austria and Japan individually, followed by the last topic that compares the situation in each place. Hence, by the comparison with Austria from the forest resources and CLT manufacturing points of view, the influence of both on the value generation of CLT panels in Japan case can be understood. The results showed the basis for a cost-effective CLT production is a continuous flow of production, meaning raw-material inflow and CLT panel output should be as constant and close to production capacity as possible. However, even though current forest resources suffice for CLT production in the short-term, long-term supply of quality timber in Japan may be threatened by the uneven distribution of timber resources. Furthermore, small demand for CLT as a result of low mechanical strength and high price hinders economy of scale potential in Japanese CLT production, leading to an idle production capacity, which maintains CLT unit price high, thus forming a vicious circle. Improvement regarding the properties of CLT panels could contribute to widening CLT application range, while promotion policies oriented towards CLT construction could help to increase awareness of general public and diffusion of Japanese CLT into the domestic market. Both strategies can lead to higher value generation regarding “Functional” and “Economic subjects”, respectively.

1.1 Forest resources and timber industry

Abstract: This chapter investigates the possibilities and limitations for Japanese CLT manufacturing from the resources point of view. This chapter is divided into three topics, the first two analyse the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place. Hence, by the comparison with Austria, possibilities and limitations for Japanese CLT from the resources point of view can be comprehended. It was found that Austria is a wealthy commercially forested country with a timber industry aimed at exporting high end-value forest timber products. Likewise, Japan presents a substantial amount of planted forest resources. However, the uneven age distribution of trees may pose a threat to quality timber lamellae supply on the long-term. Moreover, Japanese timber industry must rely on the domestic market. Therefore, the development of national CLT industry would need acceptance inside Japanese construction market.

1.1.1. Austrian forest resources and timber industry analyses

1.1.1.1. GOAL

The objective of this topic is to understand main possibilities and limitations for Austrian CLT from the forest resources and timber industry points of view.

1.1.1.2. METHOD

Statistical information on forest resources and timber industry supply/demand were retrieved from the online database of the Austrian Statistic Bureau and Federal Research and Training Centre for Forests, Natural Hazards and Landscape. After, the gathered data was visualised and analysed, focusing on the managed forest resources, notedly Spruce wood and sawn timber production. Finally, CLT possibilities and limitations from according to planted forest resources and timber industry capabilities were discussed based on the results.

1.1.1.3. RESULTS

Forest resources
Austria has a total area of about 8 millions ha, of which almost 47% (4 million ha) are covered by forests (BFW, 2015), placing the country as the ninth highest forest cover percentage among the northern-hemisphere developed countries (FAO, 2012).

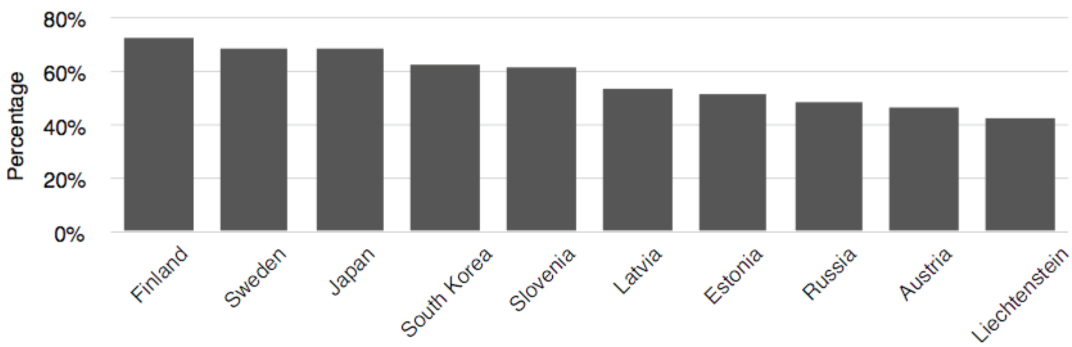
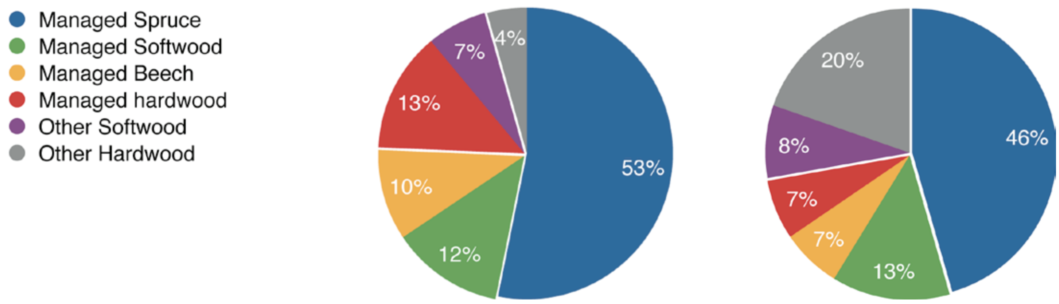


Figure 1.1.1. Percentage of forest area in northern-hemisphere developed countries, 2011. Source: raw data retrieved from FAO, 2012.

Moreover, around 90% (7.1 million ha) of the forest area in Austria is classified as commercially managed forest, i.e., cultivated for providing forest timber products. More than half of the managed forest are in Austria (4.2 million ha) is composed of

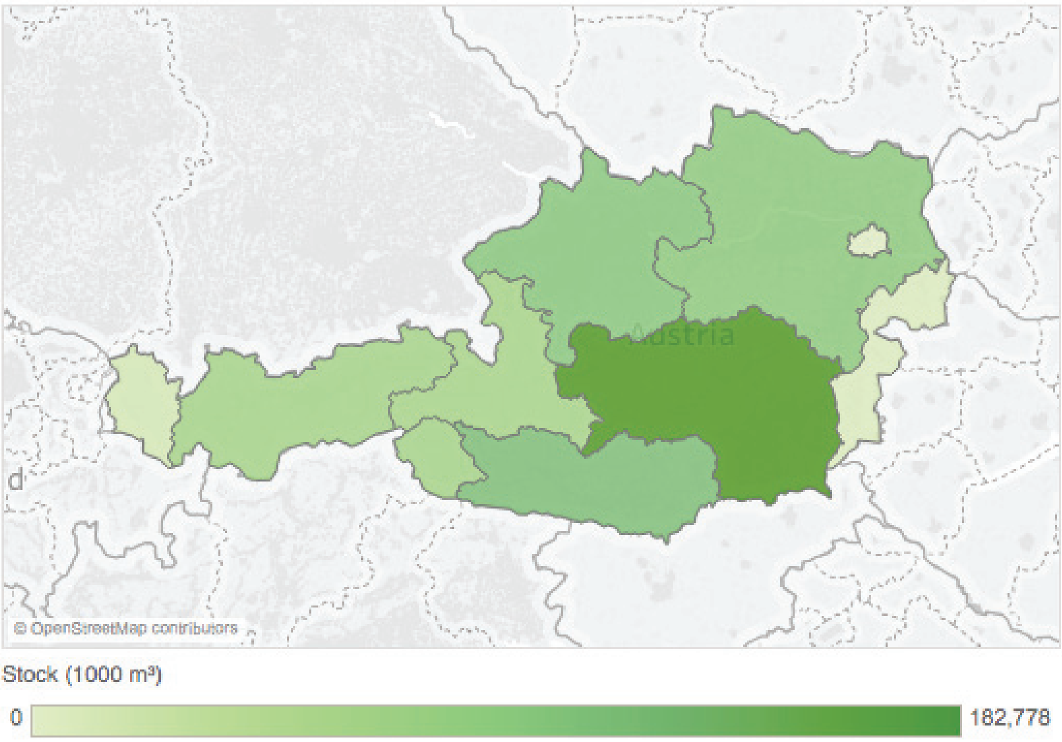
Spruce forest, whereas the remaining 11% (0.9 million ha) contain bushes, gaps and protected forest area. (BFW, 2015). Total national forest stock is around 1.3 million m3, and managed forests are also predominant representing almost 72% (1 million m^3) of it. Similarly, managed spruce is the most common wood species, representing 46% (620 thousand m^3) of all the forest stock.

Figure 1.1.2. Percentage of wood species in Austrian forests, 2012 (left: area; right: stock). Source: raw data retrieved from BFW, 2015.



The stock of Austrian managed forest corresponds to 982 million m3 and is found mainly in 4 regions: Styria (27.5%), Lower Austria (20%), Carinthia (15.5%) and Upper Austria (15%). Furthermore, managed forest stock is predominantly composed of Softwood timber species, accounting for 80% (800 million m^3). Spruce wood is the most common species, representing 61% (619 million m^3) of all the stock of the managed forests in the regions mentioned above, almost half of it located in Styria (30%) and Carinthia (20%). (BFW, 2015)

Figure 1.1.3. The stock of managed Spruce forest in Austria by regions, 2009 (1000 m^3). Source: raw data retrieved from BFW, 2015.



Austrian managed forest age distribution is dominated by matured trees, with 70% (695 million m³) within the range from 40 to 120 years old. Spruce wood from 40 to 80 years old accounts for 25% (250 million m³) of all managed forest stock and most of it is found in Styria and Carinthia regions, representing about 8% (76 million m³) and 5% (46 million m³) of all the stock of managed forests. (BFW, 2015)

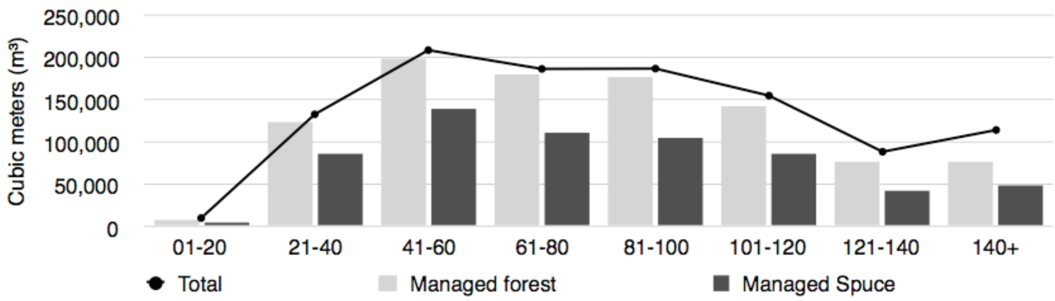


Figure 1.1.4. The stock of Austrian forests by age, by type, 2009 (1000 m³). Source: raw data retrieved from BFW, 2015.

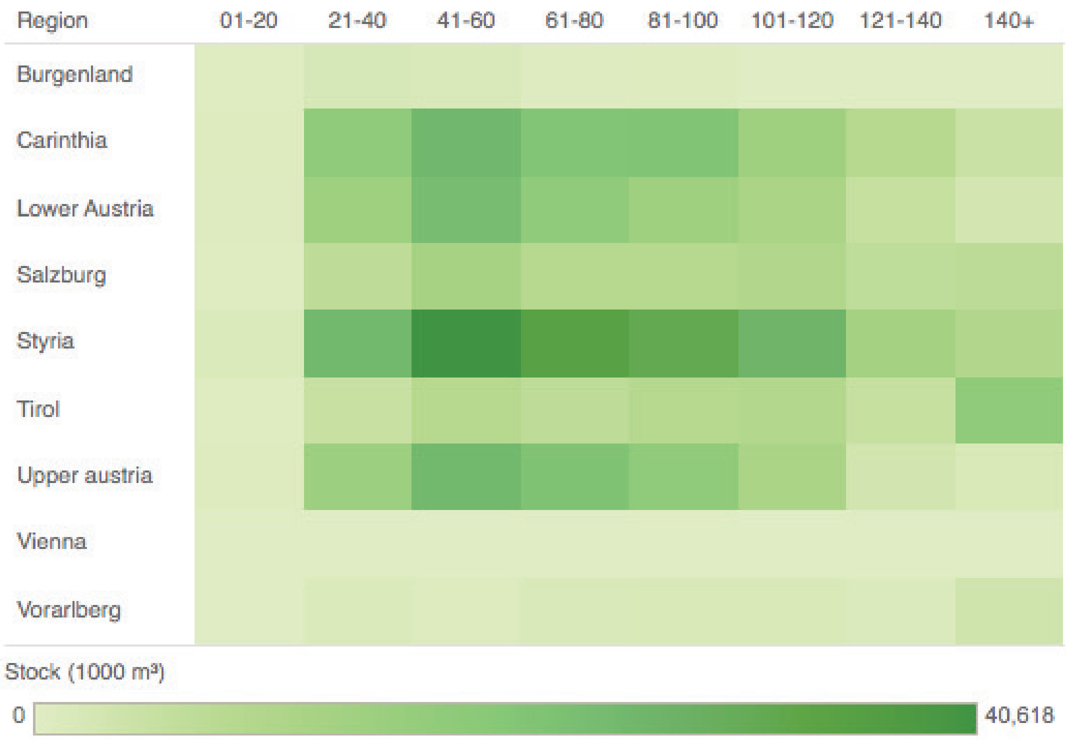


Figure 1.1.5. The age distribution of managed Spruce forest stock by region, 2009 (1000 m³). Source: raw data retrieved from BFW, 2015.

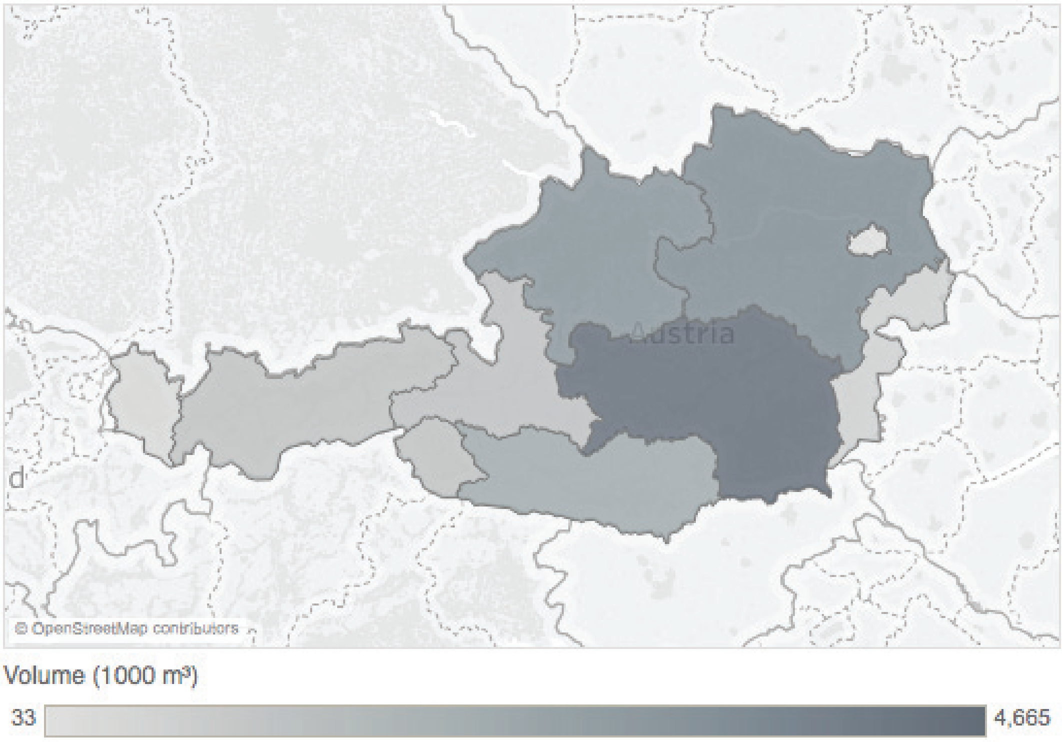
From 2007 to 2009, Austrian managed forests have grown on average 9.5 m³/ha/year. Spruce wood had the biggest growth ratio, achieving 11.8 m³/ha. Notably managed private forests showed the highest annual growth (10.4 m³/ha/year), followed by managed forests owned by companies (8.3 m³/ha/year).

Table 1.1.1. Austrian forests annual growth rate by ownership, 2007–09 (m³/ha/year). Source: raw data retrieved from BFW, 2015.

Types	Managed forests	Protection forests	Other forests	Total forests
Private forests	10.4	6.1	7.0	10.1
Company forests	8.3	4.8	4.8	7.7
Federal forests	8.0	3.2	-	7.2
Total softwood	-	-	-	11.2
Total spruce	-	-	-	11.8
Total hardwood	-	-	-	7.8
Total forests	9.5	4.9	5.8	9.0

Timber industry

Figure 1.1.6. Round-wood production by region, 2009 (1000 m³). Source: raw data retrieved from Statistics Austria, 2015.



In 2009, total round-wood demand in Austria was roughly 25 millions m³, of which 8.6 million m³ (34%) were supplied by imported timber, thus resulting in a 66% timber self-sufficiency ratio. Wood-fuel round-wood accounted for 5.1 million m³ (20%) of all volume, whereas the remaining 20 million m3 (80%) were employed in the industrial round wood processing activity (FAO, 2015). Furthermore, the biggest national round-wood production volume coincides with the four most forested regions mentioned above, namely Styria, Lower Austria, Carinthia and Upper Austria (Statistics Austria, 2015).

Domestic industrial round wood supply for other activities than sawmill and veneer use (which includes pulp, sleepers, poles, etc.) provided nearly 3 million m³ (12% of all demand), whereas 9 millions m³ of round wood (36% of all demand) were supplied as sawlogs and veneer logs. (FAO, 2015)

Finally, on 2009, considering both domestic and imported timber, about 10 million m³ of sawn timber were supplied to Austria, essentially softwood timber species (97%). Furthermore, most than half (57%) of the sawn-timber either produced in the country or imported was then exported whether in its raw format or processed into value-added materials. (FAO, 2015)

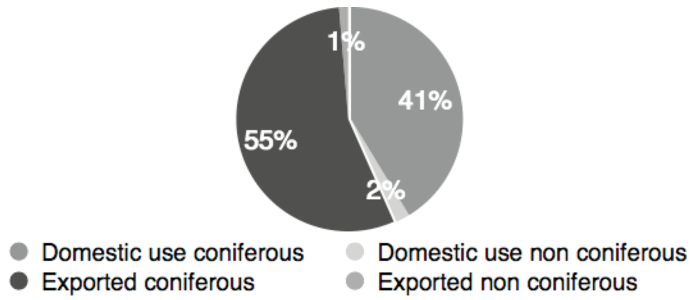


Figure 1.1.7. Austrian sawn-timber domestic use and export volume by wood species, 2009. Source: raw data retrieved from FAO, 2015.

Forest sector gross added value

In 2009, Agriculture, Forestry and Fishing's income represented 1.16% (3.31 BN euros) of Austrian Gross Domestic Product.

1.1.1.4. DISCUSSION

Austria has the highest forest cover percentage among Central European countries. Additionally, most of its area is defined as managed forest and is predominantly composed of mature (over 40 years old) Spruce wood. Considering an average annual growth of 11.8 m3/ha, managed Spruce forest would be capable of proving about 18.5 million m3 in one year. Thus, this one species alone would account for slightly more than 70% of the annual timber demand in the country. Considering not every single one of these trees can be harvest, Austria's 66% self-sufficient timber ratio seems to be a reasonable amount in the overall context.

Furthermore, domestic industrial round wood supply accounts for 60% of all demand. The domestic supply of sawlogs and veneer logs makes up for almost half of industrial round wood utilised in 2009. However, owing to the small annual national demand for new wooden construction (item 2.1), it is possible to assume there should be an equally low demand for forest timber products to be used in construction. For this reason, it could be observed that almost 60% of timber products is exported. Therefore, Austrian forests and especially the managed forest is oriented towards the production of high-quality industrial logs to be processed into forest timber products, aiming at the international market. CLT production would be no exception to this situation.

To sum up, based on the analysed data, a rough estimation of annual CLT production volume employing Spruce wood is presented. Only taking into account, the area of Spruce managed forest found in the two most forested regions in Austria, namely Styria and Carinthia, a total 750 thousand ha can be delimited, that should provide about 8.8 million m3 per year. If mature trees (from 40 to 80 years old) account for 40% of the stock in this regions, 3.5 millions m3 of mature spruce would be available for harvesting. If all this volume was utilised exclusively for CLT production, taking into account an average 40% log conversion rate (Fredriksson et al. 2015), 1.4 million m3 of CLT panels could be produced yearly, which is four times bigger than Austrian expected CLT production volume in 2015 (Plackner 2015). In other words, timber resources provide a large margin to increase CLT production in the country.

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1.1.2 Japanese forest resources and timber industry analyses

1.1.2.1 GOAL

The objective of this topic is to understand main possibilities and limitations for Japanese CLT from the forest resources and timber industry points of view.

1.1.2.2 METHOD

Statistical information on forest resources and timber industry supply/demand were retrieved from the online database of the Japanese Statistic Bureau and Ministry of Agriculture, Forestry and Fisheries in Japan. After, the gathered data was visualised and analysed focusing on planted forest resources, notedly Japanese Cedar (Sugi). Finally, considering the analyses, conclusions were drawn regarding the main possibilities and threats of employing Japanese domestic timber for CLT production.

1.1.2.3 RESULTS

Forest resources

Japan has a total area of about 37 millions ha, about 67% (25 million ha) covered by forests (Forestry Agency, 2015), which places the country in the third position regarding forest cover percentage among northern-hemisphere developed countries, after Finland and Sweden only (figure 1.1.1). Furthermore, 60% (15 million ha) of Japanese forest area is defined as native forest, thus fulfilling important roles such as recreation, fauna and flora biodiversity preservation, disaster prevention and water resources supply conservation. The remaining 40% (10 million ha) are composed of planted forests, providing forest timber products. (Forestry Agency, 2015).

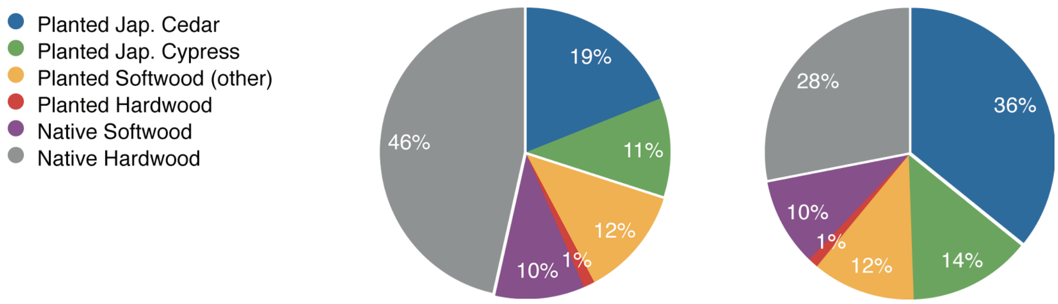


Figure 1.1.8. Percentage of wood species in Japanese forests, 2012 (left: area; right: stock). Source: raw data retrieved from Forestry Agency, 2015.

Hardwood trees account for 72% (1.3 billion m³) of native forest's timber stock. In contrast, Japanese planted forests are overwhelmingly composed of softwood trees, accounting for 97% (2.9 billion m³) of their stock. Furthermore, Japanese Cedar (Sugi) is the most common species found in the planted forests, reaching 56% (1.7 billion m³) of planted forest's stock. Almost half of Japanese cedar stock is found in the Tōhoku (Iwate, Akita and Fukushima prefectures), Shikoku (Tokushima and Kōchi prefectures) and Kyūshū area (Kumamoto, Oita, Miyazaki and Kagoshima prefectures), making up for 15%, 14% and 17% of all national planted forest stock, respectively. (Forestry Agency, 2015)

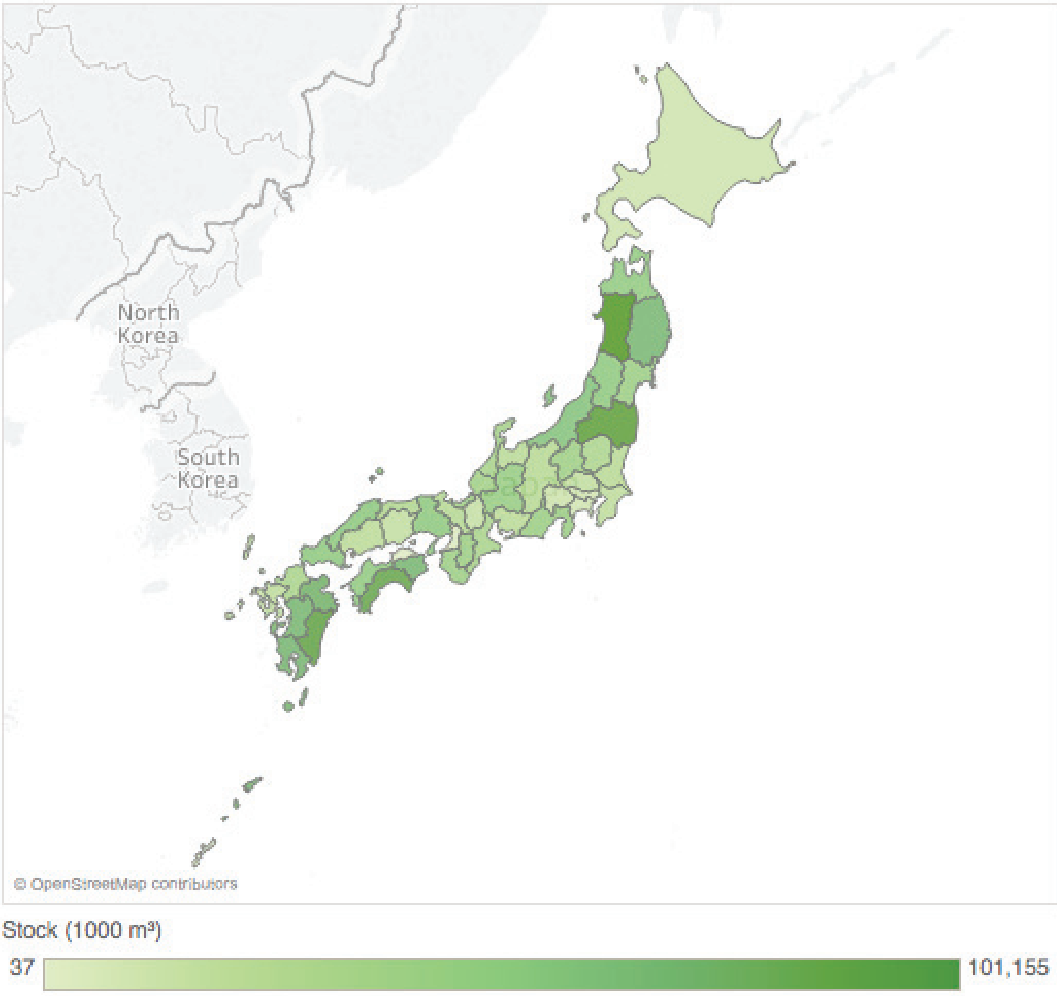


Figure 1.1.9. Stock of planted Japanese Cedar (Sugi) by prefecture, 2012 (1000 m³). Source: raw data retrieved from Forestry Agency, 2015.

In total, Japanese forests have a relatively large amount of trees over 90 years old, totalising about 14% (723 million m³) of the forest stock. However, the stock of mature trees is mostly composed of hardwood species and predominantly found in native forests, corresponding to 60% (435 million m^3) of all the stock of mature trees. (Forestry Agency, 2015)

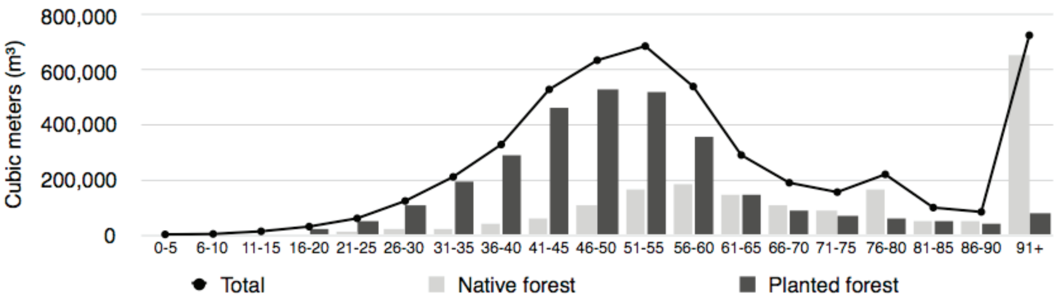


Figure 1.1.10. The age distribution of Japanese forest stock by type, 2012. Source: raw data retrieved from Forestry Agency, 2015.

On the other hand, Japanese planted forests present only 2.5% (74 million m^3) of trees older than 90 years old. In fact, most of the stock of Japanese planted forests is situated from 40 to 60 years old and representing about 61% (1.8 billion m^3) of it. Likewise, planted Japanese Cedar (Sugi) from 40 to 60 years is the most common species, accounting for about 36% (1 million m^3) of the stock of planted forests. Planted Japanese Cedar stock up to 30 years old is small and represents less than 5% (80 million m3) of its total stock. (Forestry Agency, 2015)

Finally, from 2007 to 2012, Japanese forests grew an average 3.8 m^3/ha/year. Only planted forests grew an average of 7.6 m^3/ha/year in which Japanese Cedar (Sugi) showed biggest growth ratio, achieving 10.6 m^3/ha/year. Particularly, public planted forests showed the highest annual growth (8.9 m^3/ha/year), followed closely by private planted forests (8.6 m^3/ha/year).

Table 1.1.2. Annual growth rate of Japanese forests by ownership, 2007–12 (m^3/ha/year). Source: raw data retrieved from Forestry Agency 2015.

	Planted	Native	Total
National forests	3.70	1.29	1.91
Public forests	8.93	2.45	5.19
Private forests	8.64	0.84	4.41
Softwood	7.65	0.85	6.34
Japanese Cedar	10.66	-	-
Hardwood	8.77	1.23	1.43
Total	7.55	1.18	3.74

Figure 1.1.11. The age distribution of Planted Japanese Cedar (Sugi) stock by prefecture (1000 m^3). Source: raw data retrieved from Forestry Agency, 2015.

Timber industry

In 2012, total round-wood demand in Japan was 72 million m^3, predominantly (98%) for domestic use. Additionally, 72% (52 million m^3) of all utilised timber in Japan was imported, resulting in a 28% timber self-sufficiency ratio. Woodfuel and mushroom activities together demanded slightly more than 2% (1.6 million m^3) of the timber volume. Hence, the remaining 98% (70 million m^3) were employed in the industrial round wood processing activity. (MAFF, 2014)

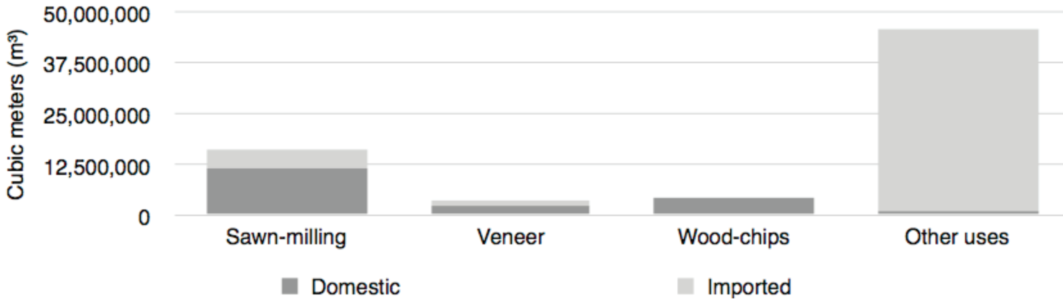


Figure 1.1.12. Round-wood supply source by industrial activity, 2012. Source: raw data retrieved from MAFF, 2014.

Industrial round-wood for other activities than sawmill and veneer use (which includes pulp, sleepers, poles) demanded 46 million m^3, nearly all of it (45 million m^3) supplied by imported timber. However, 72% (18 million m^3) of the total demand for industrial round wood sawlogs and veneer logs were supplied by domestic wood species. Furthermore, 68% (11 million m^3) of the total demand for industrial round wood sawlogs, was provided by domestic timber species. (MAFF, 2014)

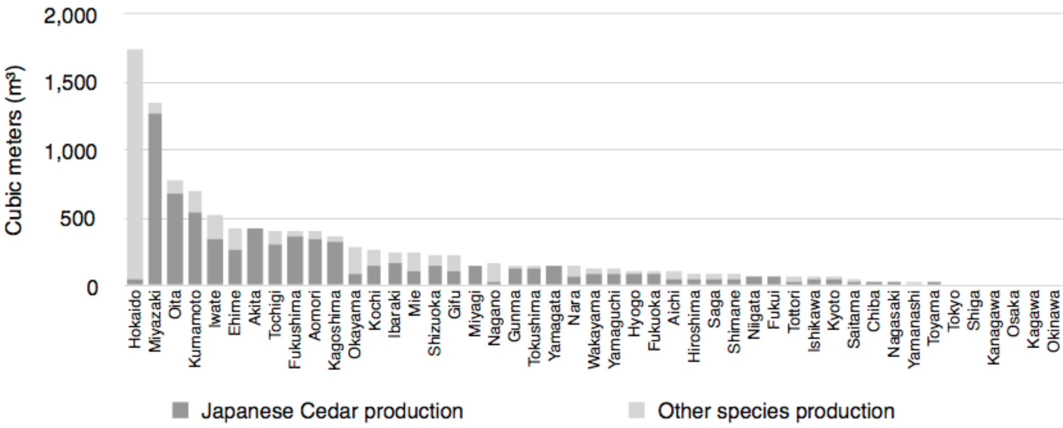


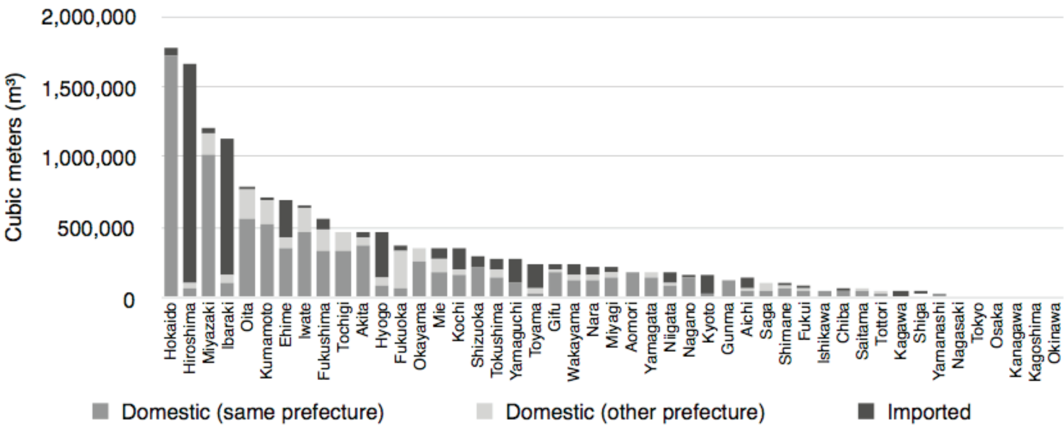
Figure 1.1.13. Japanese sawlogs production by prefecture, by wood species, 2012. Source: raw data retrieved from MAFF, 2014.

Hokkaidō prefecture had the biggest production volume of sawlogs in Japan, followed by Kyūshū area (Miyazaki, Ōita and Kumamoto) and Tōhoku area (Iwate, Akita and

Fukushima prefectures). Except for Hokkaidō prefecture which has a concentration of different native species, Japanese Cedar sawlogs production is also relatively concentrated in the same prefectures located in Kyūshū and Tōhoku mentioned above, making up for 13% and 15% of the total stock respectively.

However, considering sawmills timber consumption volume, two different prefectures, neither situated in Tōhoku or Kyūshū regions, stand out as big timber consumption places: Hiroshima and Ibaraki prefectures, representing together 17% of all timber volume consumed volume in Japan. One hypothesis that explains why these places show a large timber consumption is due to their location close to urban areas where a high demand for timber utilisation in construction is found (topic 2.1.2). Nonetheless, both mentioned prefectures process mainly imported timber. Regardless of these two exemptions and Hokkaido, the remaining largest sawmill timber consumption prefectures coincide with the wealthy Japanese Cedar resources location and account 31% of all timber volume consumed by sawmills in 2012.

Figure 1.1.14. Timber consumption volume in sawmill facilities by prefecture, 2012. Source: raw data retrieved from MAFF, 2014.



Finally, considering both the domestic and imported supply, a total of about 15.8 millions m3 of sawn timber were utilised in Japan, mainly coniferous species (97%). Furthermore, almost all of the sawn timber volume produced or imported to Japan (93%) was domestically utilised, either in its simple square format or processed into other materials. (FAO, 2015)

Forest sector gross added value

In 2012, the income of Japanese forest sector represented about 0.65% (3 trillion yens) of Japanese Gross Domestic Product. Nevertheless, the sector is dominated by the pulp and paper activity, which represents more than 70% (2.2 trillion yens) of the whole contribution (Cabinet Office, 2015). Taking into account forestry added value, it is worth note that mushroom cultivation in Japan achieves the same output value as all round-wood trade, despite requiring the smallest round-wood volume of all activities. (MAFF, 2014)

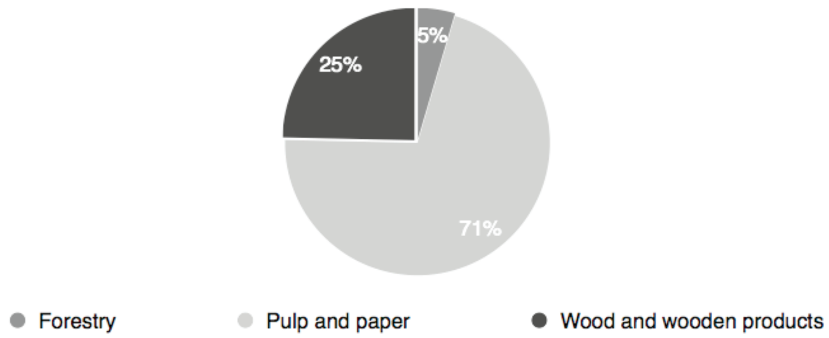


Figure 1.1.15. Gross added value in Japanese forest sector by activity, 2012. Source: raw data retrieved from Cabinet Office, 2015.

1.1.2.4 DISCUSSION

Even though Japan has a densely forested territory, the majority of it is composed of native hardwood forests. In contrast, Japanese planted forests are dominated by fast-grown softwood species, such as Japanese Cedar (Sugi), covering half of the planted forest area and almost 20% of all forested area. Moreover, planted Japanese forests are mostly composed of trees from 40 to 60 years old, accounting for about 10% of national forest area and 24% of all stock. Furthermore, the stock shows a few amount of trees up to 30 years old. This uneven age distribution could lead to a shortage of the supply of mature timber in the future, depending on the increase of the demand.

In spite of the smaller area of planted forests compared to native forests, owing to an average annual growth around 10 m3/ha, nearly 44 millions m3 of planted Japanese Cedar (Sugi) round-wood should be available for harvesting every year. Hence, only this one wood species would be able to supply more than 60% of all current national round-wood demand. Therefore, low timber self-sufficiency ratio (28%) in Japan and the consequent decline of national forestry sector (MAFF, 2012) is certainly not due to the lack of resources. Instead, it may be caused by its modest share in the national economy and lack of political bargain power. As a result, few actions aiming at protecting and promoting domestic timber industry against cheaper imported timber are taken, thus creating a very discouraging context for forest owners and overall timber industry business. However, even inside this context, about 72% of the annual demand for sawlogs and veneer logs is supplied by domestic timber. Moreover, planted Japanese Cedar sawlogs, chiefly found in Tōhoku and Kyūshū area, represent the largest part of this demand and are processed into saw timber in the same regions or regions nearby big urban consumer centres, mainly around Kantō and Kansai regions. Also, owing to the large demand for new buildings in Japan and the high percentage of wooden buildings, more than 90% of the sawn timber produced and imported to Japan is utilised domestically, which shows the potential of the local market

To sum up, based on the analysed data, a rough estimation of annual CLT production volume employing Japanese Cedar (Sugi) is presented. Considering only the mature planted Japanese Cedar area found in the most forested prefectures in Tōhoku and Kyūshū regions (namely Kumamoto, Oita, Miyazaki, Iwate, Akita and Fukushima prefectures), a total 700 thousand ha can be selected. The selected area would provide about 7 millions m3 of round wood per year. If this volume was exclusively utilised for CLT production, taking into account an average 47% yield rate from sawlog log to lamina (Jeong et al. 2013), 3.3 million m3 of CLT panels could be produced, which is around seven times bigger than the expected CLT production volume in Austria in 2015 (Plackner 2015). Hence this might opens a possibility for steadily increasing the domestic CLT production in Japan using the currently available resources. However it should be noted that not all the growing stock is suitable to use for CLT manufacturing as strength grade could vary due to the growing conditions and occurrence of defects. Therefore, it is important to actively develop the forest sector, taking measures to improve the uneven age distribution and quality of the growing stock, thus assuring the supply in the medium to long-range

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1.1.3 Austria and Japan forest sector and timber industry comparison

1.1.3.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT in comparison to Austrian CLT from the resources point of view.

1.1.3.2 METHOD

Taking into account the previous studies on forest resources and annual timber supply/demand (topics 1.1.1 and 1.1.2), Austria and Japan were compared, considering the former as a reference for understanding the possibilities and restraints of employing domestic timber for CLT production in Japan. The main differences between Austrian and Japanese forest context and how these would influence CLT production in Japan were discussed.

1.1.3.3 RESULTS

Forest resources
The total forest area and timber stock in Japan are considerably larger than in Austria (six and four times bigger, respectively). Also, area and stock of planted forests in Japan outnumber managed forests in Austria by four and three times respectively, which are commercial forests oriented towards the production of forest timber products. Commercial forests in each country are predominantly composed of softwood trees, with one clear, prominent wood species, namely Spruce in Austria and Japanese Cedar in Japan, both exhibiting an average annual growth rate around 11 m^3/ha. Nevertheless, the area and stock of planted Japanese Cedar forest are bigger than managed Spruce forest in Austria by almost three times.

The age distribution of planted Japanese Cedar forests is concentrated in the 40 to 60 years old range, outnumbering 40 to 60 years old Spruce stock in Austria by almost nine times. On the other hand, Spruce trees in Austrian managed forests are prevalent over 80 years old, outnumbering Japanese Cedar stock of the same age by almost tree times. Particularly, the small amount of Japanese Cedar up to 30 years old could affect the supply of mature timber in the mid-range period.

Table 1.1.3. Summary of forestry data inAustria, 2009 (left) and Japan, 2012 (right) (1000 ha, 1000 m³).

General data	General	Territory	8,388 ha		
General data	General	Total forest	3,992 ha 100%	1,135,385 m^3 100%	9.00 m^3/ha/year
Protection forest data	Owner	Federal	76 m^2 1.9%	21,667 m^3 1.9%	3.2 m^3/ha/year
Protection forest data	Owner	Company	128 m^2 3.2%	37,214 m^3 3.3%	4.8 m^3/ha/year
Protection forest data	Owner	Private	116 m^2 2.9%	31,706 m^3 2.8%	6.1 m^3/ha/year
Protection forest data	General	Protection forest	320 ha 8.0%	90,587 m^3 8.0%	4.9 m^3/ha/year
Protection forest data	Species	Softwood	197 ha 4.9%	72,366 m^3 6.4%	NA m^3/ha/year
Protection forest data	Species	Hardwood	59 ha 1.5%	14,235 m^3 1.3%	NA m^3/ha/year
Protection forest data	Species	Other	64 ha 1.6%	3,986 m^3 0.4%	NA m^3/ha/year
Managed forest data	Owner	Federal	362 m^2 9.1%	117,396 m^3 10.3%	8.0 m^3/ha/year
Managed forest data	Owner	Company	835 m^2 20.9%	271,988 m^3 24.0%	8.3 m^3/ha/year
Managed forest data	Owner	Private	1,436 m^2 36.0%	640,434 m^3 56.4%	10.4 m^3/ha/year
Managed forest data	General	Managed forest	2,633 ha 66.0%	1,029,818 m^3 90.7%	9.5 m^3/ha/year
Managed forest data	Species	Softwood	1,942 ha 48.6%	799,048 m^3 70.4%	11.2 m^3/ha/year
Managed forest data	Species	Spruce	1,574 ha 39.4%	619,143 m^3 54.5%	11.8 m^3/ha/year
Managed forest data	Species	G. Pine	144 ha 3.6%	70,500 m^3 6.2%	8.1 m^3/ha/year
Managed forest data	Species	Others	224 ha 5.6%	109,408 m^3 9.6%	9.4 m^3/ha/year
Managed forest data	Species	Hardwood	691 ha 17.3%	182,885 m^3 16.1%	7.8 m^3/ha/year
Other	General	Other forest	1,039 ha 26.0%	14,375 m^3 1.3%	

General data	General	Territory	37,292 ha		
General data	General	Total forest	25,081 ha 100%	4,900,510 m^3 100%	3.80 m^3/ha/year
Native forest	Owner	Federal	4,717 ha 18.8%	684,060 m^3 14.0%	1.3 m^3/ha/year
Native forest	Owner	Public	1,495 ha 6.0%	207,400 m^3 4.2%	2.4 m^3/ha/year
Native forest	Owner	Private	7,186 ha 28.7%	963,030 m^3 19.7%	0.8 m^3/ha/year
Native forest	General	Native forest	13,348 ha 53.2%	1,850,152 m^3 37.8%	1.17 m^3/ha/year
Native forest	Species	Softwood	2,369 ha 9.4%	478,882 m^3 9.8%	0.8 m^3/ha/year
Native forest	Species	Hardwood	10,979 ha 43.8%	1,371,270 m^3 28.0%	1.2 m^3/ha/year
Planted forest	Owner	Federal	2,327 ha 9.3%	467,320 m^3 9.5%	3.7 m^3/ha/year
Planted forest	Owner	Public	1,287 ha 5.1%	350,300 m^3 7.1%	8.9 m^3/ha/year
Planted forest	Owner	Private	6,662 ha 26.6%	2,221,180 m^3 45.3%	8.6 m^3/ha/year
Planted forest	General	Planted forest	10,270 ha 40.9%	3,037,503 m^3 62.0%	7.6 m^3/ha/year
Planted forest	Species	Softwood	9,968 ha 39.7%	2,981,719 m^3 60.8%	7.6 m^3/ha/year
Planted forest	Species	Sugi	4,475 ha 17.8%	1,748,776 m^3 35.7%	10.7 m^3/ha/year
Planted forest	Species	Hinoki	2,599 ha 10.4%	668,114 m^3 13.6%	7.5 m^3/ha/year
Planted forest	Species	Others	2,894 ha 11.5%	564,830 m^3 11.5%	3.1 m^3/ha/year
Planted forest	Species	Hardwood	302 ha 1.2%	55,783 m^3 1.1%	8.8 m^3/ha/year
Other	General	Other forest	1,464 ha 5.8%	12,855 m^3 0.3%	

Note: Total figures may not be equal to the sum of each item due to round off.

Table 1.1.4. Summary of timber industry data in Austria, 2009 (left) and Japan, 2012 (right) (1000 ha, 1000 m³).

	General	Industrial round-wood	Sawlogs and veneer logs	Other uses	Woodfuel
Use	Domestic 24,522 m³ 96.82% Export 805 m³ 3.18%	Domestic 19,451 m³ 76.80% Export 729 m³ 2.88%	Domestic NA m³ Export NA m³		Domestic 5,071 m³ 20.02% Export 77 m³ 0.30%
Demand	**Total** 25,327 m³ 100%	**Industrial round-wood** 20,180 79.68%	**Sawlogs and veneer logs** NA m³	**Other uses** NA m³	**Woodfuel** 5,148 m³ 20.33%
Supply	Domestic 16,727 m³ 66.04% Imported 8,600 m³ 33.96%	Domestic 12,144 m³ 47.95% Imported 8,036 m³ 31.73%	Domestic 9,105 m³ 35.95% Imported NA m³	Domestic 3,039 m³ 12.00% Imported NA m³	Domestic 4,584 m³ 18.10% Imported 564 m³ 2.23%

	General	Industrial round-wood	Sawlogs and veneer logs	Sawlogs	Veneer logs	Wood chips	Other uses	Woodfuel	Mushroom
Use	Domestic 70,769 m³ 98.03% Export 1,420 m³ 1.97%	Domestic 69,226 m³ 95.90% Export 1,406 m³ 1.95%	Domestic 23,263 m³ 32.23% Export 1,393 m³ 1.93%					Domestic 1,106 m³ 1.53% Export 13 m³ 0.02%	Domestic 437 m³ 0.61% Export 0
Demand	**Total** 72,189 m³ 100%	**Industrial round-wood** 70,632 m³ 97.84%	**Sawlogs and veneer logs** 24,656 m³ 34.15%	Sawlogs 16,247 m³ 22.51%	Veneer logs 3,837 m³ 5.32%	Wood chips 4,572 m³ 6.33%	**Other uses** 45,976 m³ 63.69%	**Woodfuel** 1,119 m³ 1.55%	**Mushroom** 437 m³ 0.61%
Supply	Domestic 20,318 m³ 28.15% Imported 51,870 m³ 71.85%	Domestic 19,686 m³ 27.27% Imported 50,947 m³ 70.57%	Domestic 18,479 m³ 25.60% Imported 6,166 m³ 8.54%	Domestic 11,321 m³ 15.68% Imported 4,926 m³ 6.82%	Domestic 2,602 m³ 3.60% Imported 1,235 m³ 1.71%	Domestic 4,556 m³ 6.31% Imported 16 m³ 0.02%	Domestic 1,207 m³ 1.67% Imported 44,770 m³ 62.02%	Domestic 196 m³ 0.27% Imported 924 m³ 1.28%	Domestic 437 m³ 0.61% Imported 0

Note: Total figures may not be equal to the sum of each item due to round off.

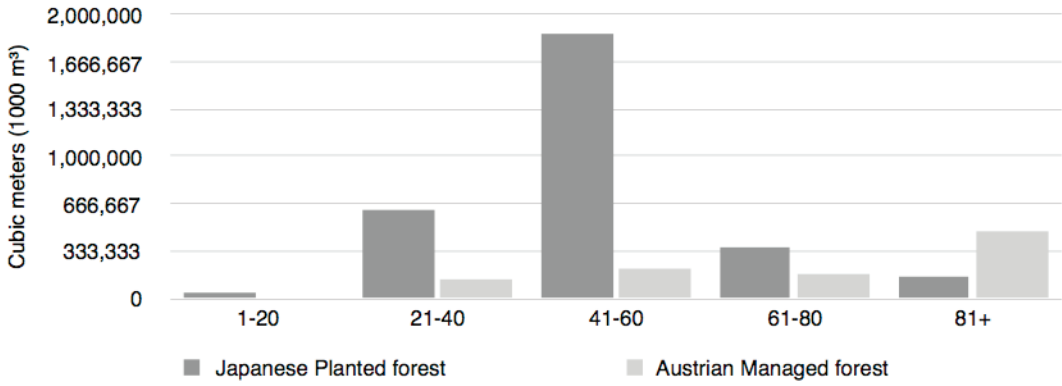


Figure 1.1.16. Forest stock (m^3) by age in Japan (2012) and Austria (2009). Source: raw data retrieved from BFW, 2015 and Forestry Agency, 2015.

Timber industry

Japanese total round-wood demand is almost three times bigger than Austrian. However, whereas the former utilises over 70% of imported timber supply, the latter employs only 33%. In both countries, industrial round wood volume accounts for most of the timber demand. Sawlogs and veneer logs account for most of the industrial round wood demand. Additionally, domestic sawlogs and veneer logs production in Austria is about half of Japanese production, but represents slightly more of the national timber demand (35% against 25%).

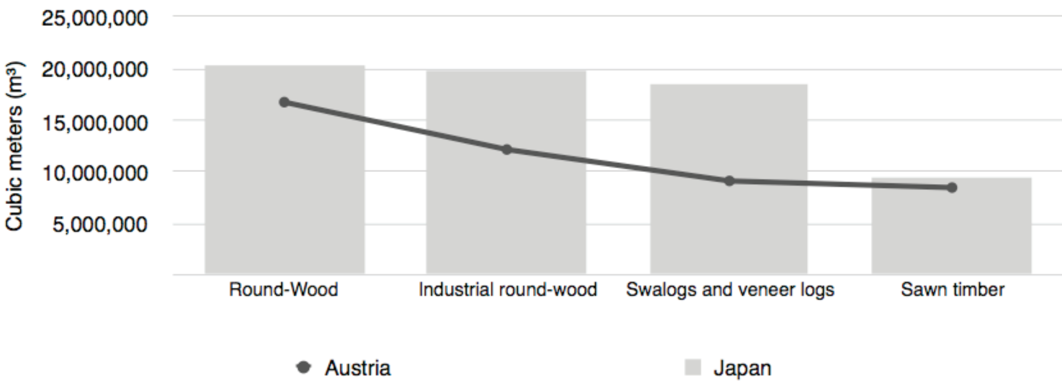


Figure 1.1.17. Production volume (m^3) of domestic round wood and sawn timber production in Austria (2009) and Japan (2012). Source: raw data retrieved from Statistics Austria, 2015 and MAFF, 2014.

The total sawn timber demand in Japan is about 55% bigger than in Austria. Nonetheless, the latter presents more than 80% of its demand domestically supplied, while the former shows less than 60% of domestic saw timber supply. Hence, annual domestic sawn timber production volume in both countries has roughly the same value, around to 9 million m^3. Finally, 57% of the produced or processed sawn timber in Austria is exported, whereas Japan utilises almost all of the sawn timber inside the country.

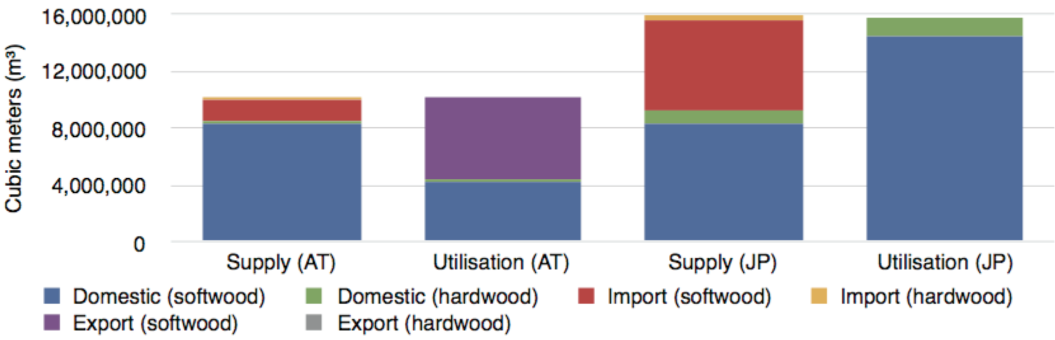


Figure 1.1.18. Volume (m^3) of sawn timber production, import and export in Austria (2009) and Japan (2012). Source: raw data retrieved from FAO, 2015.

1.1.3.4 DISCUSSION

Maps of Austria and Japan are presented in the same scale to synthesise the fundamental features of the chain of wood products in both countries.

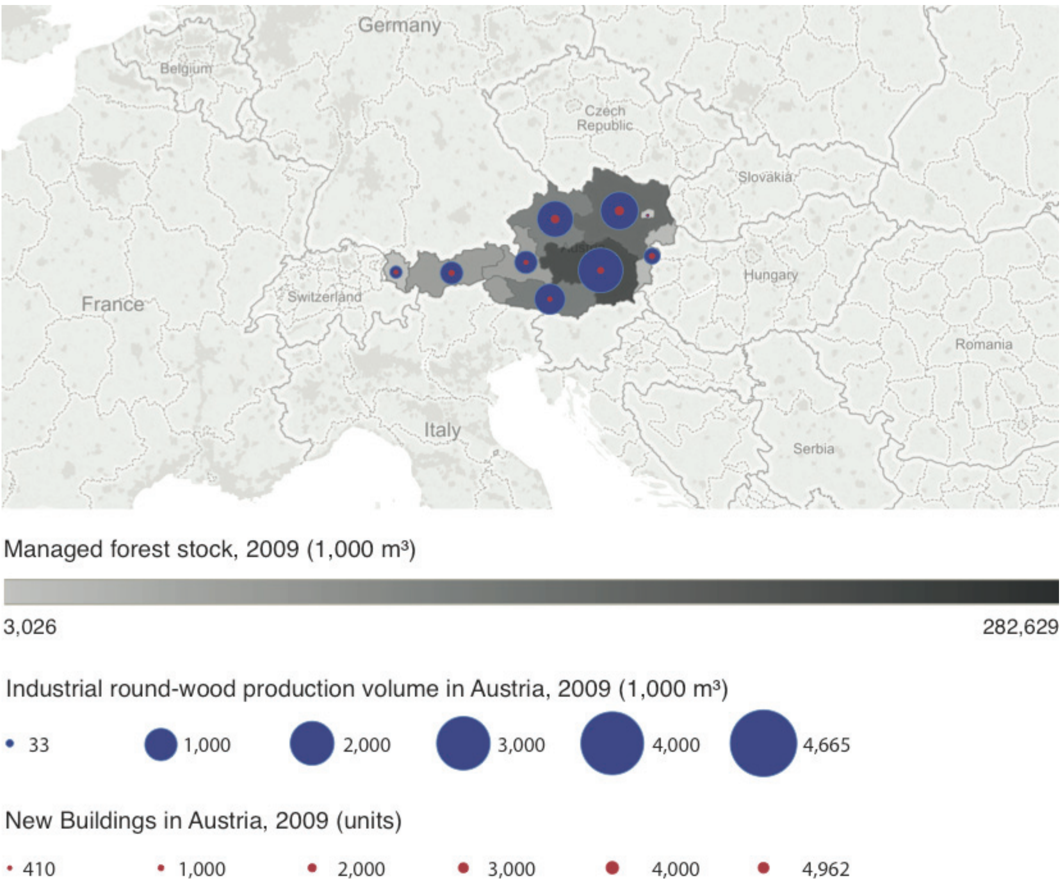
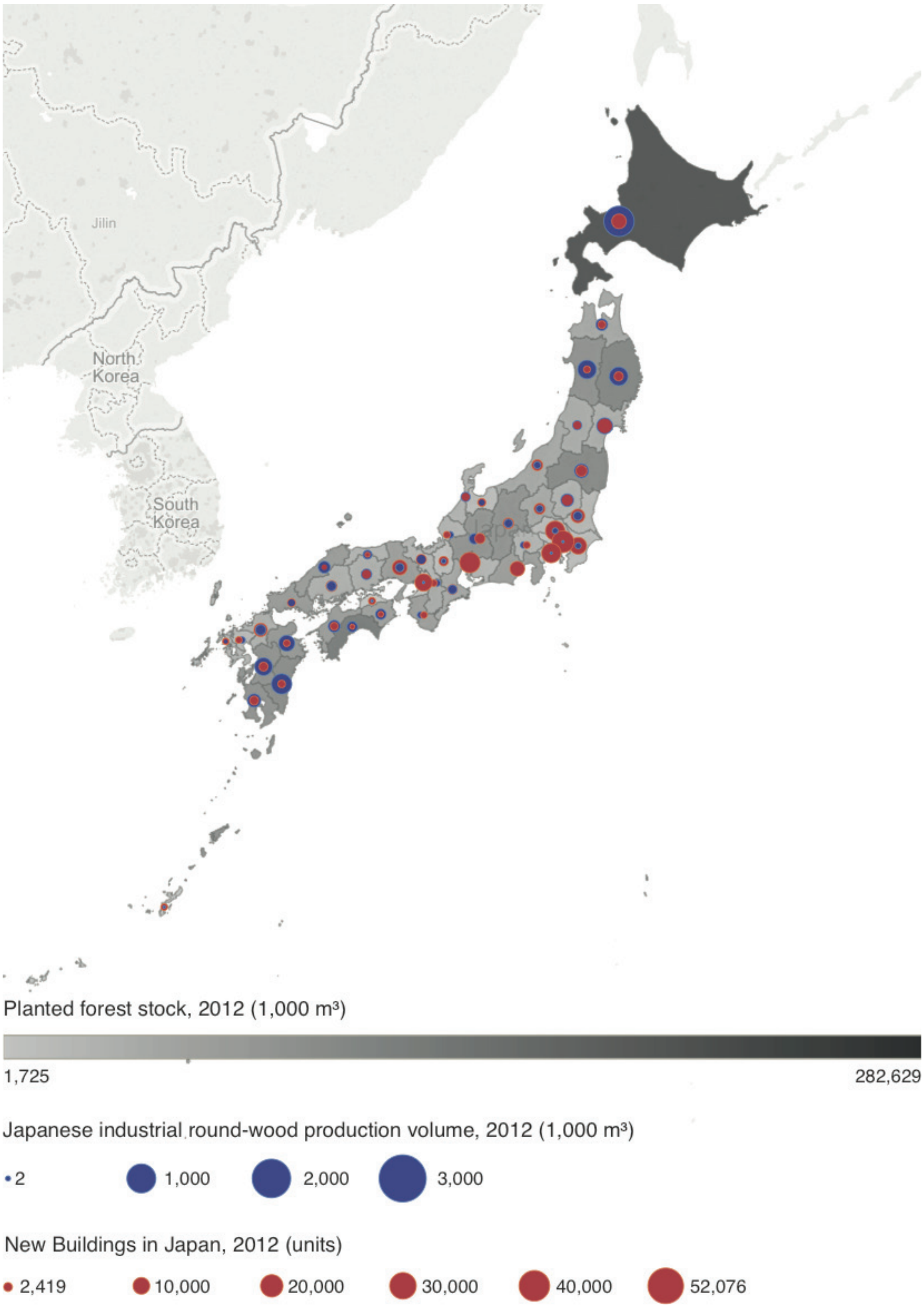


Figure 1.1.19. Forest stock, round wood production and new building units in Austria, 2009. Source: raw data retrieved from BFW, 2015 and Statistics Austria, 2015.

Figure 1.1.20. Forest stock, round wood production and new building units in Japan, 2012. Source: raw data retrieved from Forestry Agency 2015; MAFF, 2014 and MLIT, 2015.



As discussed above, abundant readily available mature Spruce or Japanese Cedar stock can supply sawn timber to the production of value-added timber products, such as CLT in both countries. However the more even age distribution observed in Austria enables further increasing the production in a longer span of time if necessary. On the other hand, due to the uneven age distribution, and especially the small amount of growing young trees, if the demand for mature Japanese Cedar increases without prior forest management, the timber industry segment employing this material could be facing a supply shortage on the mid to long term.

Finally, it is worth noting that Austria imports a small amount of timber, most of it in a raw processed format, such as round wood. Then, value-added timber products are manufactured with the round wood supply and exported. On the other hand, Japan imports both raw and processed timber products, to supply its domestic market. Hence, Japanese CLT domestic demand would most likely depend on its acceptance and diffusion in the national construction market, more specifically, in the dwellings construction segment that accounts for the biggest share of new buildings in Japan (topic 2.1.2).

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1.2 CLT Manufacturing

Abstract: This chapter investigates the possibilities and limitations for Japanese CLT from the manufacturing point of view. This chapter is divided into three topics, the first two analyse the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place. Hence, by the comparison with Austria, possibilities and limitations for Japanese CLT from the manufacturing point of view can be comprehended. It was found the location of CLT manufacturing facilities close to forest reserves in Austria is critical to reducing freight costs, whereas, in Japan, the location of one manufacturing facility far from wood extraction point may have an adverse impact on the panel cost. Furthermore, current small demand for CLT in Japan does not enable to employ full potential economy of scale from the automation as seen in Austria, once more threatening a cost-effective production of CLT panels. Finally, the little strength of Japanese cedar lamellae limits the use of CLT for out-of-plane loads due to its relatively low modulus of elasticity, which requires either a larger section or the use of CLT panels combined with other structural elements. Either way, this may hinder application possibilities and demand for the product, forming a vicious circle.

1.2.1 Austrian CLT

1.2.1.1 GOAL

The objective of this topic is to understand the possibilities and limitations for Austrian CLT from the manufacturing point of view.

1.2.1.2 METHOD

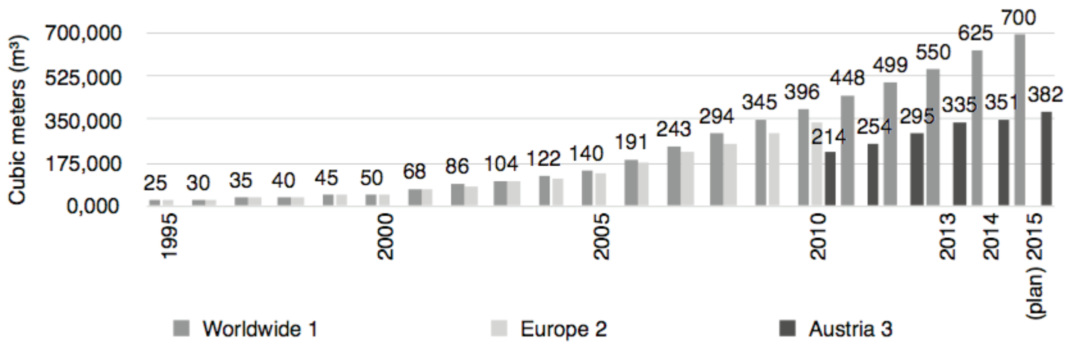
At first, a brief review of the current worldwide situation of CLT manufacturers is presented. The information was gathered from related publication and company personnel. After, the main characteristics of Austrian CLT panels, such as lamellae properties, adhesive type, standard dimensions and moisture content were retrieved from the website of the four biggest European manufacturers. Then, a case study analysing CLT manufacturing process in two of the leading Austrian manufacturing companies was developed. The information was obtained by the author during a visit to Stora Enso's Bad St. Leonard factory on August 2016 and Mayr Melhof Holz's Gaishorn Factory on September 2016. Finally, the relationship between the main features of CLT and the manufacturing process was discussed.

1.2.1.3 RESULTS

Worldwide review
History
CLT was developed during the 1990's in Central Europe's German-speaking area, formed by Austria, Switzerland and Germany. The original demand came from the Austrian Sawmill Association that at the time was facing problems to sell smaller sectioned sawn-timber pieces from the outer part of the log, obtained as a result of the log processing for more robust pieces. CLT was then idealised to make use of this side-product and emerged from a joint research effort between university and industry. As an outcome of the research, CLT's earliest manufacturer, KLH was founded and a three storeys multi-family building employing CLT structure was erected at Alchach, Germany in 1995 (Brandner et al. 2016). The first standard for CLT would come a bit later in 1998, and from after that an increasing number of buildings started to take shape in Europe in the following decades and more recently in other parts of the world, such as North-America, Oceania and Asia.

Since the beginning of CLT's commercialisation in the mid–1990's, the production volume grown at a fast pace. From 1995 to 2005 an increase bigger than 500% was seen and, in spite of the economic recession that started on 2008, worldwide CLT production volume kept growing steadily during the next ten years, once more reaching a fivefold increase from 2005 to 2015. However, a different pattern is seen when comparing these two periods. During the first 10 to 15 years, CLT production was led by the European manufacturers, especially the ones located in the German-speaking countries. In the second period, the production increment in those countries started to slow down and in 2015, an expected increase value around 10% (Plackner 2014b) has turned into a modest 3% (Plackner 2015c). Simultaneously, a decentralisation tendency for CLT production started to take shape in the last five years, with new manufacturers starting production lines outside the European continent in North America, Oceania and Asia, which kept the worldwide production volume of CLT growing, achieving a total of 700 thousand m3 in 2015. (figure 3)

Figure 1.2.1. Worldwide CLT production volume. Source: 1.(Brandner et al. 2016); 2.Schickhofer, (2011), 3.(Plackner 2015c).



Manufacturers

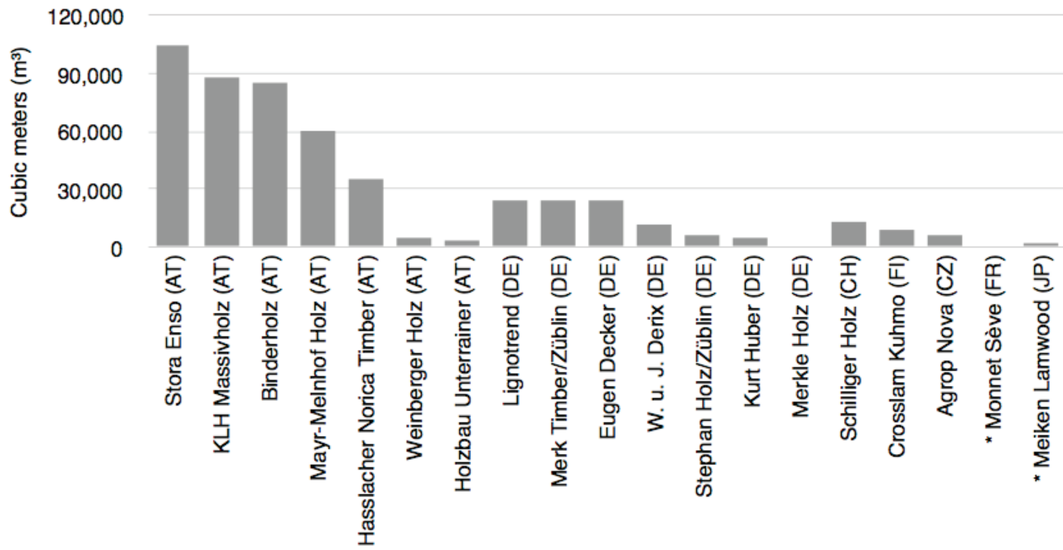
According to Plackner (2015b), there are currently 37 CLT manufacturers around the world, spread across three different continents and 13 different countries. Nevertheless, the majority of them (30 manufacturers) are still found on the European continent. Furthermore, German-speaking countries concentrate 16 manufacturers, almost half of them just in Austria.

All these manufacturers have been contacted by the author in April 2016 and inquired about their total CLT production volume in 2015 and type of press utilised. Eight of them have answered the inquiry, and six have contributed with some of the information mentioned above. After, the retrieved information was complemented with data from the Holzkurier Magazine published by the Österreichischer Agrarverlag (Austrian Agriculture

Publisher). On total, CLT production values for 19 manufacturers in 7 different countries could be gathered.

Figure 1.2.2. CLT manufacturers in the world. Source: (Plackner 2015b),(2015c)

Figure 1.2.3. CLT production volume by companies, 2015 (m3). Source: Plackner 2015c, except "*"



Europe

Austria

CLT production volume in Austria grew fast until 2010 when, contrary to the optimistic predictions, the pace has suddenly slowed down. Nevertheless, the country still figures out as the largest world producer of CLT. Altogether, the seven companies located in Austria accounted for over 380 thousand m3 of CLT in 2015, representing more than half of the world production volume and 3/4 of the surveyed companies volume.

CLT production volume growing decrease in Austria was a direct result of the lack of substantial investments in the production line that followed 2008's financial crises (Plackner 2014b), thus representing a temporary slump in the sector. Currently, Austrian CLT main manufacturers are employing their full production capacity. For instance, the waiting time for CLT elements in Mayr Melhof doubled the average time. Hence new investments on the expansion of CLT production lines have already started to take shape, such as Stora Enso new CLT production plant in Sweden. Therefore, Austrian manufacturers still play the leading role in CLT development not only considering the production volume itself but also regarding CLT building solutions. Examples such as the push towards standardisation in the past few years (Brandner et al. 2016) and the new volume elements building systems being developed by Stora Enso and Haslacher Norica are evidence.

Germany has seven companies manufacturing CLT, which altogether produced almost

100 thousand m3 in 2015, thus making it the second largest production per country, nevertheless representing no more than 1/3 of Austria's volume. Among the German-speaking countries, Switzerland has the fewest companies manufacturing CLT - only two - one them providing no more than 13 thousand m3 on 2015. On the other hand, the smaller facilities seen in these two countries provide a more flexible production line and owing to that fact, some different types of CLT panels could be developed, such as Lignotrend in Germany and Pius Shuller in Switzerland, both offering mass timber panels with hollowed sections. The benefits of such solutions would include easier installation of building services and insulation as well as a reduced weight per area unit when compared to a completely solid panel.

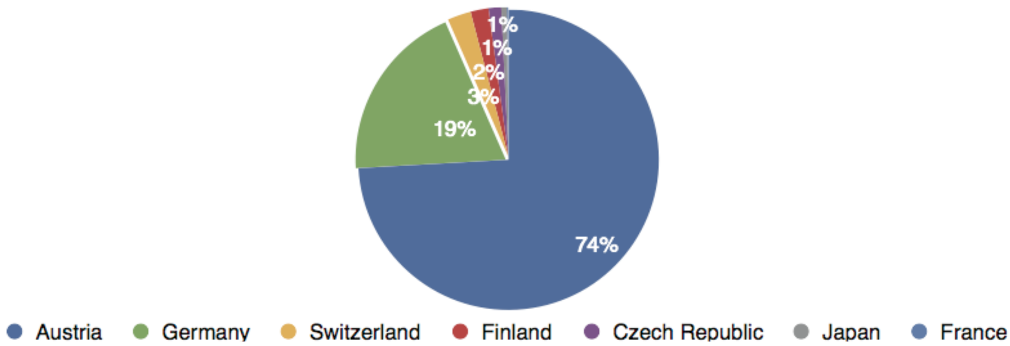


Figure 1.2.4. CLT production volume by country, 2015. Source: (Plackner 2015c)

Czech Republic

Not far from the German-speaking zone, Czech Republic's Agrop Novatop company has been producing its version of CLT, since 2011. What is unique to this material is the assembly of building elements only by combining thinner three-layered CLT panels. Moreover, the outer layers of each panel are composed by 9 mm thick lamellae, kiln-dried up to 8% moisture content, to prevent checks and cracks from happening after installation, as timber moisture content would only tend to increase under normal service conditions, thus assuring the proper airtightness of the elements. (Passarelli 2013)

France

Among other Central European countries, four companies manufacturing CLT could be found in France. One of them (Monnet Seves) has started CLT production line in 2014 using a vacuum press and has a total production capability estimated around 20 thousand m3 (Plackner 2013), though a total volume near 2 thousand m3 of CLT has been forecasted for 2016.

Italy

The Mediterranean countries count with seven companies producing CLT, only one in Spain, located in the Basque Country and the remaining 6 in Italy, all of them situated in the northern part of the country. One of these companies, Artuso Legnani, claims to be producing CLT since 2010, (Artuso Legnani, 2016)

Sweden

Martinsons company in Sweden was probably the first to manufacture CLT outside Central Europe. Its production started back in 2003, less than ten years after the beginning of CLT commercialisation in Austria. Narrow panels up to 1.2 meters wide have been provided for 13 years until a recent investment of 10 million dollars was made on the production line. Hence, starting from the autumn of 2016, the company expected to triple its initial production volume, manufacturing 3 meters wide panels. (Martinson, 2015)

Finland

As opposed to Sweden, Finland started its domestic CLT production rather late on 2015 (Plackner 2014a). One reason that would partly explain the delayed beginning of CLT in a country well known for its high-quality timber reserves and wooden architecture tradition may be exactly some sort of resistance against foreign materials and the existence of the domestic developed Kerto panel (LVL). However, after CLT has had a few successful applications in Finland, all employing Austrian CLT made by Stora Enso, such as the nine storeys high Puukuokka Building in Jyväskylä, Crosslam Kuhmo decided it was time to fill the gap in the national market for domestic CLT.

North America

Canada

On 2011, Structlam Products was established in Canada and started domestic CLT production. CLT buildings quickly gained momentum in the country associated with renowned Canadian Architecture offices, the image of innovative timber construction and strong sustainability appeal. Furthermore, a couple of them became references projects in the field, like the “Earth and Sciences Building” (2012) designed by Perkins + Will office and the “Wood Innovation and Design Centre” (2013) designed by Michael Green Architects, both of them located in British Columbia. Additionally, the engagement of Michael Green Architects disseminating CLT should be mentioned, not only introducing the material in buildings like the one above but also actively promoting it by the development of the Tall Wood study (mgb ARCHITECTURE + DESIGN 2012) in 2012 and the TED talk lecture in 2013.

The United States of America

In the USA, Smartlam Group started the first CLT production line in 2015, employing most of its production for industrial sites matting. However, the company planned a new CLT manufacturing plant during 2016, oriented towards the production of building elements. The new plant has the potential to become the largest single CLT production plant in the world, achieving up to 110 m3/year and surpassing Binderholz plant in Austria (Plackner 2015a). One of the reasons for increasing CLT production in what is otherwise almost a CLT buildings-free country lies in the fact that it is foreseen as a cost-effective solution for the mid-storey residential construction. According to cost estimations presented in the American version of the CLT Handbook, a five-storey CLT building should cost 3% less than a reinforced concrete one (Plackner 2014c), thus opening a promising market for CLT buildings in North America. To confirm whether this prediction will prove to be true or not a few more years are necessary.

Other regions

Japan

Meiken Lamwood started domestic CLT production in Japan during 2011. In the period from the beginning of its commercialisation the end of 2016, about 30 buildings employing CLT have been completed across the country. As the market grows, so does the production volume and Meiken started a new CLT manufacturing plant in the spring of 2016, increasing its production capability up to 6 times more than the previous one. Even though a natural increase in the complexity and size of buildings executed can be seen along the period, so far, the direction of market diffusion is still unclear and, for instance, as opposed to the Canadian case, Japanese CLT still has not been used in prominent buildings or by internationally acclaimed architects.

New Zealand

NZ XLam was the first CLT manufacturing company established in the southern hemisphere. The production utilises a vacuum press and has started back in 2012 (Ellegard 2012).

Main Austrian Manufacturers

The production of European CLT is concentrated in Austria, lead by the four largest CLT manufacturers. Stora Enso (100 thousand m3), KLH Massivholz GmbH (88 thousand m3), Binderholz Bausysteme GmbH (85 thousand m3) and Mayr Melholf Holz Holding AG (60 thousand m3) own a total of seven CLT manufacturing facilities distributed in four different regions. Stora Enso has 2 CLT manufacturing plants, one in Lower Austria and one in Carinthia region. Mayr Melhof Holz and KLH have two plants each, all located in Styria region, and Binderholz has one CLT plant located in Salzburg region. Furthermore, all of them employs C24 (and at most 10% of C16) Spruce lamellae as the primary material for CLT. Additionally, it is also possible to choose different softwood timber species, such as Pine, Fir and Larch for the outer layers. Lamellae thickness varies mostly from 20 to 40 mm, though Mayr Melhof Holz utilises 10 mm thick lamellae, while Stora Enso uses lamellae up to 80 mm thick. In all companies, crosswise layers are bound by Formaldehyde-free Polyurethane adhesive sprayed on each lamellae layer surfaces. Stora Enso also bonds each layer of lamellae sideways.

Table 1.2.1. Lamellae properties according to DIN–1052 (N/mm2).

	C 16	**C 24**
Strength	N/mm²	N/mm²
Bending parallel	16	24
Tension parallel	10	14
Tension perpendicular	0.4	0.4
Compression parallel	17	21
Compression perpendicular	2.2	2.5
Shear and torsion	2.7	2.7
Stifness	N/mm²	N/mm²
Modulus of elasticity parallel	8000	11000
Modulus of elasticity perpendicular	270	370
Modulus of shear	500	690
Dimensional change per %MC		
Tangential direction	0.24%	0.24%

Overall, panels with 3, 5 or 7 layers are manufactured from 2,4 m to 3 m wide by 8 m to 16 m long. Stora Enso also provides an 8-layered CLT panel. Binderholz offers a narrower panel, only 1.25 m wide, but up to 24 m long and a wider panel, 3.5 m by 22 m long. Nevertheless, all companies claim to deliver the finished CLT panel or element with 12% (+–2%) moisture content (MC). Furthermore, according to the information disclosed in the catalogues of the manufacturers, each percentile change in the MC of timber shall result in an average dimensional change of 0.01% on the length and 0.24% in the perpendicular direction. All analysed companies also provide three different surface quality types of panels: visible, standard and non-visible. The first type is recommended for permanently visible surfaces; hence the incidence of defects such as knots, resin pockets, colour variation and discoloration are reduced to a minimum. The second type allows such defects occasionally; thus the panels are suitable for buildings with low requirements on surfaces. The last type is intended for applications where no requirements for surface appearance are needed or when the panels are all covered, for the incidence of defects are the highest of all the types.

Table 1.2.2. Austrian CLT main features by manufacturer.

	Stora Enso	**MMH**	**KLH**	**BBS 125**	**BBS XL**
Lamella					
Species	Spruce, Pine or Larch (cover). Spruce, Pine	Spruce (other species on request)	Spruce (other species on request)	Spruce, larch, stone pine, white fir	Spruce
Width (mm)	>130 ~ 230	N/A	N/A	N/A	N/A
Thickness (mm)	20, 30, 40, 60, 80	N/A	10 ~ 45	20, 30, 35, 40	20, 30, 35, 40
Timber grade	C24 (up to 10% C16)	C24 (up 10% C16)	C24 (up 10% C16)		
Adhesive	PUR	Melamine or PUR	PUR	PUR	PUR
Bonding	edge, surface	surface	surface	N/A	N/A
Panel					
Width (cm)	245, 275, 295	240, 265, 275, 290, 300	240,250, 273, 295	125	350
Length (m)	8 ~ 16	16.5	8.5 ~ 16.5	24	22
Thickness (mm)	60 ~ 320	60 ~ 280	57 ~ 320	60 ~ 340	60 ~ 200
Layers	3, 5, 7, 8	3, 5, 7	3, 5, 7	3, 5, 7	3, 5
Moisture Content (%)	12 (+-2)	12 (+-2)	12 (+-2)	12 (+-2)	12 (+-2)
Change in length /%MC	0.02%	0.01%	0.01%	0.01%	0.01%
Change perpendicular /%MC	0.24%	0.20%	0.24%	0.025%	0.025%
Surface quality	Visible, Industrial visible, Non-visible	Living space, Standard, Industrial	Domestic visible, Industrial visible, Non-visible	Residencial visible, Industrial visible	Residencial visible, Industrial visible, Non-visible
Building physics					
Vapour diffusion resistance	20 ~ 50	60	25 ~ 50	40 ~ 70	40 ~ 70
Thermal conductivity	0.11 W/(mK)	0.10 W/(m2K)	0.13 W/(mK)	0.13 W/mk	0.13 W/mk
Airtightness	outside measurable range	Airtight from 90 mm thick	generally airtight	Airtight from tree layers	Airtight from tree layers
Fire resistance					
Reaction to fire	D-s2, d0	D-s2, d0	D-s2, d0	D-s2, d0	D-s2, d0
Charring rate (mm/min)	NA	0.64 ~ 0.71	0.67 ~ 0.76	0.67 ~ 0.74	0.67 ~ 0.74

Austrian CLT manufacturers produce panels with similar thermal-conductivity values, varying from 0.10 to 0.13 W/mK. On the other hand, a small difference could be seen regarding their airtightness properties. Mayr Melhof Holz and Binderholz attest airtight performance for panels more than three layers thick. KLH vaguely states CLT panels are generally airtight. Stora Enso is the only among all four company that assures its panels are airtight to a point volumetric rates of flow were outside the measurable range, based on a normative test (EN 12114). Regardless of the company, from the flammability point of view CLT panels are classified as combustible with medium smoke generation. Additionally, fire resistance was similar for all companies, showing charring rates ranging from 0.64 to 0.74 mm/min.

Taking into account the aforementioned C24 timber properties and considering that only one type of grade is utilised, Composite Theory Method (Gangnon and Pirvu 2011) was employed (with cross-layer bending properties set as 1/30 of longitudinal layers) to obtain the values for a five-layered CLT panel (30 mm thick lamella).

Table 1.2.3. Main properties of Austrian CLT panel employing Composite Theory Method.

		Strength	**Stiffness**
Out-of-plane			
Bending	Parallel	19.18	8789
	Perpendicular	9.39	2581
In-plane			
Bending	Parallel	14.72	6748
	Perpendicular	10.08	4622
Tension	Parallel	8.59	6748
	Perpendicular	5.88	4622

Case study: Stora Enso - Bad St. Leonhard factory
CLT manufacturing in Bad St. Leonhard started in 2008. About 200 people were working in the whole plant at the time of the visit, 60 of them only in the CLT division. In 2015, about 50 thousand m3 of CLT were produced, and around 60 thousand m3 are expected for 2016. The biggest feature of the CLT panels from Stora Enso is the execution of edge glueing to ensure full airtightness, regardless of the number of layers.

Manufacturing process
Timber grouping
Kiln-dried, graded Spruce lamellae are provided by the sawn-timber division. The pieces

have the moisture content checked, and are laser scanned for defects such as knots, checks, slope of grain, etc. After, the pieces are separated according to the desired mechanical or aesthetic properties.

Finger-joint milling

The sorted out Spruce lamellae are finger-jointed at the end grain (width direction) and bonded by a polyurethane-based adhesive. Two or more pieces are joined and automatically cut to the desired length, following the design of the panel to be made. The lamellae are then sanded to prevent surface irregularities at the finger jointing point.

Edge glue

EPI bonding is sprayed into the finger-jointed lamellae edges, and a conveyor belt places then side-by-side, thus creating a single-ply panel. Once the desired width is reached, a circular blade cuts the single-ply panel in the longitudinal direction. Currently, three different width dimensions are used for the single-ply panel, 2.45, 2.75 and 2.95 meters.

Lamellae positioning

The single-ply panels are positioned on two tables, each placed at one side of the press, arranged perpendicular to lamellae positioned on the opposite side table.

Panel lay-up

A vacuum-suction crane is used to move one single-ply panel at a time and place it on the centre table. After, single component polyurethane adhesive is sprayed on the surface of the lamellae layer by nozzles installed on a beam that runs longitudinally on top of the centre table. Then, the following layer is placed, and the same procedure is executed until all layers are stacked, according to the desired panel layout. Additionally, more than one panel can be assembled on top of each other if thinner panels are being pressed.

Pressing

After all the layers are placed, the panel is transferred to the pressing table by conveyor belts and pressed from above by a hydraulic press (0.6 N/m2) during 20 to 25 minutes. The press is divided into a first large 8 meters wide press, followed by a set of one meter wide presses next to each other. By doing so, fewer presses can be utilised in case of a smaller length panel, thus saving energy used for pressing.

Figure 1.2.5. Stora Enso CLT manufacturing step 1: timber grouping.

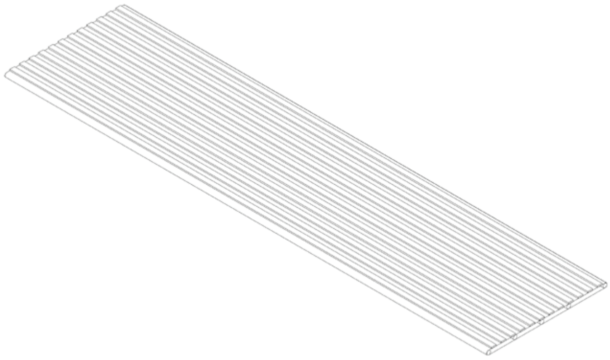
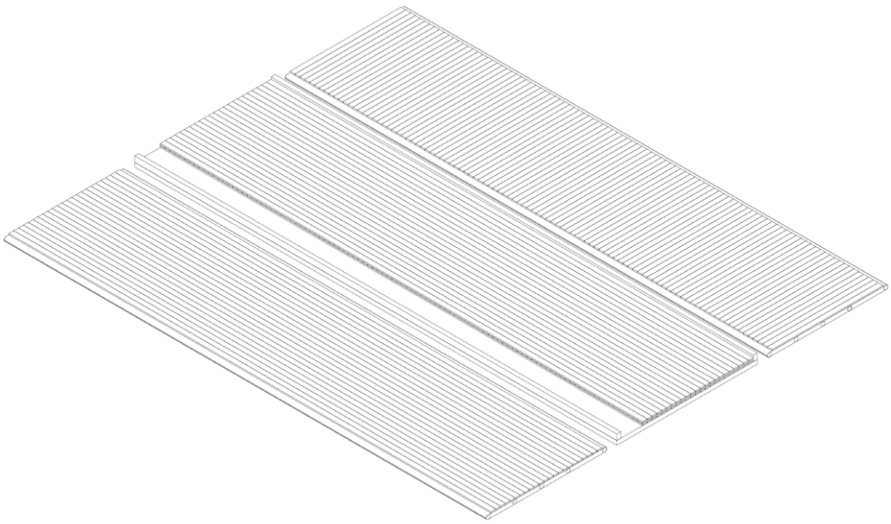


Figure 1.2.6. Stora Enso CLT manufacturing step 2: finger-joint.

Figure 1.2.7. Stora Enso CLT manufacturing step 5: panel arranging.



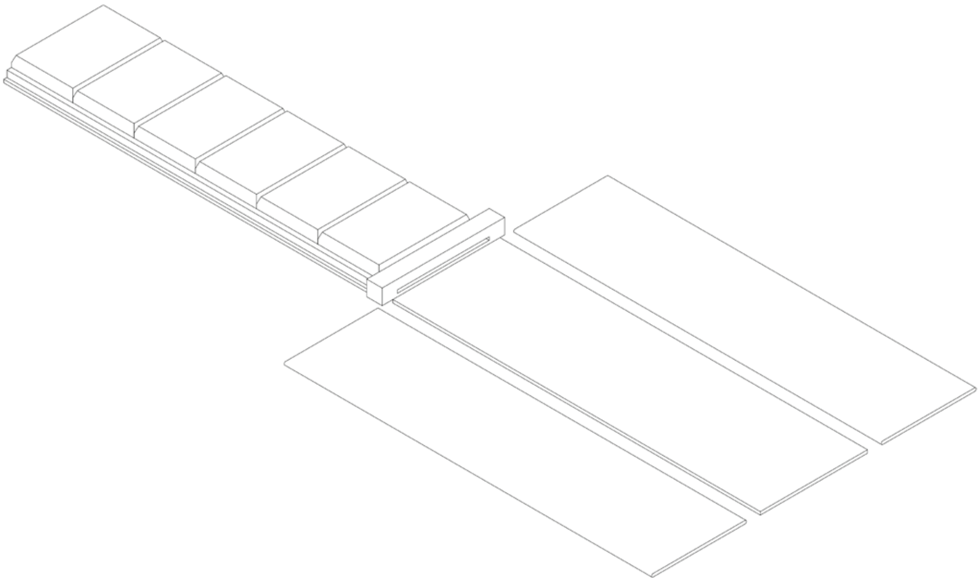


Figure 1.2.8. Stora Enso CLT manufacturing step 6: pressing.

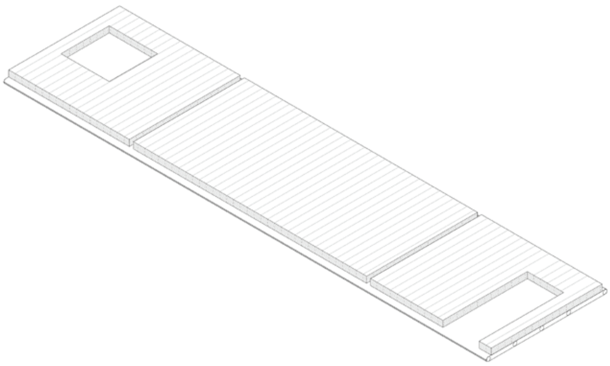


Figure 1.2.9. Stora Enso CLT manufacturing step 6: panel milling.

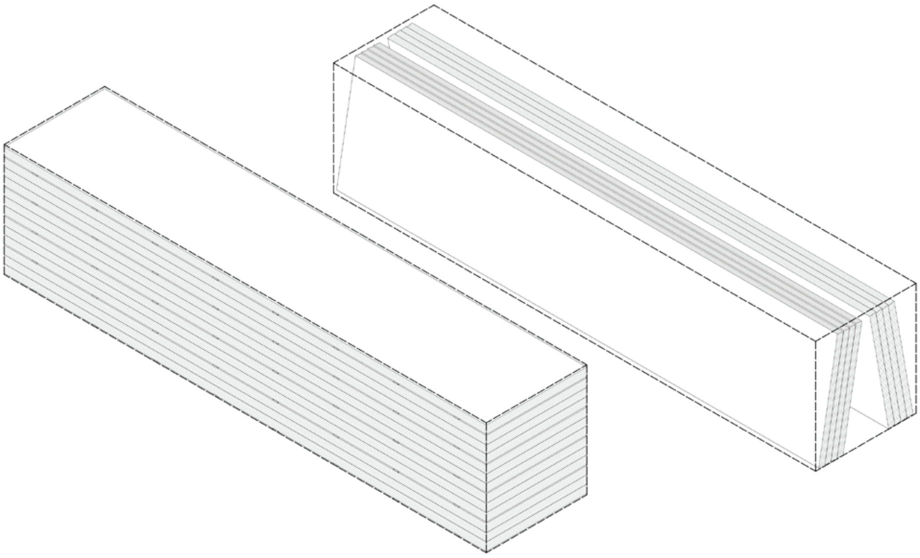


Figure 1.2.10. Stora Enso CLT manufacturing step 7: shipping.

Panel milling and mending

The CLT panel is then sanded to achieve a homogeneous and smooth surface. After, the panel is conveyed to CNC machine that mills the big panel into smaller building elements such as wall, slabs or roof elements. At this step, openings for doors and windows, as well as grooves for installations can be executed. At the moment of the visit, the factory had two Hundegger CNC machines to mill the finished CLT panels. Additionally, if necessary, surface defects such as knots will be amended by hand using wooden dowels.

Panel packaging and shipping

CLT building elements are inspected, wrapped and identified by a tag. Finally, a crane is used to load the elements on the truck or container, either horizontally or vertically. The former loading pattern is recommended for more robust elements such as slabs and presents a better usage of space, whereas the latter is appropriate to more milled and thus more fragile elements, such as walls with large or numerous openings.

Case study: Mayr Melhof Holz - Gaishorn am See factory

CLT manufacturing facilities in the Gaishorn factory of Mayr Melhof Holz's were built on 2008, after an investment of about 20 million euros. In the beginning, CLT panels were produced employing only melamine adhesive. However, from 2015, an option for CLT panels bonded by polyurethane adhesive was also added to the production line. Besides the CLT plant, the Gaishorn complex is also composed of three glulam, one CLT and one plywood manufacturing plants, one timber grading facility, five deposits for sawn timber, one deposit for finished timber products and 19 drying kilns.

Manufacturing process

CLT manufacturing process in Gaishorn site is highly automated, and only about 10 to 15 workers were along the production line at the time of the visit, 1/3 of them assigned to the milling and mending stage (step 6). Also, due to extremely high demand for CLT, most of the Austrian producers are operating very close to full capacity. Nevertheless, delivery time in Mayr Melhof, for instance, have increased from 34 to 7 weeks. CLT manufacturing process main steps are listed bellow:

Timber grouping

Kiln-dried, graded Spruce lamellae are provided at 12% (+−2) moisture content. The pieces are laser scanned for defects such as knots, checks, slope of grain, etc. and then separated according to the desired mechanical or aesthetic properties.

Finger-joint milling
The sorted out Spruce lamellae are finger-jointed at the end grain (thickness direction) and bounded by a single component polyurethane adhesive. Two or more pieces are joined and left to dry for about 12 hours on conveyor mats. Them the lamellae are sanded at the finger joint to prevent for any surface irregularities and cut to the desired length, following the design of the panel to be made.

Lamellae positioning
Finger-jointed lamellae are positioned on two tables, each placed at one side of the press, arranged perpendicular to lamellae positioned on the opposite side table.

Panel lay-up (2 different options)
A vacuum-suction crane is used to move one set of lamellae at a time and place then on the press. After, a heat-cured single component polyurethane adhesive or melamine based adhesive is sprayed on the surface of the lamellae layer by nozzles installed on a beam that runs longitudinally on top of the press. Then, the following layer is placed, and the same procedure is executed until all layers are stacked, according to the desired panel layout.

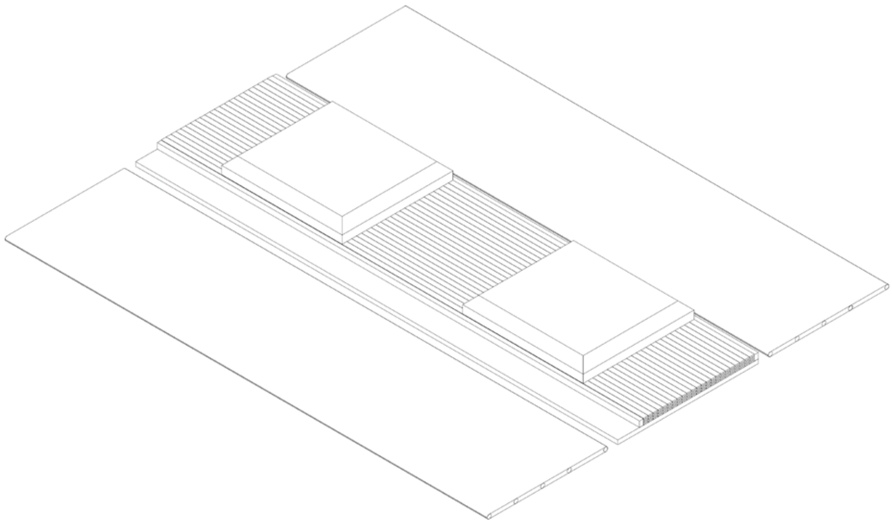


Figure 1.2.11. Mayr Melhof CLT manufacturing step 6: Melamine type panel pressing.

Pressing
4a. Melamine type: After all the lamellae layers are placed, they are pushed laterally, to obtain a gap-free surface and then pressed from above by a hydraulic hot press during 3 to 6 minutes. In fact, as the use of one large press would require too much energy, thus increasing the production cost accordingly, two 3 meters wide microwave presses, spaced

3 meters from each other are employed. Because smaller presses are used, and the pressing has to happen through all the length of the panel, after each 8 minutes of pressing, the whole panel is slid 3 meters sidewards and pressed again. This process is repeated until all the length of the panel passes through the press.

4b. Polyurethane type: After all the layers are placed, the panel is transferred to the pressing table by conveyor belts and then pressed from above by a hydraulic press during 20 to 25 minutes. The press is divided into a first large 8 meters wide press, followed by a set of one meter wide presses next to each other. By doing so, fewer presses can be utilised in case of a smaller length panel, thus saving energy.

Panel milling and mending
The pressed CLT panel is then sanded, to achieve a homogeneous and smooth surface. After, the panel is conveyed to the CNC machine that mills the big panel into smaller building elements such as wall, slabs or roof elements. At this step, openings for doors and windows, as well as grooves for installations can be executed. Additionally, if necessary, surface defects such as knots will be amended by hand using wooden dowels. It worth mentioning that because only one CNC machine is used, this is current the bottleneck of CLT production line. That means, even if the whole production capacity was utilised, only about half of it could be milled at this stage.

Panel packaging and shipping
CLT building elements are inspected, wrapped and identified by a tag. Finally, a crane is used to load the elements on the truck or container, either horizontally or vertically. The former loading pattern is recommended for more robust elements such as slabs and presents a better usage of space, whereas the latter is appropriate to more milled and thus more fragile elements, such as walls with large or numerous openings. Due to the large demand and accordingly tight schedule in which the factory is currently operating, if necessary, panels can be stored for about two days in front of the CLT plant before they are loaded into the trucks.

1.2.1.4 DISCUSSION

Austria, the country where CLT was first produced, still leads the world production and development of CLT. Nevertheless, in the past few years, a tendency for decentralisation can be observed. Foreseeing future market possibilities for the material, countries with established timber construction culture like Finland, Canada, USA and Japan have also started developing their manufacturing facilities. Canada portrayed a case where CLT construction value was associated with innovative architecture and sustainability to favour its diffusion. USA is counting with the cost-effectiveness of CLT construction and taking the risk of the investment. Additionally, timber reserves are abundant in both places, and timber structures are commonly used for housing construction. As this context shares some similarities with the Japanese one, if CLT turns out to be successful is these countries, it could be worth investigating them as a reference for Japan. However, as CLT development in North America is yet far from reaching a stable situation they still can not be used as a reference for the development of CLT in Japan. On the other hand, Austria present a similar scale to Japan, regarding forest reserves and timber industry, which means the gathered data can be directly compared. Additionally and most important, not only it is the country in which CLT's know-how has been gathered for the most time, thus making it a rich information source about the subject, it also takes a lead role in the development of CLT building technology. Finally, Austrian CLT presents a stable situation compared to the other surveyed countries, meaning it can act as a reference and balances the dynamic Japanese situation at the moment.

Softwood Spruce sawn-timber is employed as the primary material for the CLT panel in Austrian. As CLT production requires abundant timber supply for the smallest cost possible, the analysed Austrian CLT manufacturing facilities are closely located to large forest resources to reduce the transportation distances between the raw-material extraction place and the facilities in which it is processed, thus reducing freight cost incidence on the raw material. It is worth note that representatives from both analysed companies have stressed this strategy as round-wood and sawn-timber lamellae are a low-value product and added transportation costs would represent a larger part of the raw material cost, thus affecting the final CLT panel price. Hence, the location of manufacturing plants can potentially influence the economic value of the final CLT panel. Furthermore, the companies also obtain the Spruce timber lamellae straight from their saw-mill divisions, providing them full control over the supply and quality of the primary CLT raw material. Considering the direct relation between the employed timber lamellae properties and CLT panel physical and mechanical properties observed during the study, ensuring supply of high-quality lamellae is crucial for CLT panel value generation from the "Technical" and "Functional Subjects" point of view. Finally, the polyurethane adhesive employed for the bonding of CLT layers determines a relatively short time-limit between the time the adhesive is sprayed until the panel is pressed. As a result, a more robust manufacturing line with a higher degree of automation is required. The use of Melamine based adhesive for CLT production observed in Mayr Melhof was justified by the company owing to its higher charring rate, in spite of its formaldehyde emission. Either way, CLT production "on-demand" is performed in both cases, meaning CLT elements are produced and shipped within the shortest possible time. Besides, current high demand for CLT requires Austrian manufacturers to work close to their full capacity. The constant production flow leads to an economy of scale, which has a positive effect on CLT panels from the economic point of view.

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1.2.2 Japanese CLT

1.2.2.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT from the manufacturing point of view.

1.2.2.2 METHOD

At first, the main characteristics of Japanese CLT panels, such as lamellae properties, adhesive type, standard panel dimensions and moisture content were retrieved. Then, a case study analysing CLT manufacturing process in Meiken Lamwood Corporation was developed. The information was retrieved by the author during an interview with a representative from the company in November 2015 and from the website of the manufacturers. Finally, the relation between the main features of CLT and the manufacturing process were discussed.

1.2.2.3 RESULTS

Main Manufacturers
Perhaps the first experience with CLT in Japan dates from 2007, when a seismic resistance test was performed for a five stories building at the E-defense shaking table, utilising European Spruce CLT. Since then, ongoing efforts to develop and promote new timber products aiming at expanding domestic timber utilisation and timber construction in the country were made by related governmental authorities and associations (Forestry Agency 2013). Inside this context, CLT has arguably been one of the most debated and studied engineered timber products during the time.

At the time this topic was written (November 2015), two different companies were manufacturing CLT in Japan: Meiken Lamwood Corporation Ltd. and Yamasa Mokuzai Corporation Ltd., each of them owning one manufacturing plant in Okayama and Kagoshima prefecture respectively. So far the companies are essentially employing Japanese Cedar lamellae M60 grade, usually on the outer layers, whereas lower graded lamellae (M30A) is used for the inner layers, always 30 mm thick.

Figure 1.2.12. Five-stories CLT building shaking table test at the National Research Institute for Earth Science and Disaster Resilience, in Miki City, 2015.

Table 1.2.4. Lamellae properties according to JAS CLT - draft version.

	Sugi M60A
Strength	N/mm^2
Bending parallel	20
Tension parallel	12
Tension perpendicular	21.3
Stifness	N/mm^2
Modulus of elasticity parallel	5000
Modulus of elasticity perpendicular	167
Dimensional change per %MC	
Tangential direction	0.26%

Table 1.2.5. Japanese CLT main features by manufacturer.

	Meiken
Lamella	
Species	Jap. Cedar (other species on request)
Width (mm)	120
Thickness (mm)	30
Timber grade	M60A
Adhesive	EPI
Bonding	surface
Panel	
Width (cm)	300
Length (m)	12
Thickness (mm)	90 ~ 210
Layers	3, 5, 7
Moisture Content (%)	> 15
Change in length /%MC	NA
Change perpendicular /%MC	0.25 ~ 0.29%
Surface quality	One type only
Building physics	
Vapour diffusion resistance	NA
Thermal conductivity	0.12 W/mK
Airtightness	NA
Fire resistance	
Reaction to fire	NA
Charring rate (mm/min)	0.7

Overall, panels with 3, 5, 7 or 9 layers are 3 m wide by 12 m long and delivered with a moisture content (MC) equal or lower than 15%. Furthermore, each percentile change in the MC of timber would result in an average dimensional change of 0.25 ~ 0.29% in the perpendicular direction and no significative change in length. Fire resistance properties of Japanese Cedar CLT are reported to have an average charing ratio near 0.70 mm/min, according to the experiments by Naruse (2015).

Taking into account M60 timber properties and considering only lamellae with this grade is utilised, Composite Theory Method (Gangnon and Pirvu 2011) was employed (with cross-layer bending properties set as 1/30 of longitudinal layers) to obtain that basic properties of a five-layered CLT panel (30 mm thick lamella).

Table 1.2.6. Main properties of Japanese CLT panel employing Composite Theory Method.

		Strength	Stiffness
Out-of-plane			
Bending	Parallel	15.98	3995
	Perpendicular	7.82	1172
In-plane			
Bending	Parallel	12.27	3067
	Perpendicular	8.40	2100
Tension	Parallel	7.36	3067
	Perpendicular	5.04	2100

Case study: Meiken Lamwood Corporation - Maniwa factory
The first CLT trial products were made on 2011 yet in a hand-made process. The completion of the press machine in July 2012 has made possible to start CLT mechanised production, however still inside the glulam production facilities. Nevertheless, in April 2016 a new facility, solely for CLT manufacturing was completed employing a larger press and thus increasing CLT production capacity. When CLT manufacturing has been taking place in the facility built for glulam production, investment was only necessary for obtaining the press machine and built the conveyors lines, requiring about 130,000,000 yens (60,000,000 subsidies). At the time the maximum production capability was about 5 thousand m3. The new facility, however, was built from scratch after an investment of about 3,660,000,000 yens (2,565,000,000 subsidies) and can provide up to 30 thousand m3 of CLT panel per year. However, likewise in the case study of Mayr Melhof case, panel milling is limited by CNC machine. Hence, currently, only about half of the production capacity can be processed.

Meiken is manufacturing CLT panels using native timber species, most of it Japanese Cedar (90%), supplied by subsidiary saw-mill companies located in Kumamoto (Kyūshū) and Kōchi (Shikoku) Prefectures. The remaining CLT panels are manufactured with species such as Japanese Cypress (Hinoki), Japanese Larch (Karamatsu), Japanese Fir (Todomatsu) on demand, usually brought straight from their production places. Employing imported timber species such as European Pine and Spruce is also a possibility in the future according to the company representative.

Manufacturing process
The main steps of CLT manufacturing process in Meiken Lamwood are listed bellow:

Timber grouping
Japanese Cedar lamellae are provided with 15% moisture content or lower. The pieces are machine graded and separated according to their modulus of elasticity.

Finger-joint milling
The sorted out Japanese Cedar lamellae are finger-jointed at the end grain (width direction) and bonded. Two or more pieces are joined.

Lamellae positioning
The finger-joined lamellae are positioned on two tables, each placed at one side of the press, arranged perpendicular to the lamellae positioned on the opposite side table.

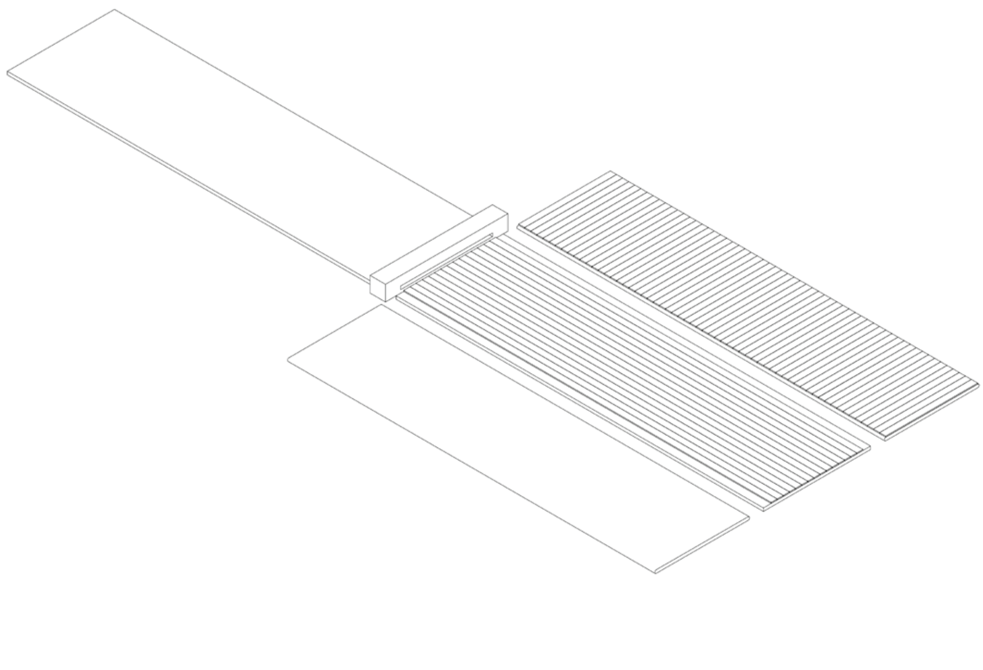
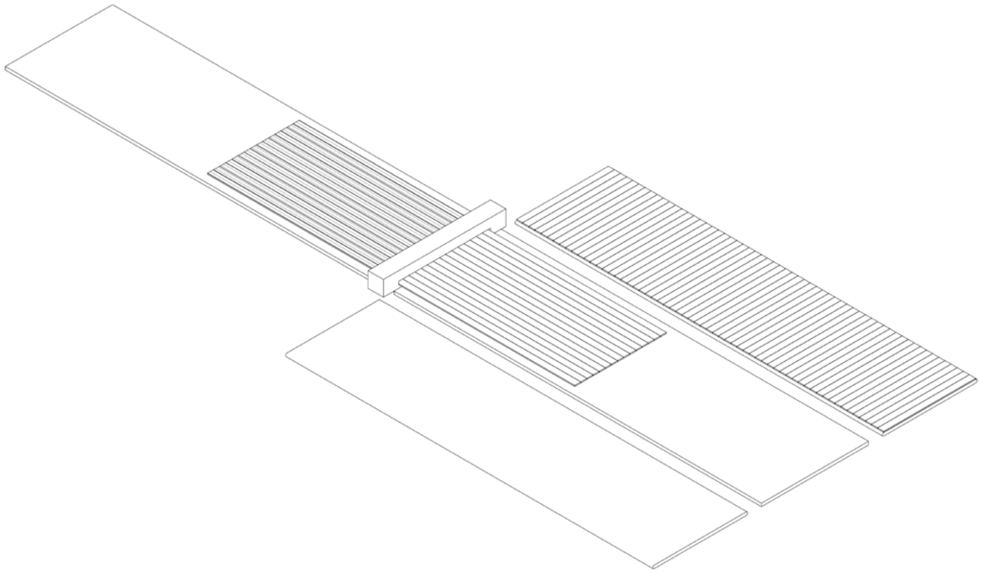


Figure 1.2.13. Meiken CLT manufacturing step 3: lamellae positioning.

Panel lay-up
Longitudinal layer lamellae are slid to the centre table and pushed through a ribbon spreader that applies the two components of the Emulsion Polymer Isocyanate (EPI) adhesive onto the surface of the whole layer at a 220 g/m2 ratio. Then, transversal layer lamellae are moved to the centre table by "L" shaped brackets, pushed through the adhesive spreaders and dropped on top of the previous layer. The following layer is placed on the centre table, and the procedure described above is repeated until all desired layers are stacked together.

Figure 1.2.14. Meiken CLT manufacturing step 4: panel arranging.



Pressing
After all the desired layers are in set in place, they are pushed laterally, to obtain a gap-free surface and then pressed from above by a hydraulic cold-press during about one hour. The press is divided into 2 meter wide sections along the whole length of the panel.

Panel milling
Pressed CLT panel is conveyed to the CNC machine that mills the big panel into smaller building elements such as wall, slabs or roof.

Panel packaging and shipping
CLT building elements are wrapped and loaded on the truck or container.

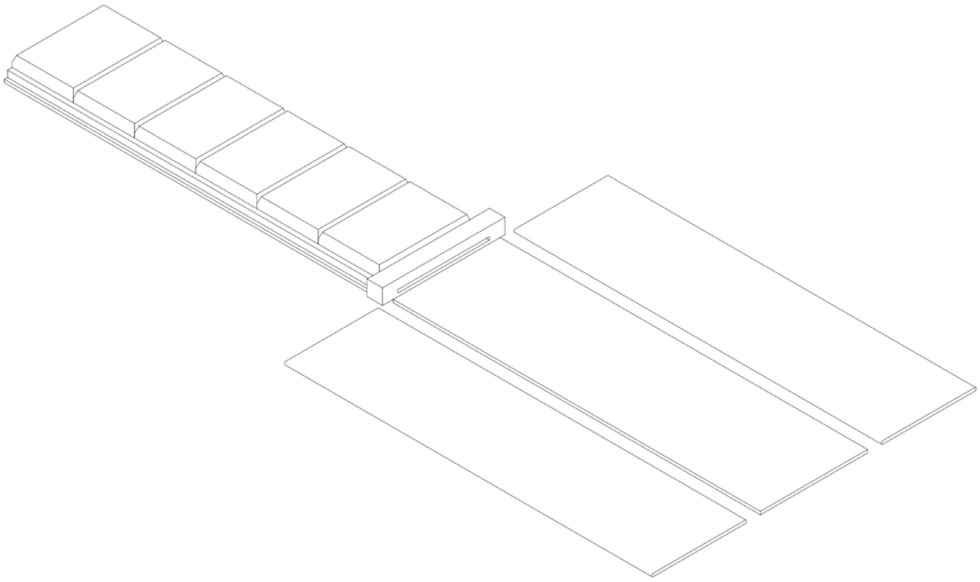


Figure 1.2.15. Meiken CLT manufacturing step 5: pressing.

1.2.2.4 DISCUSSION

Even though CLT production in Japan is still very recent, one big scale facility with large production capacity is online out of two existent CLT plants. Moreover, based on the forest resources analyses (topic 1.1.2), it can be said that the facilities are located close to large saw-mill processing places (Okayama prefecture) or nearby wealthy planted Japanese Cedar regions (Kagoshima prefecture). In both cases, Japanese Cedar is utilised for CLT manufacturing. However, the lamellae employed by Meiken Lamwood for CLT manufacturing in Okayama is brought from Kumamoto prefecture (Kyūshū) or Kōchi Prefecture (Shikoku). In this case, it is expected that bigger transportation costs are incorporated into less processed products such as the lamellae, conversely to the idea that CLT manufacturing plants should be located close to timber reserves area so that most of the freight costs fall onto the finished product. This situation may have an adverse impact on the final panel from the economic point of view. For this reason, Yamasa presents a bigger potential for a more cost-effective production of CLT in Japan than Meiken.

A direct relation between the employed timber lamellae properties and CLT panel properties was observed during the study. Hence, it would be highly convenient for CLT manufacturers to have some control over extraction and primary processing activities as well, thus ensuring the supply of timber lamella according to the needs of CLT production, particularly regarding quantity and grading. In case manufacturers do not take part directly in the forestry business, communication flow from forestry to processing should be a priority. Furthermore, considering Japanese forestry sector continued economic crises, joint ventures or specific private financing lines could contribute to a more stable forest business, thus creating a safer scenario for CLT production as well.

The EPI adhesive employed for Japanese CLT bonding determines a fast assembly time between when the adhesive is first spread until the panel is pressed, thus demanding a more robust manufacturing line with a higher degree of automation. Hence, CLT production in Japan is a capital intensive production line. Nevertheless, domestic demand for the product is still relatively low compared with total production capacity. Furthermore, even with the increase in the demand, maximum processing capacity is limited to half owing to the CNC machine milling capacity. As a result, CLT production cannot use the full benefit of the economy of scale, increasing the price of Japanese CLT panels (140,000 yen/m3) which inevitably hinder its competitiveness against already established materials and buildings systems. It is the belief of the manufacturer that price could drop with an expected increase in CLT's demand.

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1.2.3 Austrian and Japanese CLT manufacturing comparison

1.2.3.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT in comparison to Austrian CLT from the manufacturing point of view.

1.2.3.2 METHOD

Austrian and Japanese CLT manufacturing were compared based on the previous analyses (topics 1.2.1 and 1.2.2). The main possibilities and limitations for Japanese CLT in comparison to Austrian CLT from the manufacturing point of view were discussed.

1.2.3.3 RESULTS

Although Austrian CLT inner layers are always made of Spruce, all analysed manufacturers will provide different wood species for the cover layer upon request. On the other hand, in Japan, although different timber species were used on special demand, the standard commercialised CLT panel employs Japanese Cedar for all the layers. Furthermore, currently, there are no surface quality control or mending stages to correct surface defects such as knots and cracks in Japanese CLT production as seen in Austria. As a result, Japanese CLT panels lack the possibility to generate based on the visual appeal of the panel.

Regardless of the different timber species employed in each location, panel physical properties such as dimensional variation, thermal conductivity and fire resistance are nearly the same. In contrast, mechanical properties showed a significant difference. Austrian CLT employs C24 lamellae and up to 10% of C16, whereas, in Japan, M60A is employed for the outer layers only and M30A is used for all inner layers. At the time of the study, there was no certified manufacturer employing M90A, which even though showing lower mechanical properties than spruce, would allow broadening the use of CLT panels and more value to be generated, especially from the "Technical Subject" point of view.

Finally, the analysed Austrian CLT manufacturing facilities were always located close to forest resources, whereas one of Japanese CLT facilities is situated more than 300 km away from the place where the extraction and primary processing are executed.

Furthermore, despite the similar scale of investments made on manufacturing facilities in both countries, Japanese CLT demand is still low, resulting in idle production capacity. Both circumstances are expected to have an adverse impact on the CLT panel price. Consequently, Japanese CLT is almost three times more expensive than Austrian CLT.

1.2.3.4 DISCUSSION

Austrian CLT manufacturing is based on a cost-effective production of a structurally sound material. That means dimensions within "Technical" and Economic" value "Subjects" play a major role for CLT production. In order to better explore these values, 2 aspects of CLT production line can be highlighted: secure supply and significant demand, thus resulting in a continuous production flow. In comparison, Japanese CLT still presents a smaller application range due to the limits imposed by lamellae properties and panel price, which affects the possibilities of diffusion among the regular building market, thus leading to a small demand which increases the cost of the material, forming a vicious circle.

1.3 Section 1 conclusions

Even though Japanese CLT is manufactured in highly automated and capital intensive production lines, the current demand is relatively small, which results in idle production capacity, increasing production cost and the final price of each panel, thus hindering demand for the material and forming a vicious circle. In order to break the vicious circle and increase the use of CLT in construction, it is necessary to aggregate a more diverse set of value into the panels. From the technology block, the task can be pursued from two parallel sides.

First and foremost, manufacturers should work on the material improvement to broaden CLT application range. Room for improvement was particularly felt on panel mechanical and visual properties. Those improvements would aggregate value to Japanese CLT in "Technical Subjects". However, as increasing the quality may also reduce the amount of selectable timber, the feasibility of this option depends on the offer of high-quality raw material without leading to a more expensive CLT panel. Hence, close relationship and good communication between the main actors in the chain of CLT production would be necessary. Second, increasing the demand for CLT panels can be pursued by promoting more cost-effective application methods (discussed in the next section) or enacting policies favouring CLT construction and providing subsidies, tax exemption and so on. Either way, increasing value generation of Japanese CLT focusing on the "Economic Subject".

To sum up, taking into account TFV theory, an ideal model for CLT manufacturing can be synthesised in Table 1.2.7.

The basis behind the "Transformation view" in CLT production is the transformation of timber lamellae into CLT panels. Following, the "Flow view" defines different steps from resource extraction to the delivery of CLT elements to the construction site. Owing to the fact a continuous flow and large production should be targeted for CLT line, a highly mechanised and automated production line becomes the main principle in "transformation view". As a result, material flow in the production should be kept as constant as possible, meaning securing the supply of raw material, producing CLT panels and sending the finished elements to the construction site, thus reaching a "no-stock" production as the main principle for the "flow view".

Table 1.2.7. Ideal CLT production analysis (according to TFV theory)

	Transformation view	**Flow view**	**Value generation view**
Conceptualization of production	As a transformation of timber lamellae into CLT building elements	Roundwood harvesting - transportation - sawn timber processing, drying, grading - transportation - inspection, CLT manufacturing - transportation	Deliver of CLT elements according to building and client's requirements
Main principle	Automation (economy of scale)	On demand (no-stock)	Use of best quality raw-material at smallest cost
Associated principles	Decompose the task into lamellae sorting, finger jointing, pressing and panel milling	Reduce transportation distance of raw-material, panels production time and finished product variability	Ensure the correct supply of panels on time, fulfilling required mechanical, physical and aesthetic properties
Practical contribution	Production of CLT elements	Reduction of moving and waiting stages	Offer of effective building elements

2.0 CLT buildings execution

Abstract: This section investigates the relationship between building demand and CLT utilisation in Japan for the value generation of CLT buildings. This section presents two chapters: the first analyses building demand and the second focus on CLT utilisation in construction. Furthermore, both chapters have three topics, the first two analyse the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place. Hence, by the comparison with Austria, the relationship between building demand and CLT utilisation in Japan for the value generation of CLT buildings can be comprehended. The results showed that a large domestic demand for residential construction, particularly in the central and east part of the main island in Japan, provides the biggest potential for the diffusion of CLT. However, value generation of CLT buildings inside Japanese housing market has to comply at first with the predominant focus on "Value Subjects" from the "Direct Concept" such as cost and performance. The current trend of employing Japanese CLT in hybrid structures reflects this situation. In fact, instead of considering limited mechanical properties as weaknesses, it is advisable to approach it as a possibility by promoting the stiffening properties of CLT panels for the reinforcement of timber frame structures. In the second moment of implementation, though, "Dimensions" from "Environmental Subjects" should be added to value generation strategy for CLT buildings. Regardless of which value "Dimensions" to utilise, it is fundamental that the resulting design possibilities and merits are thoroughly transferred up to the side of the practitioners, so they are aware of the benefits of CLT building when choosing the material and proposing it to their clients.

2.1 Building demand

Abstract: This chapter aims to understand the possibilities and limitations for Japanese CLT from the building demand point of view. This chapter is divided into three topics: the first two analyse the situation in Austria and Japan individually, whereas the last chapter compares the situation in each place. Hence, by the comparison with Austria, possibilities and limitations for Japanese CLT buildings from the demand point of view can be understood. It was found that unlike Austria, Japan's large annual new buildings demand is sufficient based on the current forest resources and CLT production capabilities. Particularly, low-rise single-family houses could be targeted in smaller cities, whereas up to 5 storeys high multi-family housing could be a promising niche in more urbanised places. Therefore, unlike Austria, Japanese CLT industry can find a large enough domestic market. However, a more clear understanding of the merits of CLT buildings in both of the applications mentioned above in necessary to reach a pact between the main actors, thus leading to a successful implementation strategy.

2.1.1 Austrian building demand

2.1.1.1 GOAL

The objective of this topic is to understand the possibilities and limitations for Austrian CLT from the building demand point of view.

2.1.1.2 METHOD

Statistical information on building demand was retrieved from the online database of the Austrian Statistic Bureau. After, the gathered data was visualised and analysed focusing on new buildings demand. Finally, considering the analyses, conclusions were drawn regarding the main possibilities and restraints for employing CLT in the domestic market.

2.1.1.3 RESULTS

During 2014, a total of 5,020,161 m² were built across Austria. Slightly less than half of these built floor area is concentrated in the northern part of the country, corresponding to the provinces of Upper Austria and Lower Austria with 1,134,997 m2 (23%) and 999,262 m2 (20%), respectively.

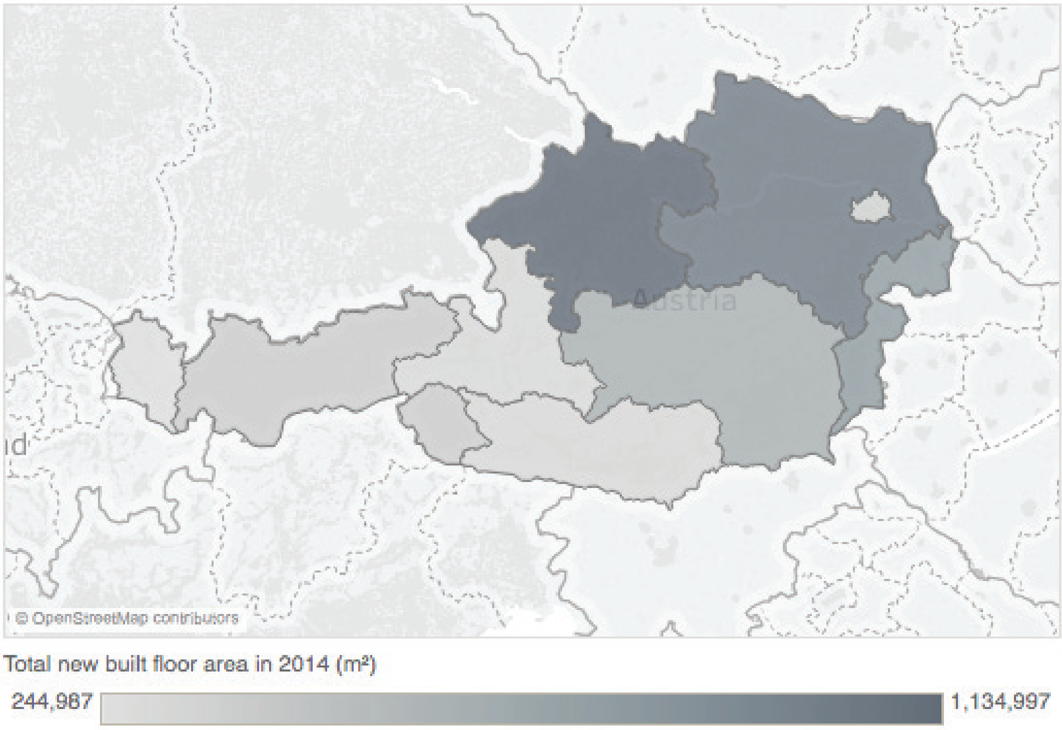
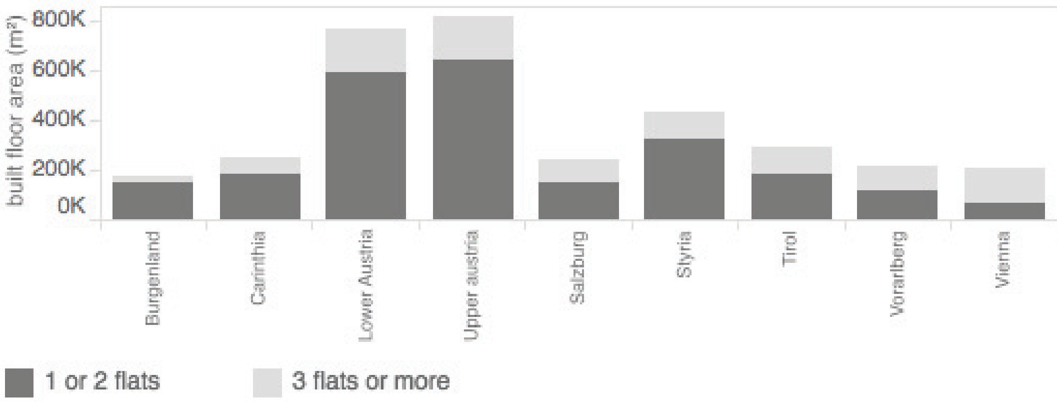


Figure 2.1.1. Total new built floor area by Provinces in Austria, 2014 (m²). Source: raw data retrieved from Austrian Statistic Bureau, 2016.

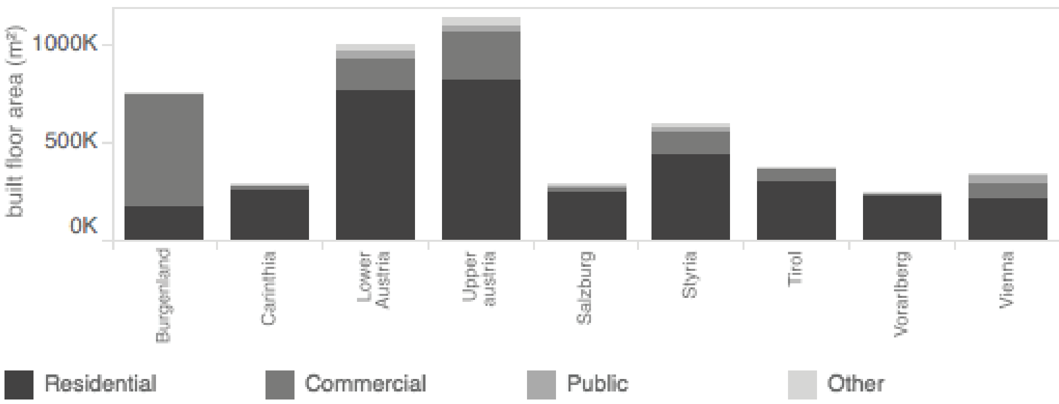
Furthermore, most of the built floor area in Austria refers to the residential application, accounting for 3,405,423 m² (68%) (Statistics Austria, 2016). Likewise, the provinces of Upper Austria and Lower Austria concentrate the major part of the residential buildings, with 816,766 m² (16%) and 763,426 m² (15%) respectively. Furthermore, single-family or two-flats house construction are most common in nearly all provinces, accounting for 2,398,091 m² (48%). Vienna is the only exception where multi-family housing (3 flats or more) are predominant, though reaching only up to 142,078 m2 (3%) of all the built floor area.

Figure 2.1.2. New residential built floor area by typology, by Province in Austria, 2014 (m²). Source: raw data retrieved from Austrian Statistic Bureau, 2016.



Following residential use, commercial buildings represent the second largest built floor area with 1,315,784 m² (26%) for most of the provinces. Burgerland is the only exception, presenting commercial use as the main built floor area with 575,253 m² (11%), which is roughly the same commercial built floor area of all the other provinces together. Finally, public use shows a modest share in the built floor area of 2014, accounting for 193,315 m² (4%).

Figure 2.1.3. Total new built floor area by use, by Province in Austria, 2014 (m²). Source: raw data retrieved from Austrian Statistic Bureau, 2016.



According to Teischinger (2011), wooden structure buildings represented 39% of Austrian building stock in 2010. Hence, considering this value as an average for the new buildings as well, it can be roughly estimated that about 2 million m^2 of wooden constructions were built in 2014 across the country.

2.1.1.4 DISCUSSION

Overall, Austria has a relatively modest national building activity. Most of it takes place in the surrounding areas of the capital and is chiefly aimed for residential use. Additionally, most of the new residential buildings in Austria are small-scale single-family or two-flats houses.

Considering the current national CLT production volume around 500 thousand m^3 per year and employing a 0.3 m^3/m^2 ratio for CLT constructions, it would be possible to build more than 1.5 million m^2 if all Austrian CLT production capability was used. This value is over three times bigger than the total annual demand for construction in Austria or five times larger than the residential building demand. Hence, Austrian CLT production cannot depend only on its domestic building market, thus, leading to a more aggressive exporting strategy by the manufacturers to expand their market to other countries and fields of construction. As discussed in the previous chapter (topic 1.2.3), cost-effective CLT production depends on significant demand and economy of scale. Therefore, this partially explains the fast diffusion of CLT through the European continent as well as its ongoing internationalisation activities. Furthermore, the opening of the multi-storey housing field is also beneficial to the manufacturers as a large amount of material is necessary for each mid or high-rise building.

2.1.1.5 REFERENCES

Statistics Austria, 2015. “Produktion und Bauwesen: fertiggestellte neue Gebäude nach Gebäudeeigenschaften und Bundesländern”. Available: http://www.statistik.at. Access: March 2015.

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Teischinger, Alfred. 2011. "Holzbauanteil in Österreich Statistische Erhebung Von Hochbauvorhaben." Zuschinitt 43 (September). Vienna: 1–24.

2.1.2 Japanese building demand

2.1.2.1 GOAL

The objective of this topic is to understand the possibilities and limitations for Japanese CLT from the building demand point of view.

2.1.2.2 METHOD

Statistical information on building demand was retrieved from the online database of the Japanese Statistic Bureau and Ministry of Land, Infrastructure, Transport and Tourism. After, the gathered data was visualised and analysed focusing on new buildings demand. Finally, considering the analyses, conclusions were drawn regarding the main possibilities and restraints for employing Japanese CLT.

2.1.2.3 RESULTS

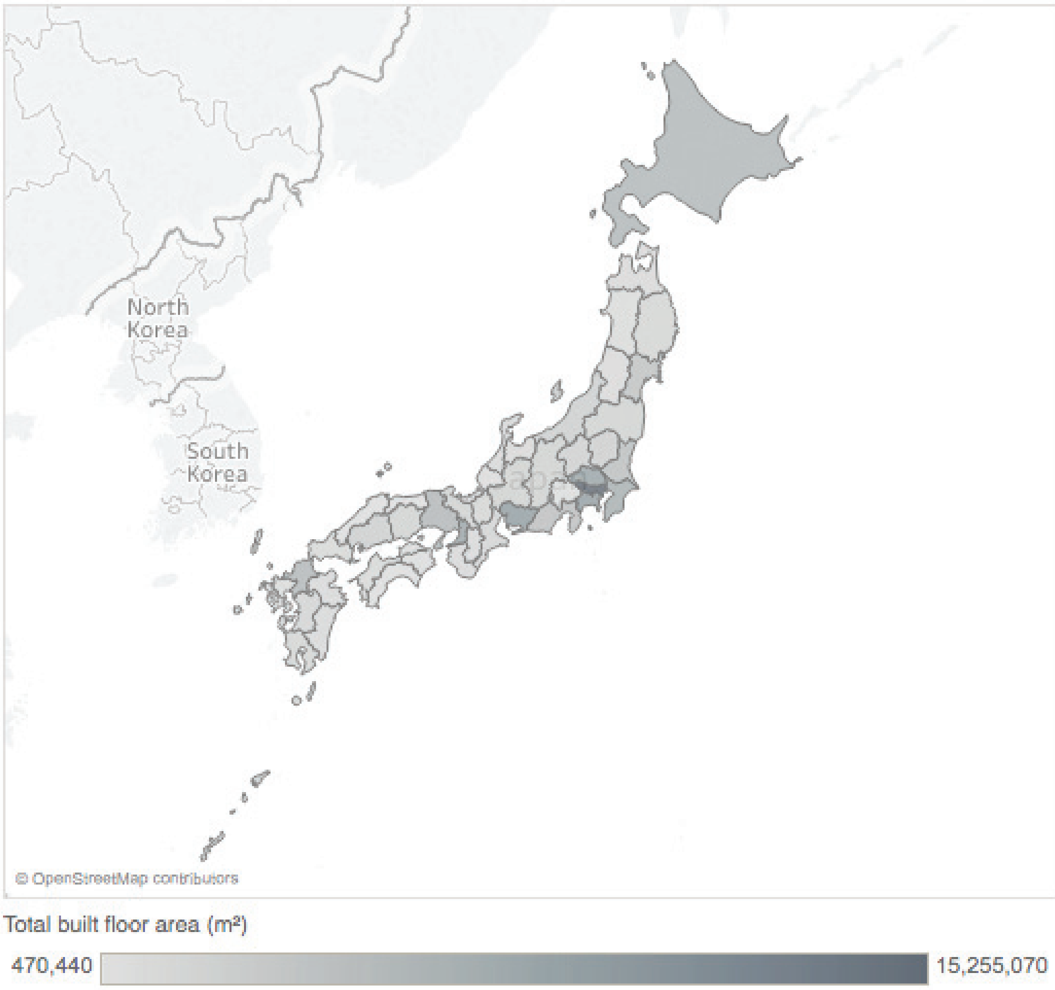
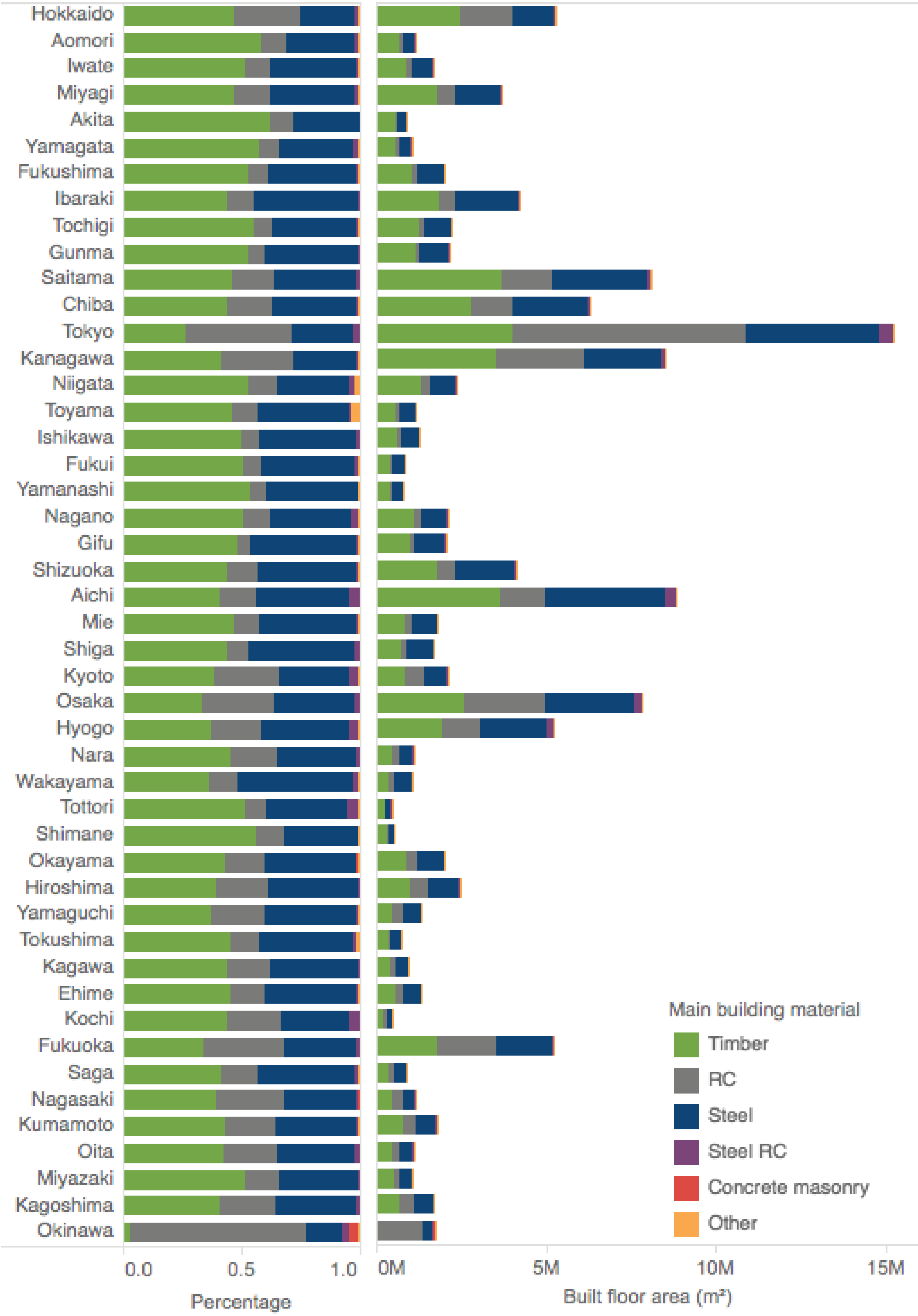


Figure 2.1.4. Total built floor area distribution in Japan, 2012 (including new buildings, renovation, expansion and excluding buildings with a floor area of 10 m2 or less). Source: raw data retrieved from MLIT, 2016.

Figure 2.1.5. Total built floor area by prefecture, by building material in Japan, 2012 (including new buildings, renovation, expansion and excluding buildings with a floor area of 10 m2 or less). Source: raw data retrieved from MLIT, 2016.



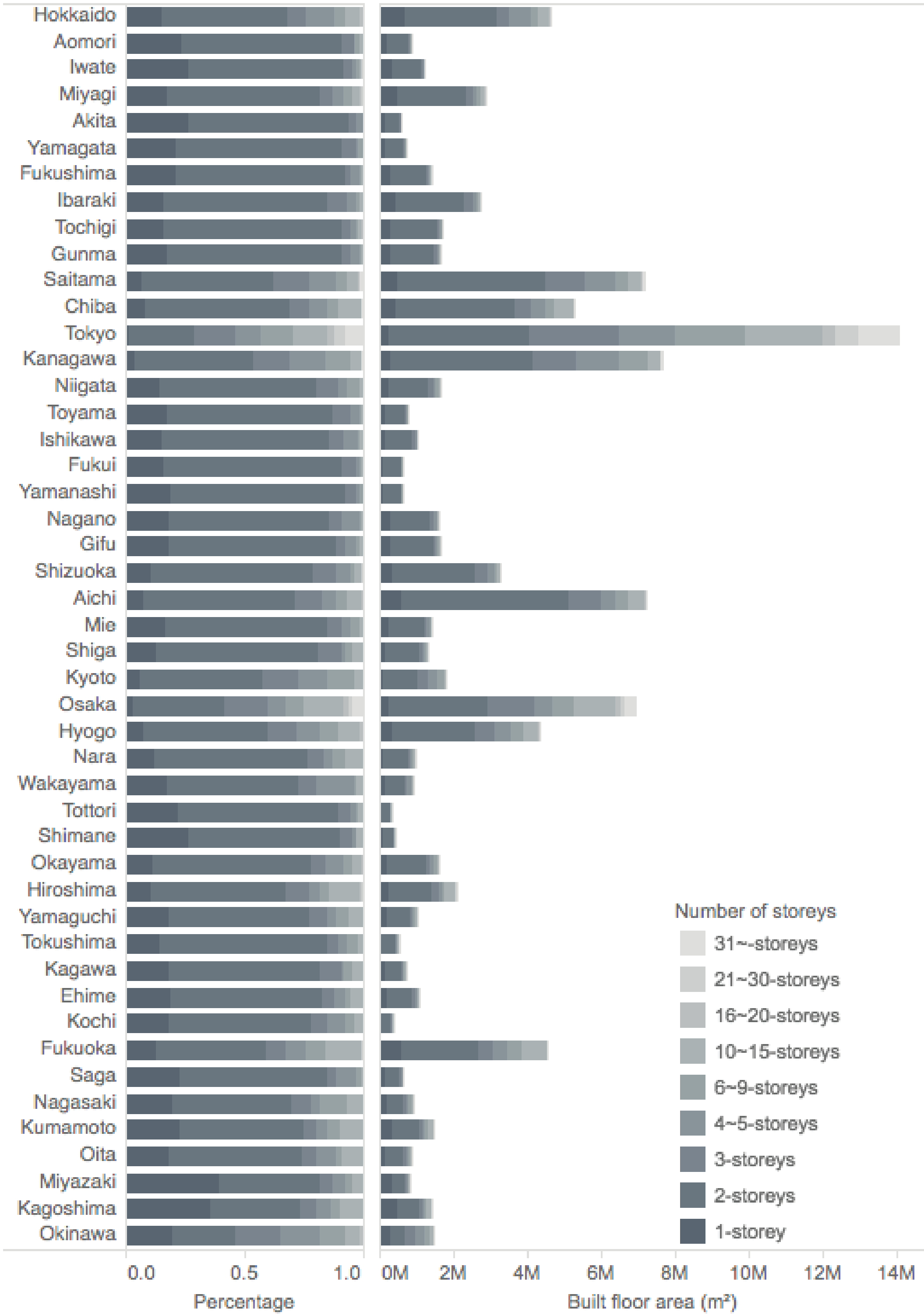


Figure 2.1.6. New built floor area by prefecture, by the number of storeys in Japan, 2012 (excluding renovation, extension and buildings whose floor area is 10 m2 or less). Source: raw data retrieved from MLIT, 2016.

On 2012, more than 600 thousand buildings (including new, renovation, expansion and excluding buildings with a floor area of 10 m2 or less) were constructed, totalising 132,608,530 m2. Almost half of all newly built floor area is concentrated in 6 prefectures. Kantō region (Tōkyō, Kanagawa, Saitama, Chiba and Ibaraki Prefectures), accounts for 38,236,570 m2 (29%), followed by Aichi prefecture in Chūbū region, accounting for 8,864,864 (7%) and Osaka Prefecture in Kansai region, accounting for 7,823,303 (6%).

Wooden construction built floor area accounts for 54,804,264 m2 (39%), followed by steel construction with 44,752,557 m2 (32%) and reinforced concrete construction with 29,891,056 m2 (22%). However, deviations from this average can be observed depending on the prefecture. Except for Okinawa which has a very peculiar situation due to its southernmost location, the share of wooden construction built floor varies from 26% in Tōkyō to 62% in Akita Prefecture. As a general trend, the northern regions of Hokkaidō and Tōhoku, the central Chūbū region and southern Shikoku region present a bigger wooden construction share than the rest of the country. This concentration is consistent with wealthy forest areas location, specially planted Japanese Cedar (topic 1.1.2).

The small wooden construction built floor area in Tōkyō is compensated by the national largest reinforced concrete construction share (45%). On the other hand, nearby prefectures in the same Kantō region, such as Kanagawa, Saitama and Chiba present a high wooden construction area percentage, varying from 41% to 46%. Furthermore, buildings in the Prefectures surrounding Tōkyō exhibit a lesser average number of storeys with a predominance of low-rise two storeys high constructions, in contrast to a larger amount of buildings over four storeys high in the capital.

Additionally, prefectures with large wooden construction built floor area percentage also present a higher proportion of built floor are of two storeys buildings, such as Akita, Aomori and Yamagata in Tōhoku region (94%, 91% and 92% respectively). In contrast, Tōkyō and Osaka present only 29%, and 42% of up to 2 storeys built floor area, respectively. Hence, wooden construction dominates the low-rise buildings application. However, the percentage of new built floor area wooden construction is severely reduced in the 45 storeys application and are null from there on, owing to the current building standard restraints. Overall, buildings over four storeys high in Japan are built with reinforced concrete structure.

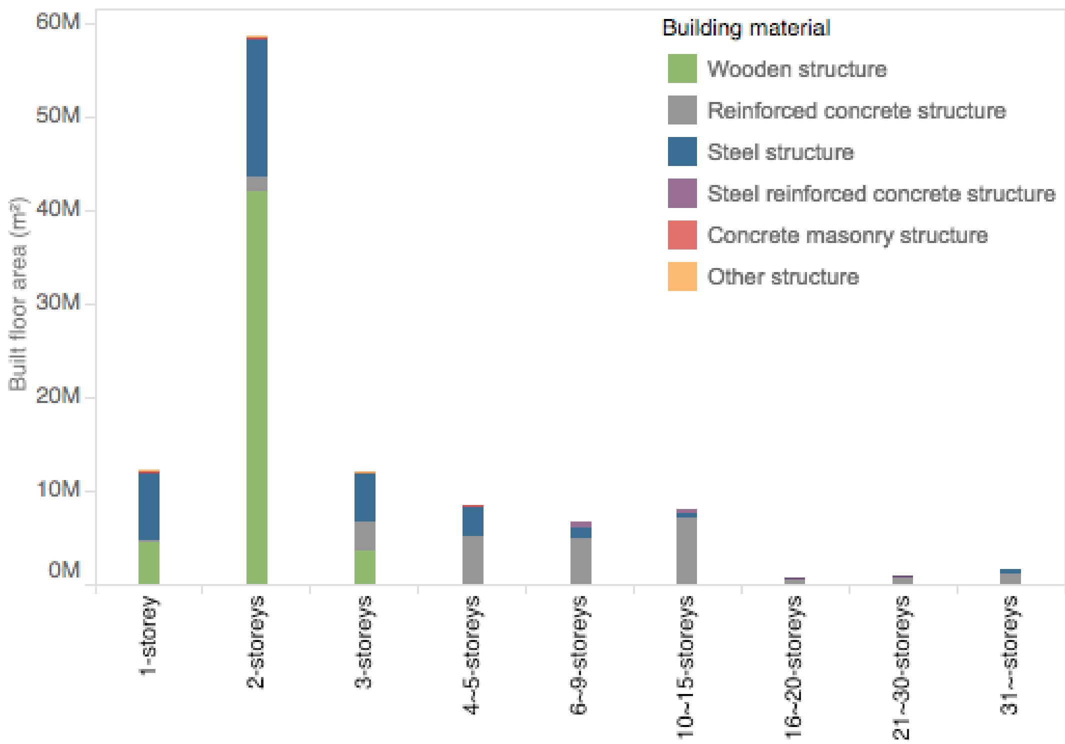


Figure 2.1.7. New built floor area by the number of storeys, by building material in Japan, 2012 (excluding renovation, extension and buildings whose floor area is 10 m2 or less). Source: raw data retrieved from MLIT, 2016.

2.1.2.4 DISCUSSION

High domestic demand for new buildings in Japan can provide different possibilities for Japanese CLT application. Regardless of the place, residential use accounts for most of the demand and therefore, is one of the most promising applications for CLT from the demand point of view. Moreover, prefectures containing large urbanised areas, such as the ones in Tokyo metropolitan area, Aichi, Shizuoka, Osaka, Hyōgo and Fukuoka account for most of the building demand in the country. The mentioned prefectures could act as key places for CLT diffusion by providing a large market for mid-storey housing application. However, in this scenario, the value of CLT buildings (topic 2.2.3) will have to excel the reinforced concrete ones. On the other hand, in the remaining part of Japan, CLT buildings will have to express their value inside a low-rise single-family context, either with new buildings or by the intervention on the existing building stock.

If Japanese CLT is oriented to commercial buildings application, it will find a rather diverse and scattered demand from the area and building height points of view. Furthermore, in this case, CLT buildings would face competition against steel constructions. Depending on the scale of the building, Japanese Cedar limited stiffness (topic 1.2.2) could impose more restraints to the design than its competitor materials. Hence, the design of building elements that could increase Japanese CLT's span capability would play a major role in spreading its utilisation through these applications.

2.1.2.5 REFERENCES

Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2015. 国土交通省総合政策局情報安全・調査課建設統計室 > 建築統計年報 > 平成24年度計・都道府県. Tokyo. Available: http://www.stat.go.jp. Access: February 2016.

2.1.3 Building demand comparison

2.1.3.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT in comparison to Austria from the building demand point of view.

2.1.3.2 METHOD

Taking into account the previous analyses on national building demand (topics 2.1.1 and 2.1.2), Austria and Japan were compared, considering the former as a reference for understanding the possibilities and limitations for CLT application in Japan. The main differences between Austrian and Japanese building context and how these would influence CLT production in Japan were discussed.

2.1.3.3 RESULTS

Even though the share of wooden construction is around 40% in both countries, the total annual built floor area is largely different. Based on the study, Japanese building industry provides over 20 times more floor area in one year than Austria. Moreover, new built floor area in Japan is highly concentrated in a few prefectures. Residential use accounts for the major part of the building demand in both countries, and there is a predominance of low-rise single-family houses outside bigger urban areas, such as Vienna in Austria or Tokyo and Osaka in Japan. Following residential constructions, commercial use also showed a large annual built floor area in both countries.

2.1.3.4 DISCUSSION

Austrian CLT companies cannot depend only on the domestic building market for the expansion of the business. Hence, spreading CLT through other countries and fields of construction was a necessary strategy since the early stages of CLT production, given the importance of the economy of scale (topic 1.2.3). Inside this context, the use of CLT in mass timber building system and for mid-to-large scale multi-family houses is comprehensive from the manufacturers and domestic demand points of view. On the other hand, Japanese extremely high annual domestic demand for new buildings would provide a large enough market for CLT, given the current production capacity (topic

1.2.2). Particularly, low-rise single-family houses could be targeted in smaller cities, whereas over five storeys high multi-family housing could be a promising niche in more urbanised places. However, a more clear understanding of the merits of CLT buildings in both of the applications mentioned above in necessary to reach a pact between the main actors, thus leading to a successful implementation strategy, especially when it shall face competition with established building materials such as concrete and steel.

2.2 CLT utilisation

Abstract: This chapter investigates the possibilities and limitations for Japanese CLT from the building utilisation point of view. The chapter was divided into three topics: the first two analyse how Austrian and Japanese CLT utilisation main features individually, whereas the last chapter compares the situation with each other. It was found that the value generation concept of CLT buildings should comply with “Technical” value “Subjects” at first. For instance, focusing on “Dimensions” such as statics or seismic performance when employing panels in hybrid building systems for new residential construction or retrofitting of existent dwellings. In a second moment, though, it is necessary that more “Dimensions” from “Environmental” value “Subjects” are added to CLT buildings, so that the use of mass timber and multi-family application becomes an attractive possibility for value generation. The results also showed depending on which value “Subjects” emphasised the preferred way in CLT is employed may also change. Hence, if with the aid of policies, regulations and educational activities, the social awareness about the environmental contribution of construction increases inside Japanese society, it is expected that the use of CLT may also change as a result. Nevertheless, it is fundamental that the value generation concepts of different design possibilities are transferred to the practitioners and the general public by efficient transfer activities, in order to increase the awareness about the benefits of CLT-based building solutions.

2.2.1 European CLT utilisation

2.2.1.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Austrian CLT from the building utilisation point of view.

2.2.1.2 METHOD

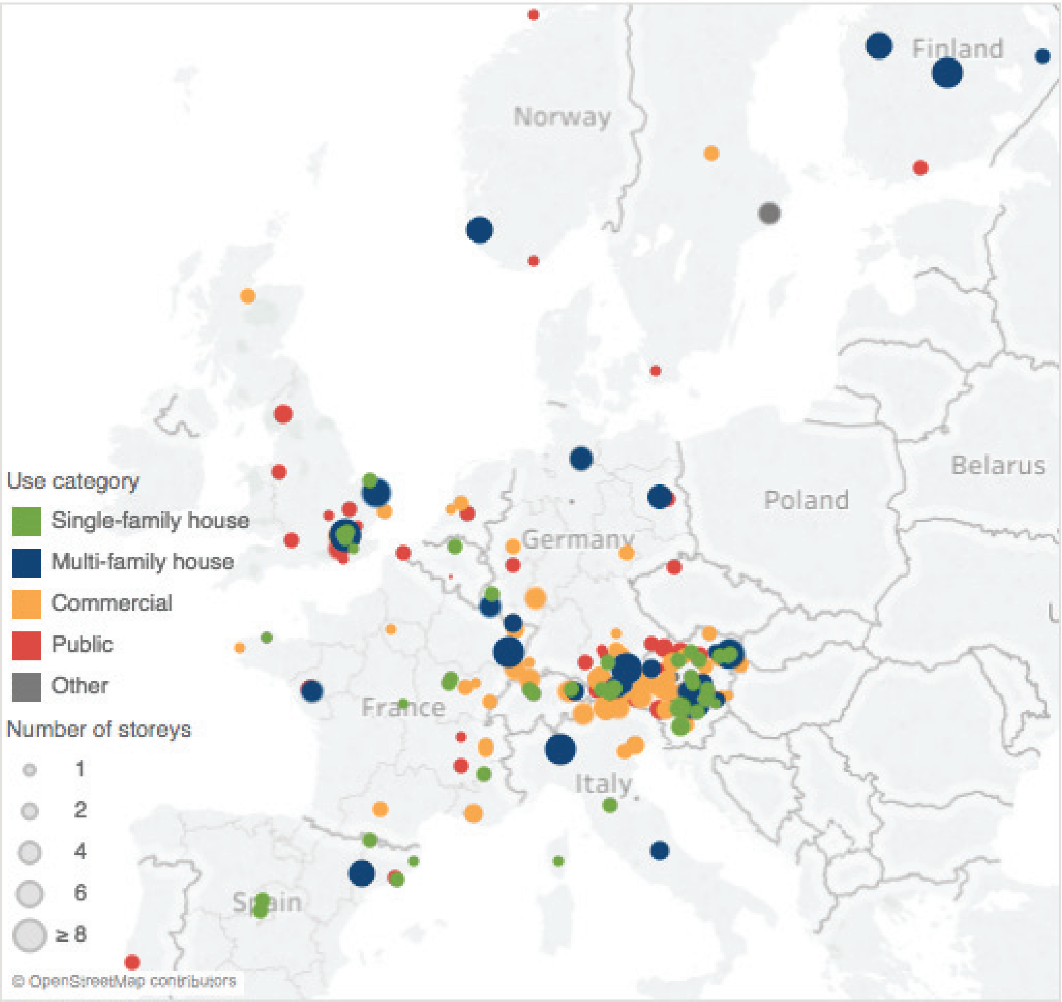
At first, general information on completed CLT buildings was retrieved on August 2015 from the website of the four biggest European CLT manufacturers, namely Stora Enso, Mayr Melholf Holz Holding AG, Binderholz Bausysteme GmbH and KLH Massivholz GmbH. The data gathered included information about CLT manufacturer, building location, construction year and main use. The buildings were divided into five categories: "single-family houses", "multi-family houses", "public buildings" (defined as kindergarten, school, religious buildings, nursery, hospital, sports centre), "commercial buildings" (defined as office, shopping centre, lodging and industrial facilities) and "other" (including tower, pavilion, cottage or hut constructions and etc). After, "multi-family house" category was further investigated. Information about utilisation (including main use, program, number of units and room layouts), structural system (including main structural system and CLT components) and construction data (including built floor area, employed timber/ CLT volume, cost and fire resistance method) were gathered for all multi-family buildings at least 6 storeys high built with timber. The information was retrieved from online publications about the related buildings. Finally, a questionnaire was sent to the architects involved in the design process of the buildings, aiming to understand main value concepts attributed to CLT buildings by practitioners who have worked with the material. The architects were asked five multiple choice questions: 1) how did you first found about CLT; 2) why a CLT structure was chosen for the building; 3) what was the biggest challenge during development; 4) biggest merit after the conclusion and 5) would you use CLT again for the same purpose. In additional to pre-defined alternatives, each question also provided the possibility to write a customised answer. Lastly, an extra space was provided at the end of the questionnaire for any comments the participants wanted to address. On total, half of the contacted architects answered the questionnaire and contributed to the survey.

2.2.1.3 RESULTS

The results have been divided into three main parts. First, an overall analysis of building typologies in which Austrian CLT was utilised, focusing on the use of CLT for high-rise multi-family buildings. Second, results of the survey with designers who have employed CLT for high-rise multi-family buildings were presented and discussed.

CLT building typologies

Figure 2.2.1. CLT buildings in Europe by category, by the number of stories.



A total of 226 CLT buildings were found on the websites of the four biggest European CLT manufacturers. Information regarding CLT manufacturer, CLT utilisation, the total number of stories, approximate location and built year were gathered, whenever available. Information on the built year and the total number of stories could not be found for

42 and 3 of the entries, respectively. Also, it is worth mention that about 78% of all the buildings gathered were found on the website of two manufacturers: KLH (46%) and Stora Enso (32%). Moreover, all the entries have were built on the European continent, except for two buildings in Australia and one in Canada. Also, most of the CLT buildings were realised in Austria, followed by nearby areas in Germany and then France. Additionally, CLT diffusion was seen in the south-east part of the United Kingdom and, to a smaller extent, in the northeast part of Italy. CLT most common application is for residential purposes, represented by 81 (36%) of all the gathered buildings, divided into 45 (20%) entries for "single-family houses" and 36 (16%) for "multi-family houses" category. Nevertheless, use of CLT for commercial buildings is also a popular application, found in 74 (33%) entries, followed by public use with 64 (28%) buildings.

Austria still concentrates a major part of completed CLT buildings with almost half of all the entries. Furthermore, CLT use distribution in the country follows the world average, showing a predominance of residential and commercial buildings. Likewise, France and Germany (26 and 23 entries respectively) present a nearly equal distribution of residential and commercial buildings. On the other hand, out of the 30 entries situated in the United Kingdom, most of them are defined within the "public buildings" category.

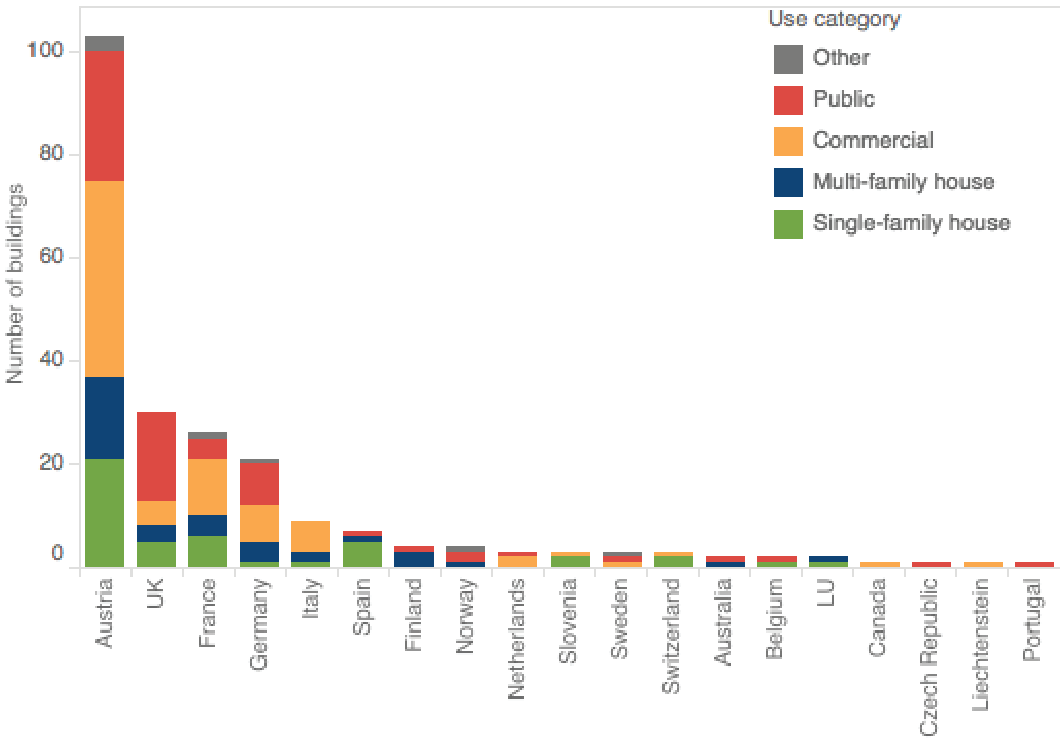
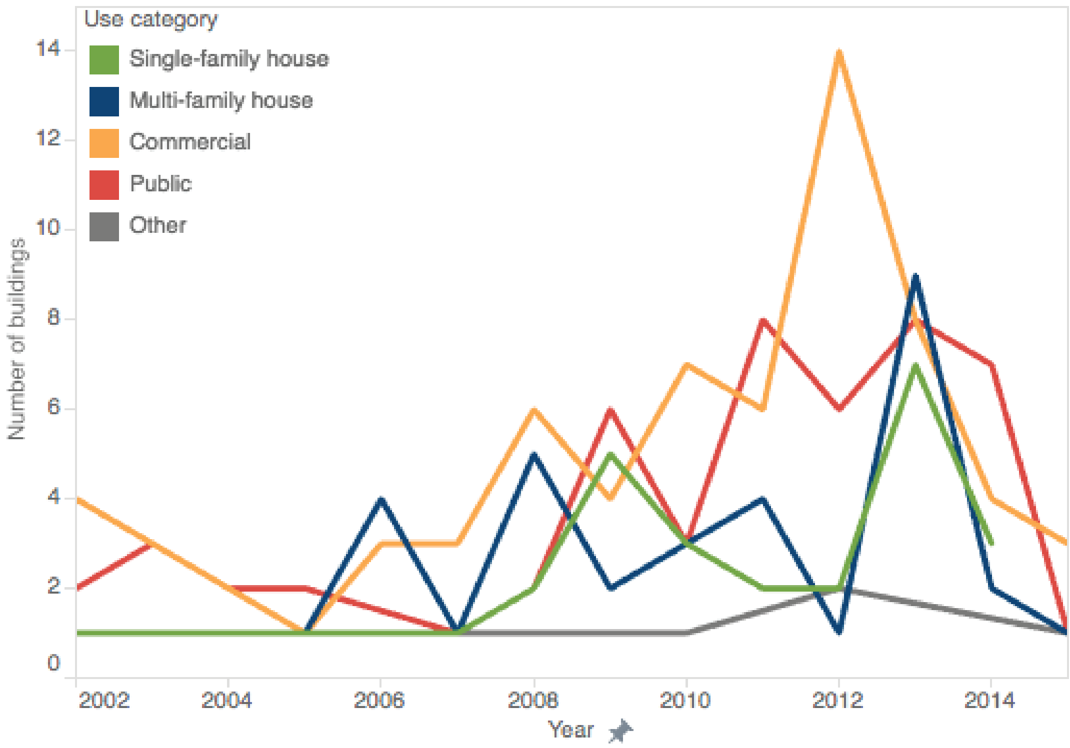


Figure 2.2.2. European CLT buildings by use category, by country.

The results also showed that up to the mid–2000's, CLT buildings could be found in Austria mainly. However, since the latter half of the same decade, they started to spread over other central European countries such as France and Germany. Later, since the beginning of 2010's a rapid increase in the number of CLT buildings can be seen in the UK, most likely stimulated by the successful experience of the "Murray Groove apartments", resulting in the second largest number of CLT buildings at the time of the study. Furthermore, when observing the evolution of CLT typologies evolution over the years, a similar trend can be seen. After a slow start until 2005, the number of realised CLT buildings per year starts to increase. From 2006 to 2013 Residential and Commercial categories will alternate the lead of completed buildings every one or two years until 2013. Additionally, the completion of public buildings using CLT is steadily increasing since 2007. From 2014, the sudden decrease in CLT construction is most likely due to the lack of update on the website of the manufacturers.

Figure 2.2.3. European CLT buildings by category, by built year.



Multi-family CLT buildings

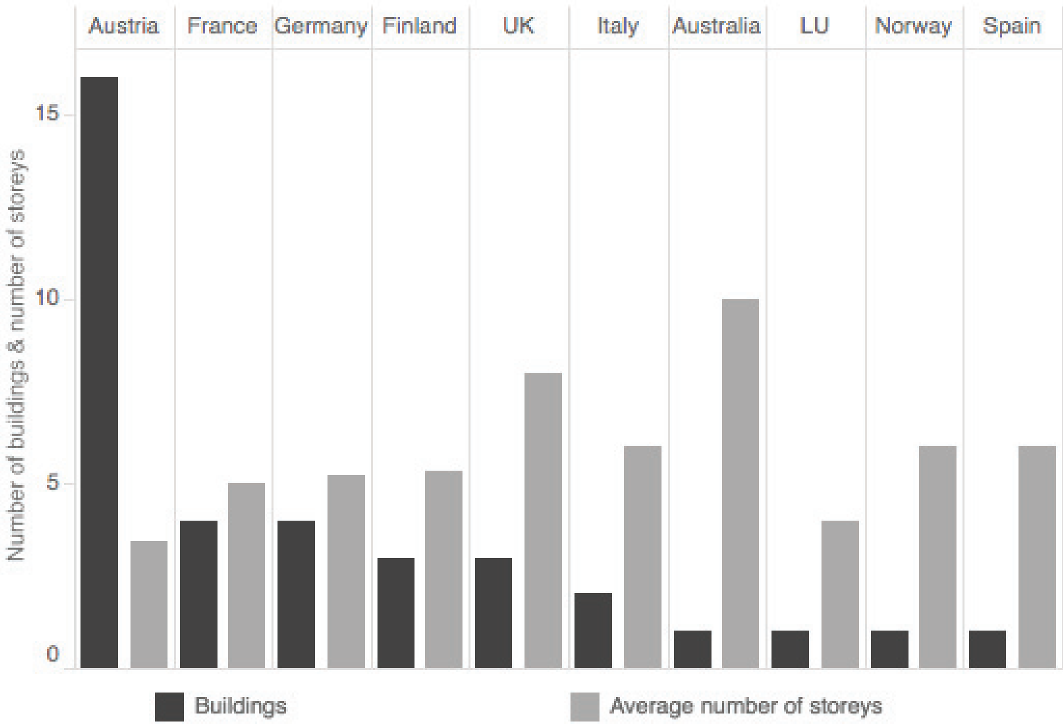
The study on CLT multi-family buildings was divided into two parts. At the first part, information on location, the number of stories and CLT maker was collected for all entries in the “multi-family houses” category. At the second part, more detailed analyses on multi-family buildings with at least six timber storeys were developed based on information about their structural system and overall construction data. Finally, the results of the questionnaire sent to the architects involved in the design of these buildings are presented aiming at comprehending the main values of CLT buildings attributed by practitioners who have worked with the material.

Mid-rise multi-family CLT housing

Figure 2.2.4. CLT multi-family buildings by the number of stories in Europe.

A total of 36 CLT buildings have been found in the “multi-family houses” category, realised between 2002 and 2015 in ten different countries. All the realised multi-family buildings found in the survey are located in Europe, except for one entry in Melbourne. The average world number of stories for CLT "multi-family houses" category was found to be 4.8 stories high. Austria showed the biggest amount of entries in the category, accounting for 44% of all the cases, however presenting a smaller average number of stories of 3.4. On the other hand, with three multi-family buildings, UK has the biggest average of about eight stories. Additionally, France and Germany are very close to the world average, each presenting a five stories national average.

Figure 2.2.5. CLT multi-family buildings average number of stories by country.



High-rise multi-family CLT housing

Ten entries in the "multi-family houses" category at least six timber storeys high were found in the survey. The buildings were completed from 2008 to 2015 and five are located in Central Europe, three in the United Kingdom, one in Finland and one outside the European continent, built in Australia. KLH and Stora Enso have supplied CLT for four buildings each, whereas Binderholz was the supplier of two buildings. Information on features such as building utilisation (including main use, program, total number of units and room layouts), the structural system (including information on structural system and CLT components) and construction data (including information on built floor area, timber/CLT volume, cost and fire resistance method) were gathered. The information is synthesised on table 2.2.1.

Utilisation
The investigated buildings are predominantly directed towards the regular real-estate market. Only two of the buildings were meant for social housing (Bridport House and Jules Ferry Residence), and in one case social housing apartments were also added (Murray Groove Apartments); one entry was designed as a student lodge (Crome Court). Additionally, three buildings presented different programs other than housing: one entry showed mixed use with offices (Bad Aibling Apartments), and retail shops mixed use was seen in two entries (Forté Living in Australia and Via Cenni in Italy), all of them placing the different functions on the ground floor level. Finally, apartment units number and room layouts varied widely from project to project: the largest one (Crome Court) contains 232 en-suite studio apartments, whereas the smallest one (Lleida Building) contains nine apartments.

Structure
Eight of the entries were built as Mass Timber construction, i.e., employing CLT elements for both wall and slabs. Only in one case (Jules Ferry Residence), a hybrid timber structure was used, combining Frame and Mass Timber Construction: glulam columns and beams were used as a primary load-bearing structure, while CLT panels were added in between this structure for bracing (vertical and horizontal). In one case (Crome Court) the way CLT elements were used could not be confirmed. A non-timber ground floor was utilised in 6 entries, on top of which the load-bearing timber structure starts. Hence, in the remaining four entries, timber construction starts directly from the ground floor. Furthermore, the number of timber stories ranges from six to nine storeys high and a small variation in the wall thickness within the same building was confirmed in two entries (Bridport House and Via Cenni), meaning the higher the storey is, the thinner the wall becomes. Also, slab thickness varies inside the same projects, most likely as a result of different spans, probably aiming for a more efficient material use.

For mass timber construction entries, platform construction is the most common method for connecting walls and slabs. Only in two buildings (Bridport House and Jules Ferry Residence), finger-joint was employed as a measure to reduce the settling of the structure. Finally, less than one-third of the surveyed buildings employed a reinforced concrete core (Bad Aibling Apartments, Wagramerstraße Apartments and Jules Ferry Residence). Among the remaining seven buildings, six employed CLT panels also for the core of the construction (elevator shaft and staircase). In one entry (Puukuokka) the material utilised in the core of the construction could not be confirmed.

Table 2.2.1. European CLT multi-story buildings with at least six timber stories.

	1. Murray Groove Apartments	**2. Bridport House**	**3. Bad Aibling Apartments**	**4. Forté Living**	**5. Wagramerstraße Apartments**
Basic info					
Built Year	2008	2010	2011	2012	2013
Location	London, United Kingdom	London, United Kingdom	Bad Aibling, Germany	Melbourne, Australia	Vienna, Austria
Designer	Waugh & Thisthleton Architects	Karakusevic Carson Architects	Schankula Architekten	Lend Lease	Schulder Architektur and Hagmuller
CLT Manufacturer	KLH	Stora Enso	Binder Holz	KLH	Binder Holz
Use info					
Function	Collective housing	Collective housing	Collective housing and Office	Collective housing and Retail	Collective housing
Program	Social housing and apartments	Social housing	Office and apartments	Shops and apartments	Apartments
Units	29	41	13	23	101
Rooms	1~4 bedrooms	1~4 bedrooms	1~3 bedrooms	1~2 bedrooms	NA
Design type	Box design	Compartment design	Box design	Box design	Box design
Structure info					
Building System	Mass timber	Mass timber	Mass timber	Mass timber	Mass timber
Storeys (concrete + timber)	1+8	8	8	1+9	1+6
Vertical Elements (mm)	CLT (128)	CLT (138, 161)	CLT	CLT (128)	CLT
Horizontal elements (mm)	CLT (146)	CLT (182, 223)	CLT	CLT (148)	CLT
Vertical-horizontal connection	Platform	Finger joint	NA	NA	NA
Core	CLT	CLT	RC	CLT	RC
Construction info					
Built Floor Area(m2)	2,756	4,220	1,320	NA	8,440
Timber Volume (m3)	900	1,576	500	1,000	2,400
Timber use (m3/m2)	0.33	0.37	0.38	NA	0.28
Cost ($)	5,800,000	9,800,000	NA	10,000,000	19,000,000
Cost / area ($/m2)	2,104	2,322	NA	NA	2,251
Fire Resistance	Encapsulation (R90)	Encapsulation (R90)	Encapsulation	Encapsulation and charring (R90, R120)	Encapsulation (R90)
Conversion ratio	1 GBP = 1,672 USD	1 GBP = 1,672 USD	1 EUR = 1,360 USD	1 AUD = 0,928 USD	1 EUR = 1,360 USD

6. Lleida Building	7. Jules Ferry Residence	8. Via Cenni	9. Crome court	10. Puukuokka
2013	2013	2013	2014	2015
Lleida, Spain	Saint-die Des Vosges ,France	Milan, Italy	Norwich, England	Jyväskylä, Finland
Ramon Liobera Serentil Arquitecto	ASP Architecture	Rossiprodi Associati	LSI Architects	Lassila Hirvilammi Arkkitehdit Oy
KLH	KLH	Stora Enso	Stora Enso	Stora Enso
Collective housing	Collective housing	Collective housing	Collective housing	Collective housing
Apartments	Social housing	Shop and apartments	Students apartment	Apartments
9	26	124 (4 bldg.)	232	58
1~3 bedrooms	3~4 bedrooms	1~3 bedrooms	En-suite apartments	1~2 bedrooms
Box design	NA	Box design	NA	Box design
Mass timber	Mass + Frame	Mass timber	NA	Mass timber
6	1+7	9	1+6	1+8
CLT	CLT + GLT columns (240)	CLT (120-200)	NA	NA
CLT	CLT + GLT beams	CLT (200, 230)	NA	NA
Platform	Finger joint (panels)	Platform	NA	Platform
CLT	RC	CLT	NA	CLT
980	2,700	17,000	6435	4,410
NA	1,000	6,100	1,680	1,700
NA	0.37	0.36	0.26	0.39
1,300,000	5,400,000	23,000,000	18,559,200	
1,327	2,000	1,353	2,884	0
NA	Encapsulation and charring (GLT)	Encapsulation (R60)	NA	Encapsulation
1 EUR = 1,360 USD	1 EUR = 1,360 USD	1 EUR = 1,360 USD	1 GBP = 1,672 USD	NA

Construction information
The largest project in the survey (Via Cenni) presented a total built floor area around 17,000 m^2, whereas the smallest one (Lleda Building) had only 980 m^2. As a result, total timber utilisation also varies from 6,100 m^3 (Via Cenni) to 500 m^3 (Bad Aibling). However, regardless of the scale of the construction, timber utilisation volume per area unit remains around 0.3 m^3/m^2. Nonetheless, in the entries where construction cost was available, despite the different locations, purposes and typologies, most of the buildings showed a value from 2,000 to 2,300 $\$/m^2$. Two exemptions (Lleda Building in Spain and Via Cenni in Italy) costing about 1,300 $\$/m^2$ each, probably achieving a more affordable value owing to the rather plain design (former) and economy of scale (latter).

Fire resistance
Among all the ten buildings, fire resistance time varied from 60 to 120 minutes, depending on the height and location of the building. Encapsulation method was predominantly used as a fire resistance strategy, i.e., covering the timber elements with incombustible or virtually inflammable materials. Charring method was utilised in two entries: Forté Building and Jules Ferry Residence. The former had one CLT wall visible as a way to emphasise timber was used in the main structure of the building; the latter employed charring method for the glulam columns that remained exposed, whereas the CLT elements have all been kept concealed.

Survey with the designers of European CLT buildings
The author contacted nine out of the ten offices responsible for the design of each of the above-mentioned multi-family buildings in May 2016. The architects were asked five multiple choice questions about their experience with CLT for the selected projects. Each question provided pre-defined alternatives and the possibility to write a different answer if necessary. Additionally, an extra space was provided at the end of the questionnaire for any comments the participants wanted to address. In the end, representatives from five different offices contributed to the survey.

The results showed the first contact with CLT for most of the architects happened at a Congress or architecture related exhibition. In no case the material was introduced by the client, meaning that ultimately the designer is responsible for proposing the use of the material whenever appropriated. According to the survey, the main reason designers chose a CLT structure was due to sustainability issues, followed by structural reasons. After completed, though, it is most of the designers chose different features than the original reason for using CLT as the main merit of the building. However, structural performance and sustainability appear again as the most important points likewise during the initial choice for CLT.

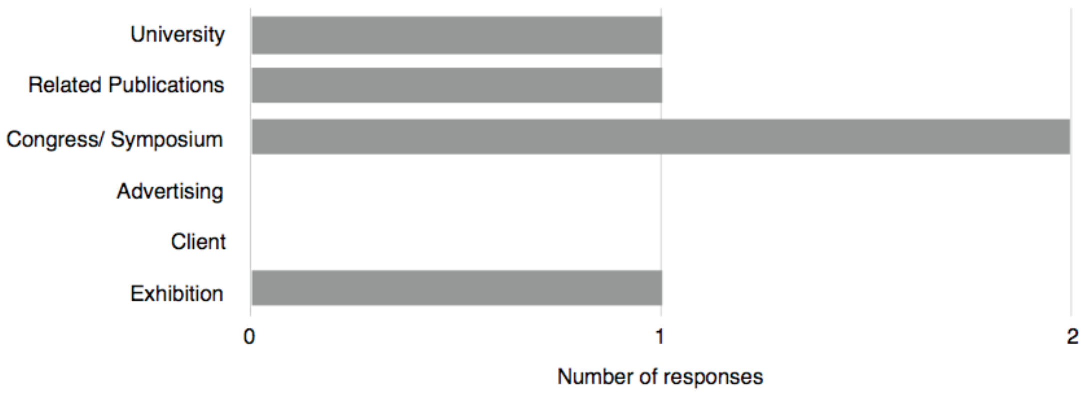


Figure 2.2.6. Questionnaire for European architects: 1) When have you first heard about CLT?

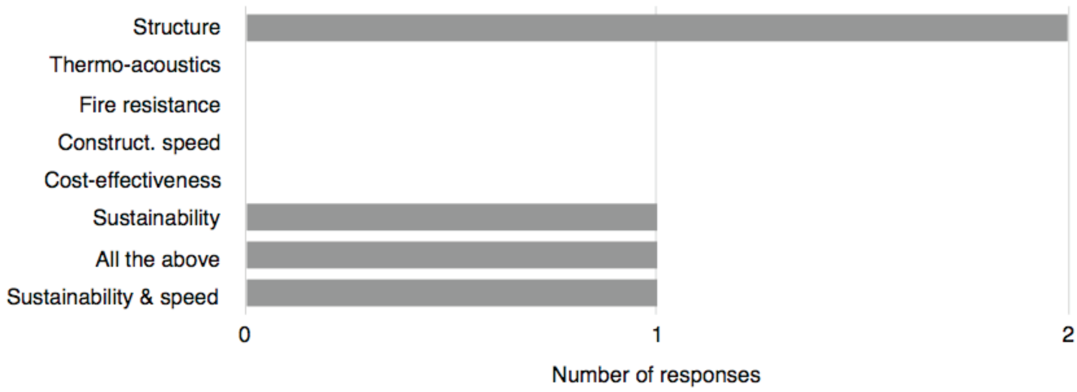


Figure 2.2.7. Questionnaire for European architects: 2) What was the main reason a CLT structure was chosen for the building?

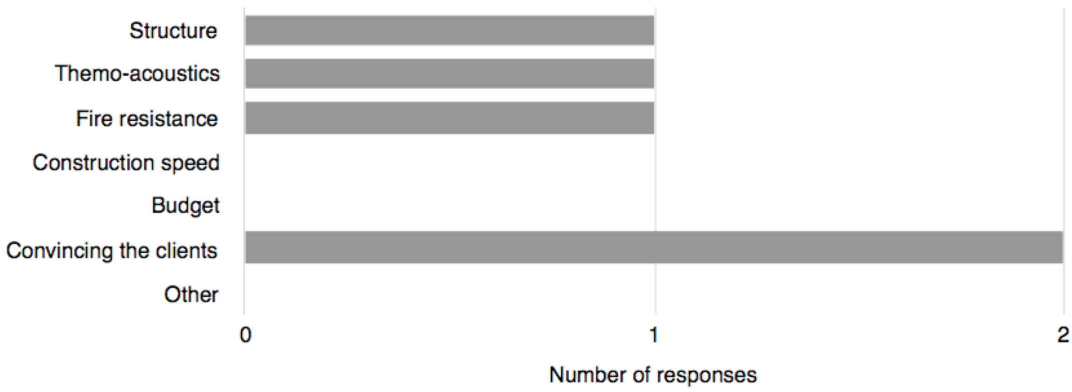


Figure 2.2.8. Questionnaire for European architects: 3) During development of the project, what was considered to be the biggest challenge?

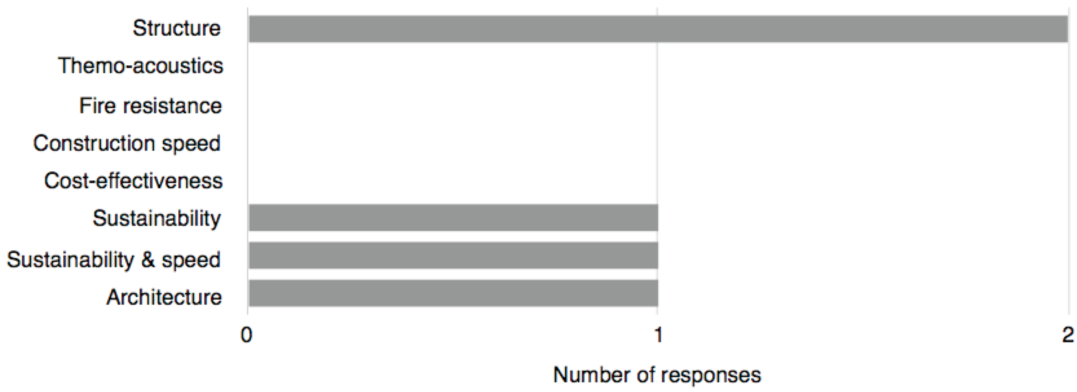


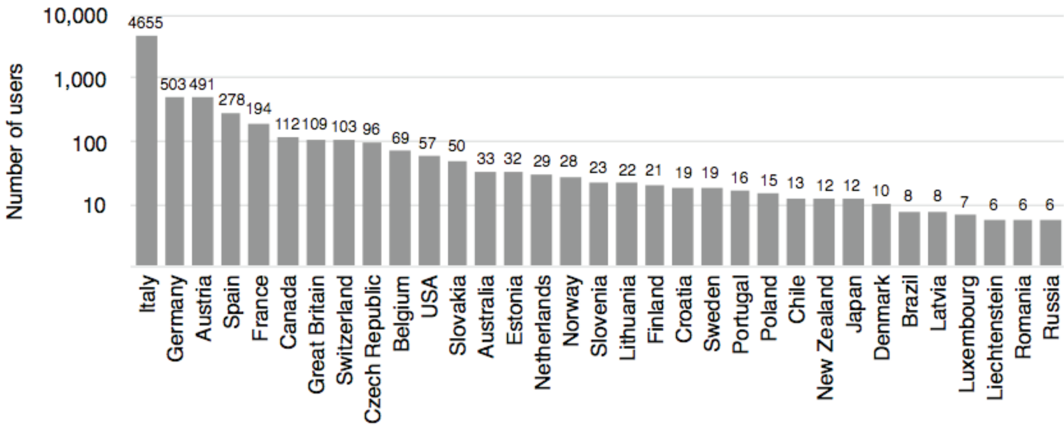
Figure 2.2.9. Questionnaire for European architects: 4) After completed, what was considered to be the biggest merit of the project?

Nevertheless, convincing the clients/buyers about the benefits of CLT construction was mentioned to be one of the biggest challenges for realising a building employing the material in countries with little timber construction tradition. All the European designers have answered they would use the material again for the same application. Furthermore, most of the participants have mentioned about some ongoing CLT projects in the comments area, and one of them declared that all the buildings designed by the office at the moment have the expectation to be built out of CLT.

Transfer activities for Austrian CLT

Transfer activities for European CLT are arguably centred on the University - TU Graz. A series of different activities are provided for the knowledge transfer of CLT, such as courses, workshops and conferences. At first, the activities promoted were focused on building design practitioners to enable a faster implementation of the material. Now, many of transfer activities are directed towards current university students. Either way, it is important to have the support of leading local timber industry associations, such as proHolz in Austria for instance, to gather the funding for the activities and enable a smooth information flow. Italy is the country where transfer activities have been undertaken during the longest time, dating back to 2001. The initial strategy was to spread the use of CLT elements as an alternative to heavy concrete flat roofs, in a way evoking the country's building tradition of mineral walls in composition with a timber roof. As a result of the transfer activities' success, Italy in now one of the most important markets for the outflow of Austrian CLT, in addition to its growing domestic CLT industry. The efficacy of the transfer activities among building related professionals is testified by the overwhelmingly large number of users for the "CLT Designer" software across several different countries.

Figure 2.2.10. Accesses to "CLT Designer" software by country. Source: Holzbau Forschungs bmgh, 2016.



2.2.1.4 DISCUSSION

By gathering information about CLT buildings featured by the four largest European CLT manufacturers, this survey was based on data that has been already arranged by third parties. Therefore, it does not portrait a complete review about everything that was done with CLT. Instead, it portraits the image CLT manufacturers want to transmit about themselves to potential clients. However, as a relatively large number of entries, built over a long period by the largest CLT manufacturers in Europe have been gathered, it is the belief of the author that the study can provide a representative sampling about Austrian CLT buildings development.

Based on the results, conversely to the idea of CLT as a Global phenomenon, it could be observed that its largest manufacturers are building in a rather concentrated territory. Half of all the retrieved CLT buildings are located in Austria, the country where all the largest manufacturers are situated, and that concentrates most of the CLT's world production volume (topic 1.2.1). Perhaps, the bigger incidence of CLT buildings in Austria is partly due to a closer relationship between manufacturing companies and designers, thus enabling a more efficient horizontal knowledge transfer. In fact, the importance of those activities for the diffusion of the material among practitioners could be confirmed by the survey, as most of the designers claim to have first heard about CLT during events such as conferences, symposiums or exhibitions.

CLT main building application has undergone a small change along the time with the increase of residential buildings over commercial ones. Moreover, the study pointed an overall a tendency for low to mid-rise residential constructions, with an average height not much bigger than three storeys. Low occurrence of mid-to-high rise buildings may be a result of the extremely recent history of the multi-storey field itself or may represent the most effective application for CLT. Whichever the reason, buildings over six stories high employing Austrian CLT are still extremely rare occurrences. Nevertheless, they arguably act as valuable publicity CLT panels, sometimes leading to the misconception that this constitutes the main application.

Regardless of the scale of the analysed buildings, the predominant use of mass timber construction method was found in multi-storey housing entries. The choice for a timber-intensive construction method can be justified by the sustainable appeal of the system, combining high physical performance with large CO2 sink effect. This hypothesis is reinforced by the questionnaire results which showed that the sustainable appeal of CLT buildings was one of the most important features for the designers of mid to high-rise residential buildings, both when assigning the material at the design phase and when evaluating the merits of the realised construction. Furthermore, the survey showed how crucial it is for designers to understand the merits of CLT's strengths to propose it and properly transmit its advantages to the clients. Hence, an efficient knowledge transfer between the different fields is crucial, for it can help to create a pact for the value generation concepts behind CLT buildings.

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2.2.2 Japanese CLT utilisation

2.2.2.1 INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT from the building utilisation point of view.

2.2.2.2 METHOD

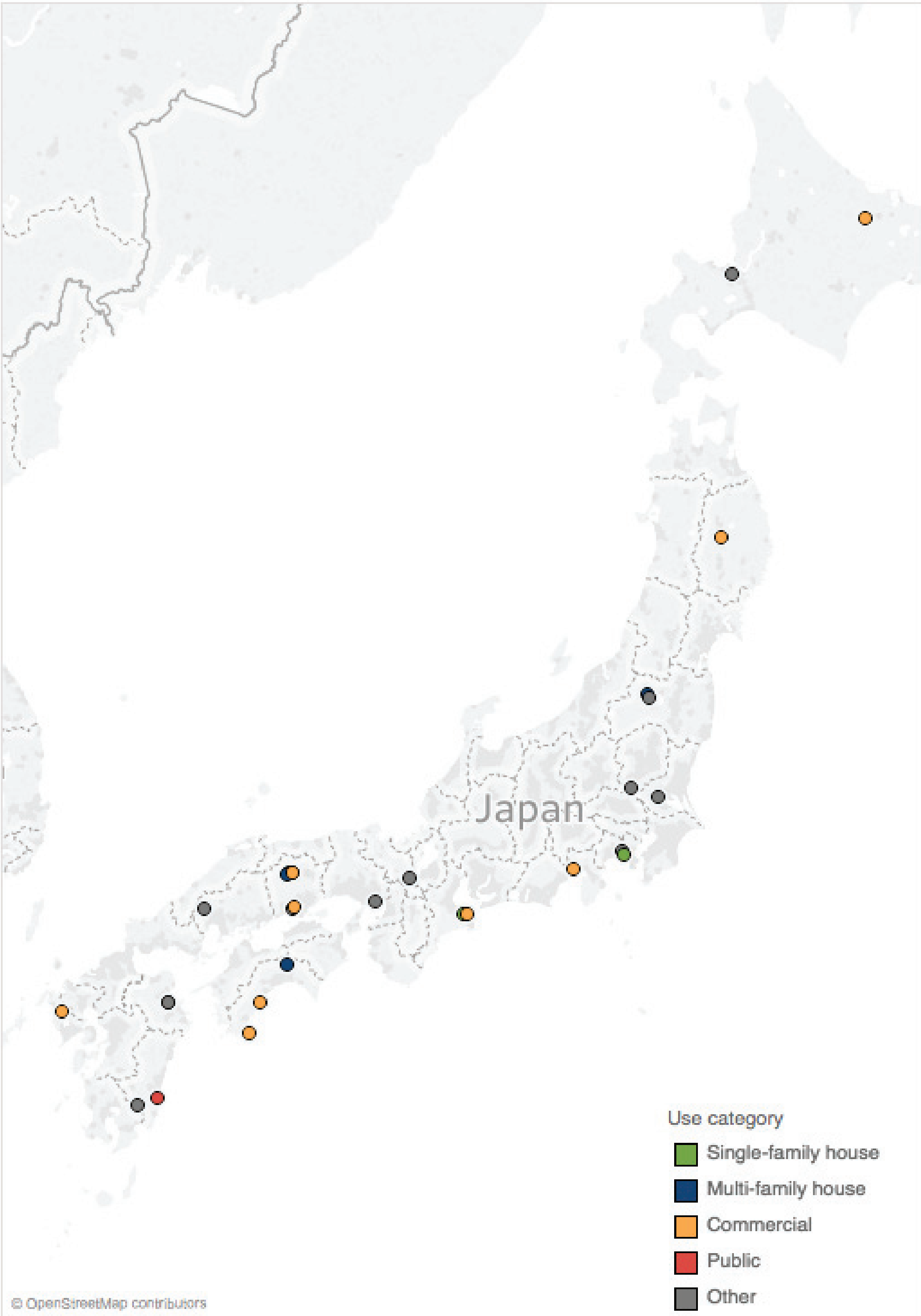
At first, general information on completed CLT buildings from 2014 to April 2016 was retrieved from the Japanese CLT association (2015; 2016). The data included location, main use, CLT volume, built year and floor area. The gathered buildings were then divided into four different categories: single-family house, multi-family house, public buildings (defined as kindergarten, school, religious buildings, nursery, hospital, sports centre), commercial buildings (defined as office, shopping centre, lodging and industrial facilities) and other types (including tower, pavilion, cottage or hut constructions and etc). After, the retrieved data was analysed and discussed. Finally, interviews with Japanese architects involved in the design process of Japanese CLT buildings were conducted, aiming to understand main value concepts attributed to CLT buildings by practitioners who have worked with the material. The architects were asked 9 open-ended questions: 1) how did you first found about CLT; 2) why a CLT structure was chosen for the building; 3) what was the biggest challenge during development and 4) biggest merit after conclusion; 5) would you use CLT again for the same purpose; 6) if not, what are the reasons for not using CLT again; 7) what would you consider to be the best application for CLT in Japan; 8) what would you consider the main value of CLT in Japan and 9) what would you consider the next task for CLT development in Japan. Then, the results were summarised and discussed.

2.2.2.3 RESULTS

The results were divided into two main parts: an analysis of building typologies in which Japanese CLT was utilised and the results of the interviews with Japanese designers who have employed domestic CLT for buildings in Japan.

CLT building typologies
A total of 29 buildings employing CLT were found, built from 2014 to April 2016

Figure 2.2.11. Japanese CLT buildings location by use in April 2014.



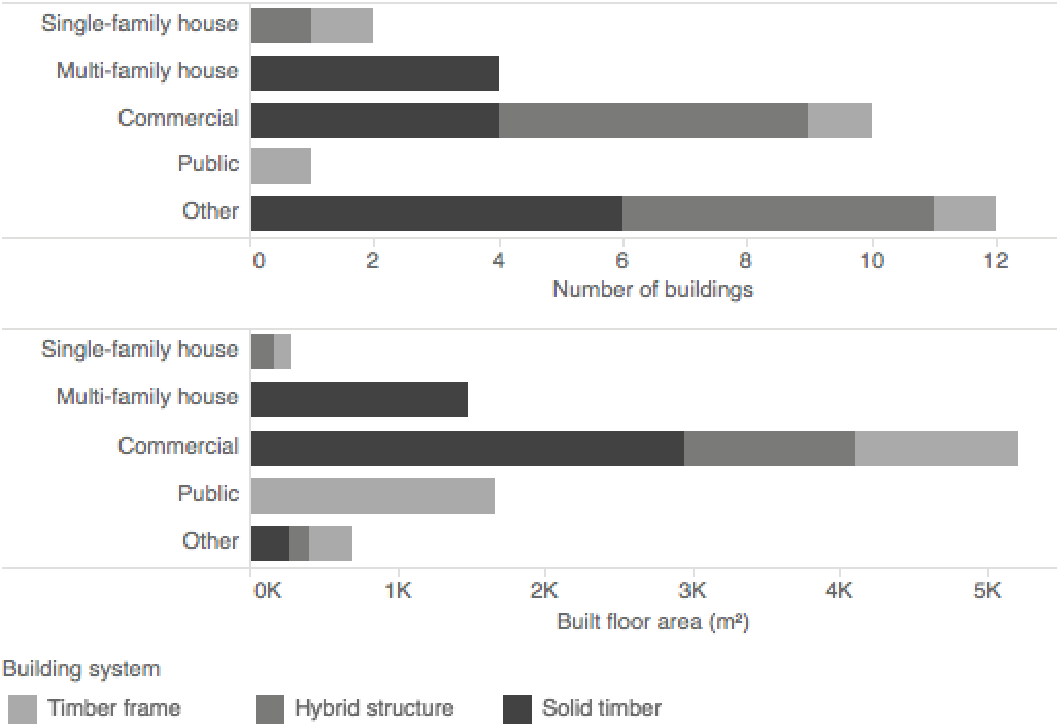
and distributed along 16 different prefectures in all main four islands of the Japanese archipelago. Nine buildings are located in the southern islands of Shikoku and Kyushu, whereas Honshu Island presents 18 buildings, 6 in Chūgoku, 4 in Kansai, 1 in Chūbu, 3 in Kantō and other 3 in Tōhoku region.

In 2014, only six Japanese CLT buildings were built, four of them small trial projects such as two bus stops (Okayama and Kyoto prefectures) and two experimental buildings (Fukushima and Kanagawa prefectures). CLT was also used as a truss member for a school building in Miyazaki and a 3-storeys multi-family houses in Kochi prefecture. A two-fold increase in the number of entries was seen in 2015 with the realisation of 14 buildings using Japanese CLT. Small-scale projects, such as one bus stop in Oita and Hiroshima prefectures each, one experimental building in Gunma Prefecture and one temporary Kiosk in Hokkaido Prefecture were built. Additionally, one commercial building was built in Hokkaido, Iwate, Mie and Oita prefecture. Also, 3-storeys multi-family houses were built, two in Okayama and one in Fukushima Prefecture. Finally, CLT was used for one single-family house in Kanagawa and Mie Prefecture. Afterwards, taking into account the first trimester of 2016, a large increase in the number of commercial buildings is seen, mostly located in the south-west part of Japan: one in Nagasaki, Okayama, Kochi and Shizuoka prefectures. Moreover, one experimental building has been built in Ibaraki prefecture and one bus stop in Hyōgo and Miyazaki Prefecture.

Hence, a total of 1 public building, two single-family houses, four multi-family houses, ten commercial buildings and 12 other types of buildings utilising Japanese CLT were found in Japan at the time of the study. Even though the latter category accounts for the biggest number of entries, due to its smaller scaled buildings, total built floor area is not the most expressive in the whole scenario. On the other hand, commercial buildings category alone accounts for more than half (56%) of the total Japanese CLT built floor area, followed by the one existing public building in which CLT was modestly employed and the multi-family houses category (with 17% and 15% of the whole area respectively).

Furthermore, from the CLT volume point of view, multi-family houses category exhibit a higher share (29%), whereas Public building category drops (1%), due to the different building systems used in each category. The former utilises Mass timber construction system in all entries, employing around 0.4 m^3 of CLT per square meter of construction. This value is also consistent with commercial buildings employing the same system. It is worth noting even though there are only four out of 10 buildings using Mass timber construction inside this category; they account for about four times more CLT volume than Hybrid system, defined as a primary frame structure, braced by CLT panels either horizontally or vertically or both. Frame system, utilised in the Single-family house, Commercial, Public and Other categories, refers to a standard timber frame construction in which CLT was used scarcely in one element or part of it and therefore, presents the smallest average value of CLT volume per area unit.

Figure 2.2.12. Number of Japanese CLT buildings (top) and built floor area (bottom) by use category, by building system.



Residential buildings

Single-family house

Only two single-family residential houses were built in Japan during the studied period, both 2-storeys high. One of them (Kanagawa Prefecture entry) presents a conventional timber frame structure with one slab element of CLT, used to achieve a 2.5-meter cantilever on the second floor. The second one (Mie Prefecture entry) employs CLT in a hybrid system between timber columns and beams for both the vertical and horizontal bracing of the structure.

Multi-family CLT buildings

Only four multi-family houses were built with CLT in Japan, three 3-storeys high, and one 2-storeys high. All of them employed mass timber construction system, which means that a special permit had to be issued as there were no standards for mass timber construction in Japan at the time. Also, all four buildings were designed by the same company, which was part of the research group for the development of Japanese CLT national standards since. Hence, using a mass timber system was a condition for the construction of these buildings, to apply and verify the preliminary results of the research.

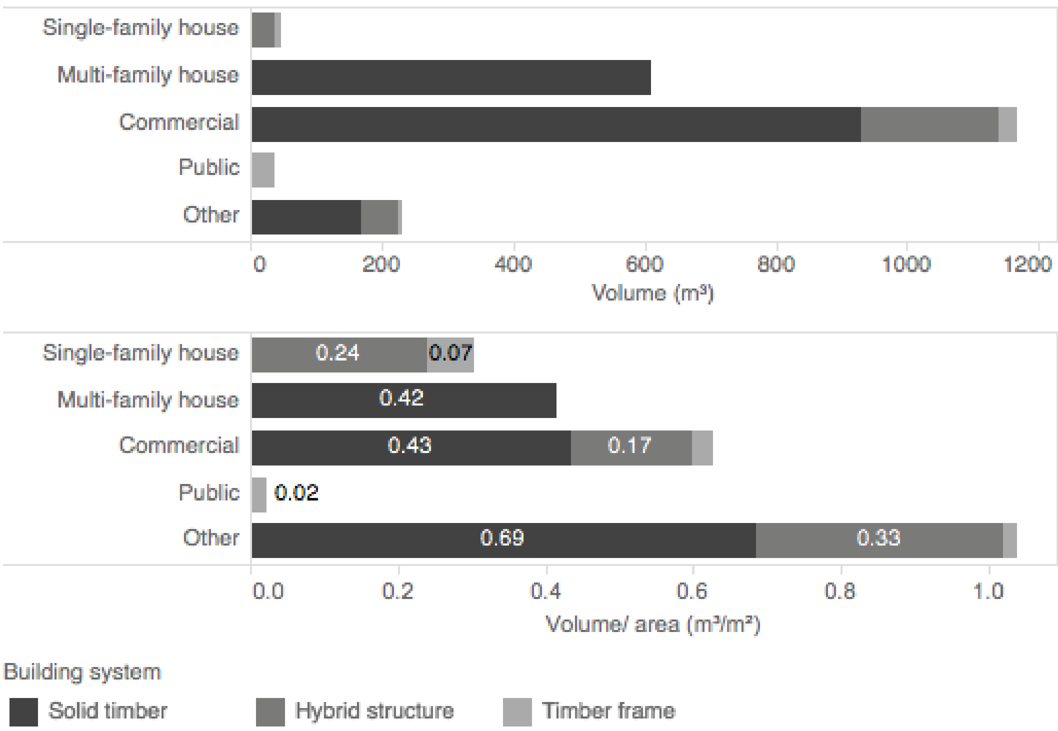


Figure 2.2.13. Japanese CLT buildings total CLT volume (top) and average volume of CLT by built floor area unit (bottom), by function, by building system.

Survey with Designers

Excluding small buildings, with built floor area around 10 m^2 and buildings where CLT was not used consistently as a structural material, meaning utilisation ratio smaller than 0.1 m^3, 15 buildings are left from the total 29 found in the previous survey. Interviews with four architecture offices, responsible for the design of 9 CLT buildings were conducted by the author. The representatives of the offices were asked nine open-ended questions about their experience with CLT for the selected projects.

Except for one case, the Japanese designers had their first contact with CLT at the time of the project, either through the client or structural engineer. Also, in the analysed cases, all the clients were people or companies directly related to the timber business. Hence, most of the times the designers were not the ones who actively pursued the use CLT for the buildings, but instead, had to use it as a condition. Besides client requirement, in one case the designer also mentioned the thermo-acoustic performance of CLT structure as a reason for the use of the material.

During design and construction, designers had struggled with two basic issues. First, the lack of standards for CLT structure at the time, making it difficult to assess the mechanical strength, thus leading to over dimensioning and cost increase as a result. Second, low milling precision of the panels, which created problems during the assembly of the structure due to insufficient clearance space. The issue of milling precision was particularly felt in buildings utilising hybrid structures, where CLT panels had to be slid in between columns for instance.

Once the buildings were completed, different judgements were made concerning the strengths of CLT, varying from the structural performance to the indoor space environmental comfort, owing to timber moisture buffering and thermal inertia properties. Furthermore, in most of the cases, the designers claim they would use CLT again. However, they would rather use it in hybrid structural systems. Just in one case, the interviewee declared he would not actively propose to use CLT, especially for single-family house construction, due to the high costs of the material.

When asked about what kind of building they consider most suitable for the utilisation of CLT, once again different opinions were expressed, usually, referring to the same kind of use the interviewees had contact.

Finally, the answers on the value of CLT in Japan were diverse, referring to “Technical”, “Functional” and “Social” value “Subjects”. Likewise, there are many points for the further development of Japanese CLT in the view of the designers, usually coinciding with the main issue that had to be dealt throughout design and construction process described in question 3.

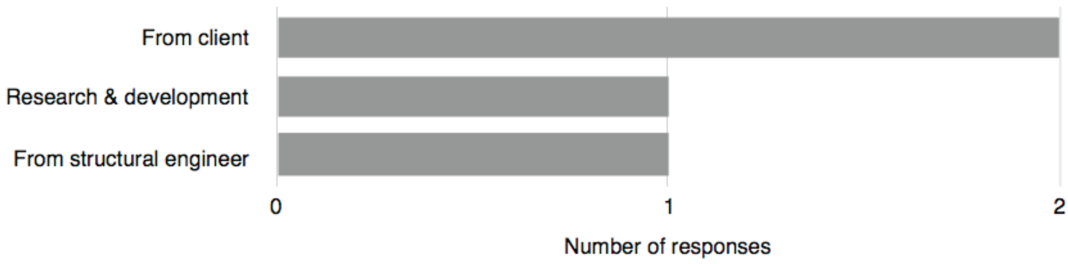


Figure 2.2.14. Questionnaire for Japanese architects: 1) How did you first heard about CLT?

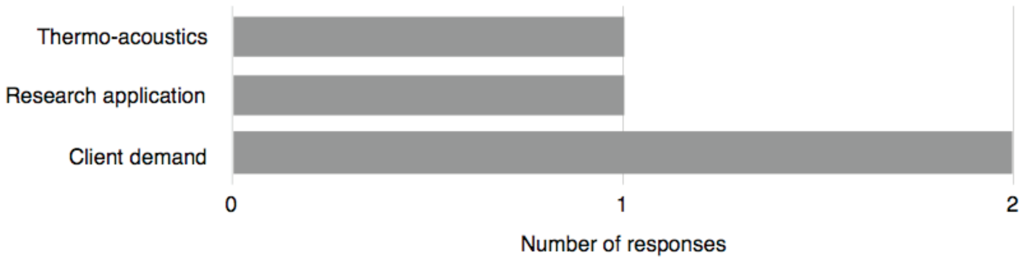


Figure 2.2.15. Questionnaire for Japanese architects: 2) What was the main reason a CLT structure was chosen for the building?

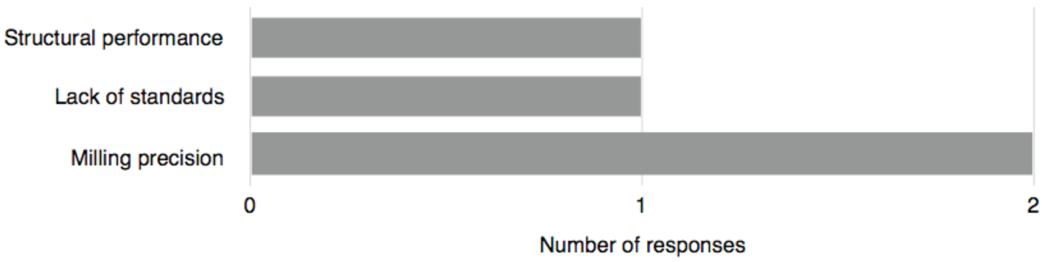


Figure 2.2.16. Questionnaire for Japanese architects: 3) During the development of the project, what was considered to be the biggest challenge?

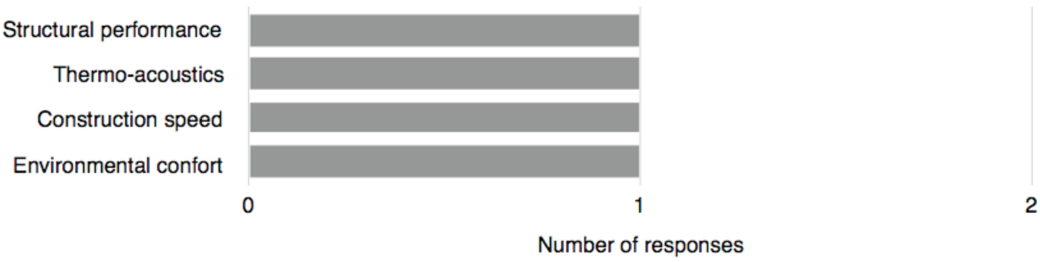


Figure 2.2.17. Questionnaire for Japanese architects: 4) After completed, what was considered to be the biggest merit of the project?

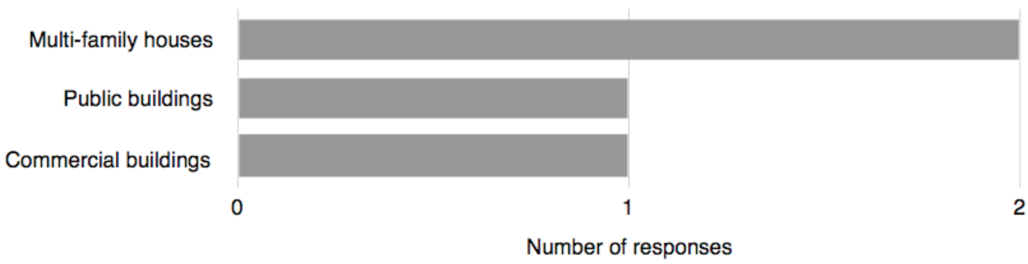


Figure 2.2.18. Questionnaire for Japanese architects: 7) what would you consider the best application for Japanese CLT?

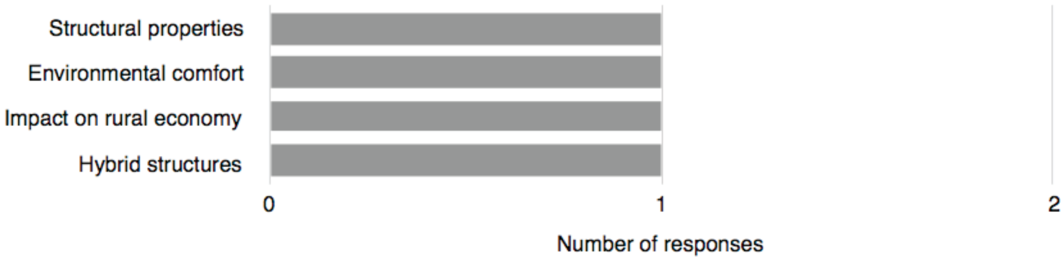


Figure 2.2.19. Questionnaire for Japanese architects: 8) What would you consider the main value of CLT in Japan?

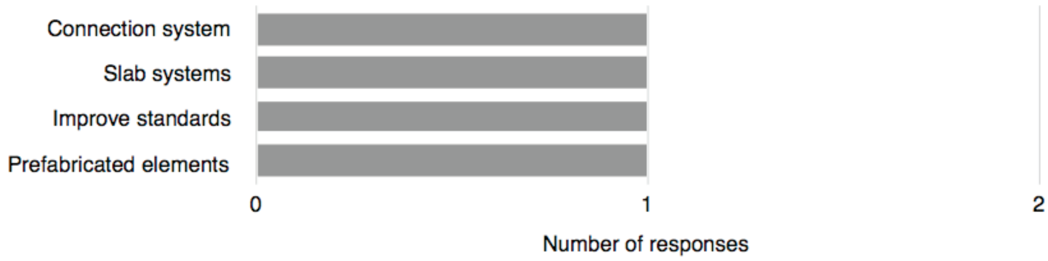


Figure 2.2.20. Questionnaire for Japanese architects: 9) What would you consider the next main task for CLT development in Japan?

The limited amount of completed CLT buildings in Japan during the time of this study makes it difficult to have conclusive results as the utilisation of CLT is still an ongoing dynamic process. The same is valid for the results of the interview which shall be understood not as an established thinking of Japanese CLT but more as a point of the development of material. On the other hand, the small number of buildings allowed that extensive data on almost all realised Japanese CLT buildings at the time of the research were gathered. Hence it is the belief of the author that this study provides insight on the current state of the development and, also, the main trends related to the utilisation of CLT in Japan in the next few years.

At first, excluding "Other" category, the realised Japanese CLT buildings are slightly concentrated in the southern part of the archipelago. Likewise found in Austrian case (Topic 2.2.1), this might be related to the proximity to the area of influence of the manufacturers. Hence, the largest number of realised CLT building in a single prefecture are situated in Okayama Prefecture, where the biggest CLT manufacturing plant is located (Topic 1.2.2). After, a large number of CLT buildings are found in Kochi Prefecture, where besides the location of timber reserves used for CLT manufacturing (Topic 1.2.2), a permanent subsidiary aid for CLT buildings is available, provided by the local government. Thus, providing an evidence of the influence of economic aspects at this stage of implementation in Japan.

Realised Japanese CLT buildings can be divided into "Mass timber" or "Hybrid" construction systems. The former requires more than double the amount of CLT volume per area unit than the latter, due to the fact all vertical and horizontal elements are made of CLT. Additionally, the lack of standards for mass timber construction in Japan at the time of construction required a special permit to use the material as a vertical load-bearing element. On the other hand, the use of a hybrid construction system, mostly employing CLT panels for the stiffening of frame structures, was executed without the need for a special permit. Furthermore, the use of hybrid structures achieve larger spans by the combination with the linear load bearing elements and is potentially cheaper, owing to the smaller amount of CLT employed. Hence, making this building system an attractive option for commercial or public buildings, coinciding with Japanese CLT main application field at the time.

In contrast, according to the survey with the designers, Japanese CLT application in a residential building might be difficult from a cost-effective point of view. As a result, mass timber construction was not used for single-family houses yet, and in the cases where it was employed for multi-family residential buildings, it was deliberately chosen despite the performance or cost issues, aiming to verify research hypothesis. After the standard for mass timber construction with CLT panels was enacted on March 2016 (Ministry of Land, Infrastructure, Transport and Tourism 2016), it is expected that CLT mass buildings shall face fewer problems with over dimensioning, thus having a positive effect on the cost. On the other hand, panel milling issues mentioned in the survey, which were also pointed out as a bottleneck for manufacturing stage (Topic 1.1.2), can only be solved with further investment on CNC machine, which is highly unlikely to happen without a sharp increase in the demand. Finally, the survey with Japanese architects who have employed CLT showed the use of the material was always a condition of the clients, which were, in fact, individuals, companies or institutions directly related to the timber business or CLT industry. Therefore, the awareness concerning CLT has not yet reached either the designers or the general public. For the same reason, there was no consensus about the strengths of CLT from the point of view of the designers.

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2.2.3. Austrian and Japanese CLT utilisation comparison

2.2.3.1. INTRODUCTION

The objective of this topic is to understand the possibilities and limitations for Japanese CLT in comparison to Austria from the building utilisation point of view.

2.2.3.2 METHOD

Austrian and Japanese CLT utilisation were compared based on the previous analyses (topics 2.2.1 and 2.2.2). The main differences between Austrian and Japanese CLT possibilities and limitations from the building utilisation point of view were discussed.

2.2.3.3 RESULTS

The results showed a proximity of CLT buildings with the location of the main manufacturers in both cases. In the Austrian case, even though most of the CLT buildings are located inside the country, there is also a large number of several locations throughout Europe. The propagation of buildings reflects the area of influence of the companies as well as the efficient transfer activities. In contrast, little diffusion through other regions than near the manufacturers is seen in Japan, thus indicating insufficient transfer outside the companies area of influence. Additionally, owing to the high price of CLT panels in Japan, a significant dependence on subsidies can be verified by the building occurrence matching prefectures where such aid is available.

Main CLT application was different for each case. In Austria, residential construction is the most popular application, whereas in Japan the use of CLT in commercial buildings shows a larger number of entries. Furthermore, the different uses are directly related to the preferred building system in each case. Austrian CLT is primarily employed in mass timber building system, whereas Japanese CLT is commonly employed as a reinforcement for timber frame structures. The use of a timber-intensive construction system such as mass timber construction in Europe implies “Functional”, and “Environmental” value “Subjects” of buildings are equally important as “Technical” and “Economic” ones. However, because so-called “green buildings” in Japan achieve lower market prices in comparison to normal ones (topic 0.1.1), less timber-intensive and more cost-effective hybrid systems are preferred, focusing on “Technical” and “Economic” value “Subjects”.

The focus on the latter “Subjects” was also verified during the interviews with Japanese designers who said they would use CLT again but not in a mass timber system. Moreover, the interviews with designers who have employed CLT showed there is still no consensus regarding the strengths of CLT in Japan, whereas in Europe it alternates between technical and environmental aspects. These results indicate there is little awareness about the merits of CLT in Japan from the designers.

2.2.3.4 DISCUSSION

First, following Austrian example, better knowledge transfer activities in Japan along the production chain from manufacturers to the designers have an important role in reaching a pact between the main actors about Japanese CLT value generation strategy. As a result, different CLT-based building systems, as well as their particular benefits and disadvantages, would be easily apprehended by practitioners who would then be able to make the best choice for a specific situation, among a variety of application possibilities, thus maximising value generation. One way to diffuse a better understanding of the material would be manufacturers and research institutions working together to develop Japanese CLT building elements and their performance in several “Dimensions”. The results of this studies could be synthesised in reports and brochures open to public access. By doing so, value generation possibilities in each “Subject” and “Dimension” would be clearly stated, contributing to the development of CLT among both designers and the general public. However, at least during an initial implementation period, promotion policies such as subsidies or tax incentives prove to have a large impact on the realisation of the CLT buildings. Hence, policy and decision makers have a crucial role in the diffusion of Japanese CLT.

The comparison with Austrian CLT showed the need to unite “Direct” value “Concepts” with “Indirect” ones, as the emphasised value “Subjects” can potentially affect the preferred way in which CLT is employed. For instance, the current situation in Japan which focus mainly on some “Dimensions” of “Technical” and “Economic value ”Subjects“ makes the hybrid use of CLT more attractive. The reason lies in the possibility to improve the relatively low stiffness of Japanese CLT panels by combining it with stronger timber or steel linear load bearing elements, achieving longer spans, while reducing the use of CLT, which has an effect on the material costs. On the other hand, focus on ”Dimensions“ from ”Functional“ and ”Environmental Subjects“ in Europe engenders a situation in which mass timber construction can achieve bigger value generation, given its building physics performance and low greenhouse gases emissions. Hence, if through policies, regulations or education activities, the social awareness about ”Environmental“ value ”Subject” increases inside Japanese society, it is expected that the use of CLT may also change as a result, likewise the European case.

2.3 Section 2 conclusions

Considering domestic building demand in Japan, manufacturers should aim at spreading CLT in the central and east part of the main island. Furthermore, the residential application seems to provide the biggest potential for the diffusion of CLT, based on a large number of new dwellings built every year (topic 2.1.2). More specifically, low-rise single-family houses could be targeted in more urbanised areas, while multi-family housing from 4 to 10 storeys could be a promising niche in a metropolis, such as Tokyo or Osaka. Nevertheless, the study showed that Japanese CLT main application field at the moment lies in the low-rise commercial buildings application. This popularity is associated with a bigger focus on some dimensions of "Technical" and "Economic Subjects", which favour the use of hybrid CLT-based building systems in Japan. As discussed on topic 1.2.3, the mechanical properties of the employed timber lamellae limit the value generation on the "Technical Subject" of CLT, and to improve the stiffness of the panel, it is necessary to use higher graded lamellae. However, no certified manufacturers were employing better quality lamellae at the time of the study, meaning this was not yet considered a viable option, most likely considering the possible price increase. Hence the trend to employ CLT panels in hybrid building elements or building systems was seen during along the study (topic 2.2.2).

Rather than focusing on the out-of-plane loading limits, it would be advisable emphasise the current possibilities for the material. First, the use of CLT panel for the bracing existent or new timber frame structures should be promoted. The bracing use would open a broad application range for new low-rise residential construction or retrofit of existent dwellings. In addition to the "Technical Subjects", the value generation strategy could be further developed by highlighting this particular use of CLT together with "Functional" and "Social Subjects", using indicators such as thermal resistance and moisture buffering properties and rural communities economy, for instance. In the second moment of implementation, though, it shall be necessary to add more "Dimensions" from "Functional" and "Environmental Subjects" into CLT buildings benefits, which would increase the possibility for the value generation in mass timber construction in Japan. In this new situation, CLT could spread to the multi-family field easier than on the current scenario. Concurrently, transfer activities shall have a major role in this paradigm shift, educating policy makers, practitioners and the general public about those merits to create a qualified demand for CLT construction. For this reason, one of the most urgent tasks now is the creation of a pact between the main actors regarding Japanese CLT current and future value generation concepts.

To sum up, taking into account TFV theory, an ideal model for CLT buildings' production can be synthesised in Table 2.2.2.

Table 2.2.2. Ideal production conditions for CLT buildings (based on the TFV theory)

	Transformation view	**Flow view**	**Value generation view**
Conceptualization of production	As a transformation CLT building elements into a finished building structure	Design - panel order - transportation- deliver - structure assembly	Deliver of CLT buildings according to building regulations and client's requirements
Main principle	Pre-fabrication	Just in time delivery	Variable (technical, environmental)
Associated principles	Decompose the task into unloading, hoisting and fixing, building services installations and finishings	Reduce storage on site, construction time and product variability	Ensure the delivery of CLT elements to the site on time, fulfilling required mechanical, physical and/or aesthetic properties
Practical contribution	Production of CLT buildings	Reduction of waiting stages	Offer of effective CLT buildings

The basis of the "Transformation view" in CLT buildings production is the transformation of single CLT building elements into a determined building. Pre-fabrication of each building element becomes a key concept in the transformation process, aiming at reducing the construction time and product variability. Following, the "Flow view" will define different steps from the design phase to the assembly of the structure considering just in time delivery to the site as the main concept. Finally, by fulfilling clients expectations of delivery and installation as well as by complying with the necessary regulations, CLT buildings can disclose two principles for the "Value generation view", focusing on different "Dimensions" from either "Technical" or "Environmental subjects" or both.

3.0 CLT implementation

Abstract: this section proposes and evaluates a favourable scenario for Japanese CLT value generation from a multidimensional point of view based on the results from the previous sections. The section presents three chapters. The first presents general recommendations for domestic CLT implementation in Japan from timber resources, manufacturing, building demand and utilisation points of view; The second establishes an action plan divided into three different periods of time (10, 30 and 50 years) defining main objectives, outcomes, leading actors and beneficiaries of each task. Finally, the third evaluate some of the propositions in comparison to the current situation from a multidimensional point of view, notably focusing on economic and environmental value subjects. The results showed that a pact between four main related groups should be created, defining the value of Japanese CLT in construction. The leading actors of these groups would each have a set of tasks to accomplish that would enable the implementation and diffusion of CLT buildings following the previously decided value concept. The study also demonstrated how a multidimensional analysis could be used to clarify value generation possibilities and limitations of CLT building system, signalising the choice of a determined solution, based on the expected value outcome. More specifically, 2nd level hybrid assemblies employing Japanese CLT provided intermediary options from both environmental and economic points of view. Frame + Mass (wall) + Panel (slab) could be employed for the refurbishment of existent buildings as reinforcement for conventional timber frame structures, thus associating Japanese CLT with an objective value concept during an initial stage of implementation. Frame + Panel (wall) + Mass (slab) could be an option to introduce CLT in the multi-family housing construction, taking advantage of the know-how and cost-effectiveness of timber frame and panel structures, nevertheless introducing the indirect value concept.

3.1 General recommendations

3.1.1 Goal

The objective of this topic is to define a set of recommendations, based on the findings from the previous sections, aiming at maximising Japanese CLT value generation from timber resources, manufacturing, building demand and utilisation points of view.

3.2.2 Method

Taking into account main possibilities and limitations for CLT inside Japanese context addressed though the previous analyses (sections 1 and 2), basic recommendations aiming at a successful implementation of the material were defined from the timber resources, CLT manufacturing, building demand and CLT utilisation points of view. After, the main actors involved in each field for the CLT implementation, as well as their roles in the process, was discussed.

3.1.3 Results

The main recommendations aiming at a successful CLT implementation were presented divided into the four different fields, namely timber resources, CLT manufacturing, building demand and CLT utilisation.

3.1.3.1 TIMBER RESOURCES

Arguably, the first and foremost condition for an enduring CLT production lies in the timber resources field. It is crucial to secure the supply of good-quality timber lamella at enough quantity and for an extended period (Topic 1.2.3). As this is a condition directly related to the sustainable management of domestic forest resources, having a strong forestry sector from the economic point of view becomes a key point. Nevertheless, despite recent achievements, decades of economic depression in the Japanese forest sector led to an age gap in the planted forest stock (Topic 1.1.2). The age gap may represent a threat to the supply of good-quality timber in the medium to long-range, especially in the event of an increase in the demand due to the diffusion of timber-based building systems such as CLT. Accordingly, the shortage of supply could lead to the retraction of domestic CLT industry or utilisation of imported timber lamellae to fulfil the demand (Topic

1.2.2) and keep the production line flowing, either way meaning the decline of Japanese domestic forest sector and an unstable scenario for CLT.

Unfortunately, there is no short-term solution for this situation as trees need time to grow before they can be felled and processed into timber products. However, the situation could be improved on the long-range by fomenting the domestic forest sector and actively promoting the use of domestic timber-products. To do so, decision and policy makers have to provide means for the forestry sector to once again establish itself as an attractive investment field. At first, it is important to offer special training programs for forest owners, such as intended by the "Forest and Forestry Basic Law" (2001)(Forestry Agency 2013) followed by several other policies, which promote best practices among small owners, in order to increase the productivity and income of domestic forests. Initiatives such as the above could lead a more favoured position to compete with the inflow of affordable imported timber. Nevertheless, considering Japanese fragmented forest land ownership, expanding the reach and quantity of educational programs like these is a laborious task that can only be realised with the interest and aid of governmental organisations.

Furthermore, as seen in the case of European CLT manufacturers (Topic 1.2.1), it is not rare for the biggest companies to take care of all the steps from cultivating the tree to CLT elements production. This control over the whole the material transformation cycle ensures a good flow of information between resources management, saw-milling and panel manufacturing phases. In contrast, partner saw-mill companies supply the raw material to Japanese CLT manufacturers. In this case, information transfer between CLT manufacturers and timber suppliers becomes even more important as it should enable the former ones to obtain the raw material according to their specific needs, whereas the latter ones need to have the guarantee their products will find a suitable market and their investment redeemed. Hence, in addition to the education on forest practices, if the secure supply of good-quality timber is aimed at the long-range, it is also necessary to provide forest owners with the means to capitalise their production from the start, that means before trees reach a mature age and are sold as timber products. Especial public financing lines with low-interest rates, directed towards smaller forest properties can help forest owners to capitalise their business. Additionally, it is also possible to involve the private sector, represented by the main timber products buyers, namely saw-millers or CLT manufacturers, in the financing of the forestry activity during the early stages of cultivation. Essentially, buyers would be paying for part of the timber production in advance, thus ensuring the inflow of the raw-material according to their needs into the production lines, while forest owners would be able to work on their production and secure the return of the investment. Once again considering Japanese pulverised forest production situation, this would increase the communication between the forest owners, saw-milling and CLT companies, thus minimising chances of variation or even inadequacy of raw-material. Finally, an indirect benefit of developing the forest sector would be the creation of job posts in the rural municipalities of Japan, thus contributing to fixate population into places that otherwise are bound to become uninhabited if current trends continue. The forest sector can help to cope with rural areas depopulation problem in Japan on a national scale, for instance, as intended by policy measures such "Comprehensive Strategy for Regional Revitalization" (Forestry Agency 2016).

3.1.3.2 CLT MANUFACTURING

Owing to the capital intensive production line of CLT, a primary goal for an ideal production situation is to work on a continuous flow, meaning that inputs (mainly sawn timber) are constantly transformed into outputs (CLT elements). By doing so, a cost-effective CLT production can be achieved, redeeming the investments made and reducing the final price of the product through economy of scale (topic 1.2.3). However, one of the clear aspects hindering Japanese CLT diffusion is precisely its high unit prices (Topic 2.2.2). Therefore, to get as close as possible to an ideal CLT production, two main conditions should be met: one related to the production inputs and the other related to the outputs.

Firstly, in case new manufacturing plants are established in Japan, a location close to the raw-material supply should be targeted. The proximity to the timber resources would ensure a more stable material input flow, thus reducing the risks related to a shortage of supply. Furthermore, freight costs associated with the transport of less processed materials (sawlogs and sawn timber), which usually present a higher impact, could be reduced and a positive effect on the final price of CLT panel shall be achieved. Additionally, the reduction of transport distances also has a positive effect on the carbon footprint of the panel, thus strengthening its environmental appeal. Secondly, to have a constant output of CLT panels, sufficient demand considering the total production capacity of CLT in manufacturing facilities is required, thus sustaining the flow of the production lines. In order to increase the market for CLT, it is important that national and local governmental organisations contribute to develop and establish an initial demand the early implementation phase by providing subsidies to buildings employing the material. For instance, isolated initiatives from the Forestry Agency (2016b), Ministry of Land, Infrastructure, Transport and Tourism (2015) and Kochi Prefecture Forestry Promotion (2016) were enforced since 2014. Though locally limited, the influence of these initiatives is seen by the gradual increase of CLT construction during the same period. Particularly on the latter one, the large concentration of CLT buildings built floor area in Kochi prefecture (Topic 2.2.2) attests the success such policies can achieve. Accordingly, other initiatives such as the "Public Buildings Wood Use Promotion Law" (2010) (Forestry Agency, 2016c), requiring all local and national buildings within a certain size to employ domestic timber materials can indirectly benefit CLT.

At the same time, manufacturers should work on improving their products, to broaden current CLT application possibilities. Sensible features that need further development include the mechanical properties and aesthetic features of the panels (Topic 1.2.2). As a higher grade of timber lamella would most likely be more expensive, the benefits for the mechanical performance should be evaluated in comparison with the added price. Nonetheless, the next stage for CLT utilisation will inevitably require visually graded outer surfaces for exposed use. Alternatives include the use of sapwood Japanese cedar or a finishing lamella layer using different timber species, such as Japanese Cypress (Hinoki), Japanese Fir (Karamatsu). As this layer would only fulfil the visual requirements, it could be executed as thin as 10 mm, thus reducing its impact on the self-weight of the panel and cost.

3.3.1.3 CLT BUILDINGS DEMAND

Annual wooden built floor area in Japan represents the largest category of all main building materials, nearly all of it 1 or 2 storeys high. Moreover, most of the new wooden buildings erected in Japan fulfil residential purposes and are concentrated around big urban centres (Topic 2.1.2). However, despite extensive annual demand for construction, the usual practice of building poor-quality houses with short lifespan creates an economic and environmental wasteful vicious circle, which threatens a more affluent lifestyle for the residents of Japan (Topic 0.1.3). Under current circumstances, one possibility for CLT application would be an incremental introduction of the material inside established timber building systems for low-storey residential construction, thus consolidating the primacy of timber construction inside the 1 to 3 storeys range. The diffusion of CLT in such context shall aim for two different goals: 1) contribute to a building culture of durable houses which the next generations shall be proud to inherit and 2) modernise existent building asset. In the first goal, CLT can be used in hybrid structural systems, for instance as an in-plane load reinforcement for timber frame structures, generating value through "Technical Dimensions" such as superior seismic resistance and reliable fire safety. The same can be said for the second goal, especially when employed in older timber buildings that do not comply with the newest seismic resistance procedures after the review of Building Standard Law. Furthermore, the improvement in "Functional Dimensions" such as thermal and acoustic insulation should also be mentioned as a direct benefit of employing CLT panels for the enclosure of the space.

In this context, official policies encouraging the improvement of the built environment and overall construction quality in Japan will have a decisive effect on the future implementation of CLT. These policies shall be responsible for creating a qualified demand by introducing or consolidating new value concepts such as energy efficiency, life-cycle costs, environmental impact, social commitment, that can favour timber-based buildings systems. A paradigm shift concerning the quality of the constructions may be achieved through improvement of national policies and regulations on building performance such as the "Energy Conservation Act", as well as by proposing new evaluation parameters for the buildings such as annual energy consumption and carbon footprint, for instance. Hence, other benefits of timber-based buildings and particular CLT mass timber construction could be emphasised. "Dimensions" for value generation would include airtightness and thermal resistance from the "Functional Subjects" point of view or its advantages over non-timber products regarding embodied energy and feedstock energy content, meaning the recovery of biofuels along the manufacturing process that can be used instead of fossil fuels. A carbon tax system, for instance, can be an objective way to bestow economic value to environmental attributes.

By converging several different values that can be acknowledged by society, CLT should become a suitable option not only for the residential low-rise construction but also for the substitution of mineral based systems in the multi-storey field. If the circumstances above are met, CLT construction shall also be able to compete in the mid-to-high rise buildings field. CLT buildings could then claim a share in a field dominated by reinforced concrete structures. Furthermore, provided the evolution on fire safety technology for timber structures (2-hour fire resistance certification) and gradual development of the building code (currently limiting timber buildings to 4 storeys high) it is possible to foresee a market expansion for CLT buildings on the 4 to 15 storeys high range.

3.1.3.4 CLT BUILDINGS DESIGN

The design of CLT buildings is the point converging different promotion policies (subsidies or regulations), material supply (raw and processed) and building demand (clients and users). That means, ultimately designers are the ones bridging the main actors together and rendering the construction itself. Therefore, it is essential for the practitioners to be aware of the possibilities and limitations of the material to propose the best solution for each situation regarding value generation for the stakeholders.

If Japanese CLT utilisation value is focused on the “Direct Concept”, including parameters such as construction cost and structural performance, employing the CLT elements in hybrid building elements or systems is arguably the most straightforward approach. By doing that, the low modulus of elasticity of the panel is overcome by the combination with stronger linear structural components, such as glulam or even concrete and steel, allowing larger spans, thus widening the application to public and commercial buildings, as seen in the current trend (Topic 2.2.2). Also, if CLT panels only bear in-plane loads, less thickness can be used, thus decreasing its volume per area unit of construction, leading to a more cost-effective utilisation. On the other hand, to highlight “Subject Concepts” such as the “Environmental Subject” a more timber-intensive approach may be preferred. Furthermore, taking full advantage of CLT prefabrication possibilities may be a way to bind both “Direct” and “Indirect” concepts for value generation. In this approach, fully pre-fabricated volume modules could be prepared at the factory, then transported and installed on the site, leading to smaller construction costs, owing to the reduction of assembly time on site and increase of building performance (mechanical and physical), due to production system under an industrial quality control. This application would particularly benefit if a stronger yet affordable panel is produced (as recommended above).

Whichever path is chosen, CLT buildings implementation in Japan will require an effective knowledge transfer through all the chain of production, from manufacturers to the designers. Following the example saw in Europe (Topic 2.2.1) this could be achieved by holding events not only with a commercial appeal but also with a strong educative character, thus providing spaces where latest developments in Japanese CLT construction can be discussed by the most prominent specialists. Furthermore, attention should be given to current students, so that after becoming practitioners CLT is within their range of options since the beginning of their careers. Japan Cross Laminated Timber Association is attempting to create such spaces, for instance by organising “CLT Forum” since 2013 and

“CLT Idea Competition” since 2015. Another example is the exhibitions held by the non-profit organisation “Team Timberize”, such as “Timberize Tokyo 2020” (2014) and “Cross Laminated Timberize” (2016) trying to convey the advantages of timber constructions and lately CLT, to the non-architecture related public. That means, the practitioners need to be aware of the benefits mentioned above when employing CLT in their buildings so that their value generations choice is fully transmitted to the clients and the society as a whole. Hence, there should be a pact between the main involved actors, reaching some consensus about CLT utilisation value in Japan.

3.1.4 Discussion

Based on the general recommendations, four main groups of actors involved in CLT buildings implementation can be defined: 1) policy-makers, representing national and local governmental authorities; 2) material suppliers, referring to forest owners, saw-millers and CLT manufacturers; 3) designers, including engineers architects, builders and overall construction related personnel; 4) educators, standing for non-governmental organisations and research institutions.

Policy-makers are responsible for creating the context where long lasting and stable production of resources can develop as well as the framework for a qualified demand for construction in which timber-based systems like CLT. Material suppliers have to establish communication between themselves to to guarantee the secure inflow of material to the production lines, as well as work on product development to expand the market and thus increase the potential demand for their products. Designers should be able to bridge the demand from clients and users with the possibilities and limitations offered by the manufacturers and then propose the best solution regarding value generation according to each situation. Finally, for all the former mentioned actors to be in tune and moving towards the same goal, it is critical to have the educators group working on knowledge transfer actives. As seen in the European or Canadian case (Topic 1.2.1) a pact between the main actors enables a consistent line of thinking though all different knowledge blocks, thus unifying the efforts and reaching larger persuasive power.

Although it is important to take advantage of the possibilities found in the current situation possibilities to maximise CLT buildings value generation and increase its diffusion in the short term, it is crucial to foresee the desired long-term future scenario and consider the necessary modifications to realise it. For instance, based on the previous analyses (Topics 0.1.3 and 2.2.2,) current domestic CLT application may have better chance to succeed focusing on “Technical” and “Economic Dimensions” for value generation, such as mechanical resistance and cost. Nevertheless, as discussed above, a more generous scenario for CLT implementation would also include “Functional” and “Environmental Dimensions” such as the building physics environmental impact. Hence, to achieve such a situation that can direct benefit CLT construction, related actors and also provide a better-built environment for the residents of Japan, a chronological implementation strategy was proposed in the following chapter, taking into account the recommendations above.

3.2 Action plan

3.2.1 Goal

The objective of this topic is to propose an action plan, based on the previous chapter recommendations, towards a more favourable scenario for the implementation of CLT in Japan, considering a maximum time range of 50 years from the time this chapter was written.

3.2.2 Method

An action plan towards a more favourable scenario for the implementation of CLT in Japan was elaborated, based on the previous topic of “General recommendations”. The plan is divided into three different periods of time: “Short-range” (10 years), “Medium-range” (30 years) and “Long-range” (50 years). On total, three main tasks and 4 secondary tasks were specified along the periods mentioned above. Each task was then further described, divided into six features: 1) “Main objective”, meaning the goals to be achieved by accomplishing the task; 2) “Expected outcome”, discussing the potential changes for CLT resulted from achieving the goals; 3) “Leading actors”, representing the main participants responsible for carrying out the specified tasks; 4) “Beneficiaries”, representing the social groups who shall directly benefit from the outcomes; 5) “Tools”, explaining possible methods to be utilised in order to achieve the goal; 6) “Application or Illustrative examples”, where applicable, exemplifying already tried out methods or yet to be tested experimental visions, respectively. It is worth stressing that all the time periods have the same starting point, nevertheless, extending through different lengths of time. That choice was made considering all the proposed measures within each period are cumulative and can be implemented concurrently. Hence, rather than different steps, the time periods should be understood as a recommended time limit for measures to be realised.

3.2.3 Results

The proposed CLT implementation action plan is presented bellow, divided into three time periods: short-range (up to 10 years), middle-range (up to 30 years) and long-range (up to 50 years).

3.2.3.1 SHORT-RANGE PERIOD (~ 10 YEARS)

Main Task 1: to achieve effective knowledge transfer between all the main related fields and actors.
Objective: to increase the awareness of CLT possibilities among related actors.

Expected outcome: to build a consensus on current and future value generation strategies for CLT buildings in Japan.

Leading actors: research institutions and non-governmental organisations.

Beneficiaries: All related actors.

Tools: Educational and promotional events for both practitioners and students in design and construction field.

Application examples: forums (CLT Forum), seminars, conferences, exhibitions (CLtimberize exhibition).

Secondary Task 1: to increase the utilisation of domestic CLT.
Objective: to employ as much as possible of the currently installed CLT production capacity.

Expected outcome: CLT price decrease through economy of scale and diffusion among established timber building systems for new constructions or refurbishment of old buildings.

Leading actors: Governmental organisations

Beneficiaries: CLT manufacturers.

Tools: to take advantage of the current wood buildings' demand by developing promotional policies and regulations aimed for utilising CLT panels.

Application examples: Subsidiary aid by national and local organisations (MAFF, MLIT and Kochi prefecture).

Illustrative example: use in hybrid building elements or systems, for instance employing

CLT panels as reinforcement for conventional frame structures.

Secondary Task 2: to expand the application range of domestic CLT.
Objective: to unveil new applications for domestic CLT that can lead to higher value generation.

Expected outcome: to increase appeal and competitiveness of CLT-based building systems in comparison to other timber or mineral-based building systems.

Leading actors: CLT manufacturers

Beneficiaries: CLT manufacturers, designers and final users.

Tools: Product improvement, particularly related to the mechanical properties and the aesthetic features of domestic CLT.

Application example: use of Japanese cedar sapwood or Japanese Cypress external layer for exposed use (Yukiharu Takematsu)

Illustrative example: commercialisation of visually graded CLT panel and utilisation of stronger graded lamellae.

3.2.3.2 Medium-range period (~ 30 years)

Main Task 2: to create a qualified building demand for CLT-based building systems.
Objective: to introduce policies and regulations that can benefit CLT and other timber-based building systems in comparison to conventional mineral-based building systems.

Expected outcome: to increase the social awareness and acceptance of neglected "Value Subjects", especially related to functional and environmental aspects of the construction.

Leading actors: Policy-makers from governmental organisations and pressure from organised civil society.

Beneficiaries: forestry sector, timber industry and final users

Tools: laws defining performance standards for features such as life-cycle costs, embodied energy, carbon footprint.

Application examples: regulations on building energy efficiency (Energy Efficiency and Conservation - METI), promotion of timber-based building materials (Public Buildings Wood Use Promotion Law - MAFF)
Illustrative example: utilisation of energy efficient systems with high feedstock energy, such as prefabricated mass timber and hybrid CLT building systems.

Secondary Task 3: To increase domestic CLT manufacturing capacity.
Objective: to answer the possible increase in the demand for CLT.

Expected outcome: implementation of 2 or 3 new CLT manufacturing plants in suitable locations.

Leading actors: Timber industry, CLT manufacturers

Beneficiaries: CLT manufacturers

Tools: investment on new CLT manufacturing plants

Illustrative example: 4 CLT manufacturing plants inside the Japanese archipelago, two already existent (Okayama and Kagoshima prefectures) and two new (1 in Tohoku area and 1 in Hokkaido prefecture). On total, Japanese annual production capacity could increase to about 200 thousand m3, allowing 500 thousand to 2 million m2 of CLT-based built floor area per year, depending on the building system employed.

3.2.3.3 Long-range period (~ 50 years)

Main Task 3: to promote domestic forestry sector.
Objective: to improve forestry productivity and competitiveness against imported timber

Expected outcome: resume of domestic forestry as a profitable business, increase of future timber supply and foment of rural areas' economy.

Leading actors: Policy-makers from governmental organisations

Beneficiaries: Forestry sector

Tools: Forestry promotion measures and policies.

Application examples: Forest and Forestry Basic Law (MAFF)

Illustrative example: following the example of "Secondary Task 3", the four CLT manufacturing plants would require about 500 thousand m3 of sawlogs. Hence, assuming a yield rate around 50% from the standing tree to the sawlog and an average growth of 10m3/ha year meaning, over 100 thousand hectares of planted forest across the Japanese territory would be necessary for the annual supply of CLT manufacturers.

Secondary Task 4: to ensure communication flow through CLT's chain of production.
Objective: to reduce variability and guarantee the supply according to specifications needed.

Leading actors: Governmental Organisations and related Trade Associations such as foresters, saw-millers, CLT manufacturers.

Expected outcome: capitalise forestry and increase security for the forestry business

Beneficiaries: forestry sector and timber industry

Tools: public and private financing programs

Application examples: Forestry and timber industry promotion measures and policies (Forest and Forestry Basic Law - MAFF).

3.2.4 Discussion

"Main Task 1", effective knowledge transfer, is one of the major issues to be solved currently. It is crucial for the successful implementation of CLT in Japan that the main related actors can reach a consensus about present and future value generation concepts so that a collective effort is conducted in the medium to long range. On the other hand, the increase of domestic CLT utilisation ("Secondary Task 1") reflects urgent steps to be taken following the current trends, to ensure the continuation of CLT development in

Japan. Even though some isolated efforts are seen as stated in the “application examples”, a more comprehensive approach that could consolidate the demand for CLT in Japan is still missing. Simultaneously, domestic CLT improvement, described on “Secondary task 2” shall contribute to speed up the market acceptance process.

“Main Task 2”, the creation of a qualified building demand, is a natural evolution from “Secondary task 2” and represents an important turning point for CLT implementation in Japan. An effective knowledge transfer process realised during “Main Task 1”, has the potential to organise important sectors from the society in this stage. Therefore, more pressure could be put on the national institutions to forward policies and regulations, introducing new value concepts into the building sector that shall benefit CLT and other timber-based building systems. In fact, the success or failure to accomplish this task can determine whether CLT becomes a widely diffused building material, claiming the share of the market of established mineral-based materials, or stays only as niche material for exceptional projects. Furthermore, if the conditions stated on “Main task 2” are met, the increase of domestic CLT manufacturing capacity stated on “Secondary Task 3”, shall happen as a natural consequence. The increase in the production capacity would then constitute the second wave of investment in CLT production in Japan, and e the evidence the implementation process is moving forward as planned.

Finally, the tasks described in the long-range period close the cycle of CLT production, as they should provide the conditions for a secure supply of enough quantity of quality timber for CLT manufacturing. Hence, this task arguably contains the most significant measures concerning the continuation of Japanese CLT as an entirely domestic product. Furthermore, they also have a potential effect on the forestry sector and the recovery of the economy of rural areas. However, these are also the most vulnerable fields in the production chain, thus largely depending on governmental organisations support to improve. Some steps were already taken by main institutions such as MAFF, and slow but steady progress can be seen. It is worth noting, though, that owing to the relatively long growing time of the trees, a failure on this field would certainly mean a great delay in medium to long range implementation of CLT in Japan.

3.3 Multidimensional evaluation

Abstract: this chapter evaluates the proposed scenario for Japanese CLT value generation in comparison to the current situation, from a multidimensional point of view. The chapter is divided into two parts. The first one evaluates the effect different multimodal transport combinations for three CLT supply options in Japan have on the panel's Global Warming Potential (GWP) and freight costs from cradle to the construction site gate. The second one evaluates the effect different CLT building elements and combination possibilities for the construction of mid-storey multi-family housing have on the Global Warming Potential (GWP) and material costs from the cradle to the grave. The results demonstrated how a multi-dimensional analysis could be used to clarify value generation possibilities and limitations of CLT building system, signalising the choice of determined solutions, based on the expected value outcome. From the environmental point of view, Japanese CLT panels and building systems showed better results than any other of the assessed options, due to its large timber mass in addition to effective freight route. In contrast, from the economic point of view, results showed homogenous or 1st level hybrid combinations employing panel system, regardless of supply origin, are the most affordable options, followed by homogeneous or 1st level hybrid combinations employing imported CLT panels. However, homogenous or 1st level hybrid combinations employing domestic CLT panels show more expensive options. Hence, the urge to develop and establish an initial demand, while forwarding new value concepts into the construction field, thus creating a qualified demand for CLT-based building systems. Nevertheless, domestic 2nd level hybrid assemblies provided intermediary choices from both environmental and economic points of view and could be used to associate Japanese CLT with "Direct" values at a first stage and also to introducing "Indirect" value concepts on a later stage of development.

3.3.1 Building technology view: cradle to construction site

3.3.1.1 GOAL

The objective of this study is thus to understand the effect that different multimodal transport combinations for the supply of CLT panels have on Global Warming Potential (GWP) and freight costs from cradle to the construction site gate. This topic is derived in part from an original article published by the author in the International Wood Products Journal, available online: http://www.tandfonline.com.

3.3.1.2 METHOD

Scope and system boundary
According to EN 15804 Sustainability of construction works (Technical Committee CEN/TC 350 2014), the life cycle assessment of buildings is composed of five main stages, each composed of different modules: the first one (Product stage) includes modules A1 to A3 and refers to the inputs and outputs from cradle to factory gate. The second one (Construction stage) comprises modules A4 to A5 and deals with the impacts during products transportation from factory to construction site and the construction process itself. The third one (Use stage) includes modules B1 to B5 and accounts for the impacts of the installed products during their projected service time, taking into account necessary maintenance and repairs. The fourth one (end-of-life stage) is composed of modules C1 to C4 and refers to the management of the product after it is replaced or dismantled from the building when its service time comes to an end. Finally, the fifth one (Benefits and loads beyond system boundary) takes into account impacts that result from reuse, recycle or energy recovery of the product.

Table 3.3.1. Life cycle assessment stages and modules as defined by EN 15978 (2012) and selected scope of the study.

Product stage	Raw material	Transport	Manufacturing	**Construction stage**	Transport	Construction, installation	**Use stage**	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy	Operational water	**End-of-life stage**	Demolition	Transport	Waste processing	Disposal	**Benefits and loads beyond system boundary**	Reuse, recovery, recycle
	A1	**A2**	**A3**		**A4**	**A5**		**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**		**C1**	**C2**	**C3**	**C4**		**D**

This work investigates the environmental and economic impacts of different multimodal transport combinations for CLT panels from cradle to a hypothetical construction site in Tōkyō, Meguro-ward, Naka-Meguro district. Henceforward, defined as "cradle to gate with options" study (Technical Committee CEN/TC 350 2012) for the supply of CLT panels in Japan. A functional unit of $1m^3$ of CLT is used to assess the impacts of modules A1 to A4 for the evaluation of four different supply possibilities. One case from an Austrian company (Company 1) and tree cases from Japanese companies, one of them located in the West region of the main island, one based in the southern part of Kyūshū Island and the last one situated in Tōhoku area (Company 2, Company 3 and Company 4, respectively). The first three companies were modelled based on the location of CLT manufacturing facilities that were active at the time of the study, whereas the last one was modelled based on the previous topics (3.31 and 3.3.2) proposal.

Assessment of data

Global warming potential (GWP) was calculated according to EN 15978 (2012) for a functional unit of $1m^3$ of CLT, using the life cycle inventory values retrieved from Ökobaudat (defined as GHG emissions/kg)(Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2016). GWP for each of the different assessed modules was calculated separately in all three cases, aiming to understand the environmental impact of transportation modules (A2 and A4) in comparison with material extraction and manufacturing modules (A1 and A3, respectively). Afterwards, GWP values in all assessed modules were added together for each company and compared. Finally, a relative GWP value was calculated so as to facilitate the comparison between the three cases. The highest value (Company 1) was considered as 100 %, whereas GWP values for the other two companies were displayed as a percentage (Equation 1).

Equation 1:

$$\text{Relative GWPno} = (\text{GWPno}/\ \text{GWP1}) \times 100$$

Where "no" = number of the company.

The freight costs were calculated multiplying travel distances of each means of transport by its specific costs corresponding to $1m^3$ of CLT. We added freight costs in each module and compared the total values from all three companies. After this, aiming to represent the weight each transportation module has on the final CLT panel price, we calculated a weighted freight cost value dividing the freight costs for each means of transport by the unit costs of the transported raw material, corresponding to a functional unit of $1m^3$ of CLT (Equation 2). Finally, we added the weighted freight costs in each module and compared the results for all four companies.

Equation 2:

$$\text{Weighted freight X cost} = (\text{Freight cost } A_{n,x} / \text{Raw material x cost}) \times 100$$

where "x" = number of freight type; "n" = number of the assessed module.

Road freight distances were modelled after interviews with company personnel, whereas road freight costs were retrieved from technical publications on the subject (Schade et al. 2006; Kanagawa Trucking Association 2016). Ocean freight distances and costs were modelled using data extracted from World freight rates (2013). Raw material costs per volume unit were retrieved from official publications on the subject (Forestry Department 2015; Ministry of Agriculture, Forestry and Fisheries 2016).

Production Stage (module A1-A3)

Data about GWP of CLT during raw material extraction (A1) and manufacturing modules (A3) were assumed the same in all four cases and retrieved from Ökobaudat for a functional unit of $1m^3$. Then, we modelled the transportation module (A2) according to two different situations.

1) Primary processing (lamella) and CLT manufacturing happening in the same place: option assigned to companies in which CLT manufacturing facilities are located close to forest resources, namely companies 1, 3 and 4. In this situation, only the transportation of sawlog from the extraction point to the manufacturing facilities was considered. A conservative average distance of 50 km road transportation by a 12t lorry was assumed. Additionally, the yield rate from sawlog to planned lamella was included in the freight costs calculation as 43.7% for Spruce CLT (Fredriksson et al. 2015) and 47.4% for Japanese Cedar CLT (Jeong et al. 2013). Hence, transportation cost corresponding to an additional 0.564 m^3 and 0.526 m^3 of Spruce and Japanese Cedar sawlog was added together, respectively.

2) Lamella processing and CLT manufacturing happening in different places: option

assigned for company 2 in which CLT manufacturing facility is located away from forest resources. Besides sawlog transportation from the extraction point to the primary processing facilities described in “1”, 250 km transportation by a 12t lorry was included, accounting for timber lamellae transportation from the primary processing facility to the CLT manufacturing facility. Although some studies point out the cumulative yield from sawlog to finished CLT panel can be up to 26% (Han et al. 2016), no consistent data for each production step of the timber species used in this study was found. Hence, an ideal situation of 0% yield was assumed during this transportation phase, meaning all the transported lamellae shall be turned into a CLT panel.

Table 3.3.2. Multimodal transport combinations for module A2 Transport (Product stage) in the assessed companies.

Cases			Sawn log (B class) transportation			Sawn timber (B class) transportation		
Company	Species	Primary unit (1m3)	Mat. price (yen/m3)	Road 1 (km)	Freight (yen/t)	Mat. cost (yen/m3)	Road 2 (km)	Freight (yen/ t)
01	Spruce	489 kg	11,561	50	1,091	NA	NA	NA
02	Jap. Cedar	400 kg	14,400	50	4,422	66,600	250	12,444
03	Jap. Cedar	400 kg	14,400	50	4,422	NA	NA	NA
04	Jap. Cedar	400 kg	14,400	50	4,422	NA	NA	NA

Conversion rate: 1 euro = 117.983 yen; 1 USD = 111.068 yen

Construction Stage (module A4)

The transportation module (A4) was modelled according to four different situations.

1) CLT imported from Austria (Styria region) to Japan, Tōkyō (Meguro-ward): option assigned to Company 1. First, road transportation by a 12t lorry from Styria region to Genoa port in Italy (700 km) was modelled. Then, ocean transportation in a container ship from Genoa port to Shin-Toyosu port in western Tōkyō (17.500 km) was modelled. Average container utilisation ratio of 70% was assumed for a 20ft container. Finally, an additional 30 km of road transportation by a 12t lorry from Shin-Toyosu port to the hypothetical construction site in Naka-Meguro district was modelled.

2) Domestic CLT transported from western Japan (Okayama Prefecture) to Tōkyō Prefecture (Meguro-ward): option assigned to Company 2. Road transportation by a 12t lorry from Maniwa district in Okayama prefecture to the hypothetical construction site in Naka-Meguro district (700 km) was modelled.

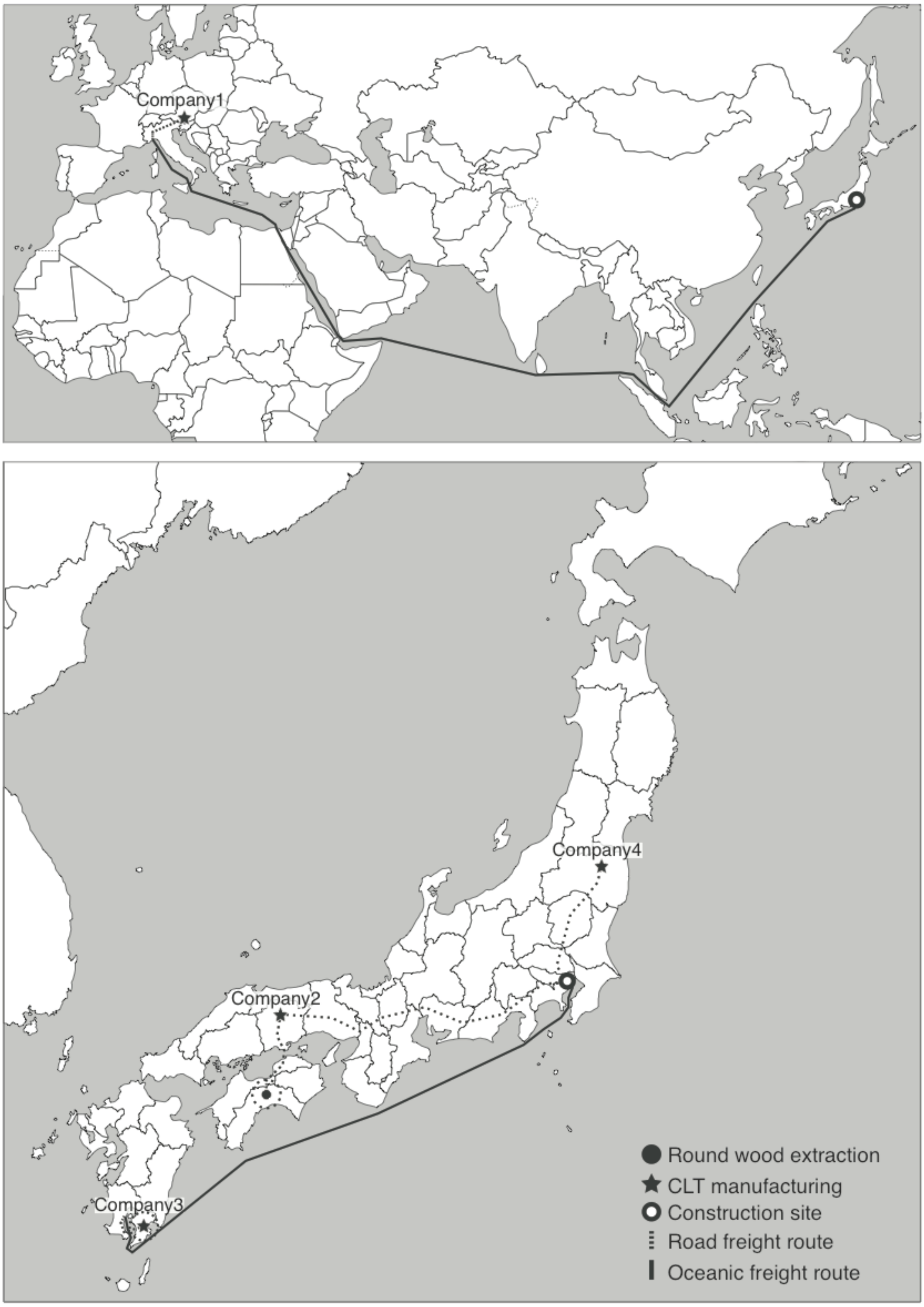


Figure 3.3.1. Map of transportation routes and means of transport from cradle to construction site: Company 1 (top); Companies 3, 3 and 4 (bottom).

3) Domestic CLT transported from southern Japan (Kagoshima Prefecture) to Tōkyō Prefecture (Meguro-ward): option assigned to Company 3. First, road transportation by a 12t lorry from Kimotsuki District in Kagoshima Prefecture to Kagoshima port (100 km) was modelled. Then, ocean transportation in a container ship from Kagoshima port to Shin-Toyosu port in western Tōkyō (1100 km) was modelled. Average container utilisation ratio of 70% was assumed for a 20 ft container. Finally, an additional 30 km of road transportation by a 12t lorry from Shin-Toyosu port to the hypothetical construction site in Naka-Meguro district was modelled.

4) Domestic CLT transported from Tōhoku area in Japan (Fukushima Prefecture) to Tōkyō Prefecture (Meguro-ward): option assigned to Company 4. Road transportation by a 12t lorry from Fukushima Prefecture to the hypothetical construction site in Naka-Meguro district (280 km) was modelled.

Table 3.3.3. Multimodal transport combinations for module A4 Transport (Construction stage) in the assessed companies.

Cases			CLT panel transportation						
Company	Species	Primary unit (1m3)	Mat. price (yen/m3)	Road 3 (km)	Freight (yen/t)	Ocean (km)	Freight (yen/t)	Road 4 (km)	Freight (yen/t)
01	Spruce	489 kg	47,193	700	15,279	17,500	7,283	30	3,330
02	Jap. Cedar	400 kg	140,000	700	22,410	NA	NA	NA	NA
03	Jap. Cedar	400 kg	140,000	100	7,157	1,100	2,879	30	3,330
04	Jap. Cedar	400 kg	140,000	280	12,972	NA	NA	NA	NA

Conversion rate: 1 euro = 117.983 yen; 1 USD = 111.068 yen

3.3.1.3 RESULTS

Global warming potential (GWP)

At first, modules A1 presented a negative GWP value in all four cases, owing to the biogenic carbon contained inside the raw timber material. Observing the results from Company 1 (Figure 3.3.2), A4 Transport module shows the biggest GWP among all assessed modules, more than twice as big as the CLT manufacturing module (A3). Ocean transportation from Europe to Japan was the primary cause of the high GWP in module A4, accounting for 60% of its total GWP. A2 Transport module's GWP comes in third place, however with an almost negligible value, due to the proximity of the raw material extraction spot with CLT manufacturing facilities.

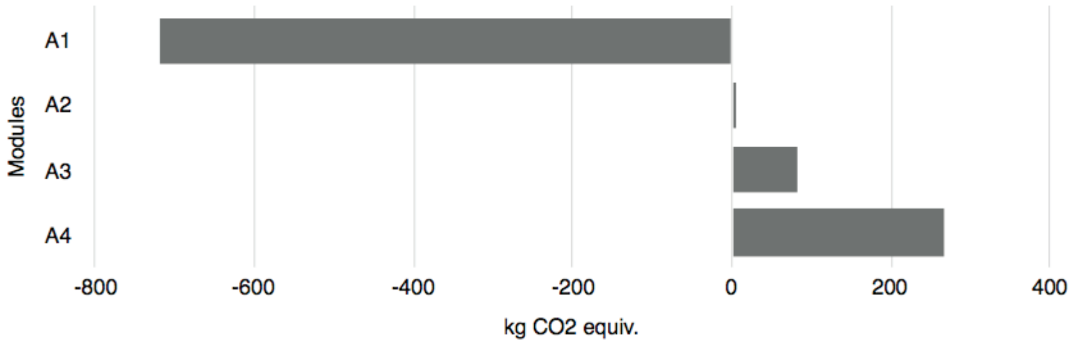


Figure 3.3.2. Global Warming Potential (GWP) of Company 1 for assessed modules A1-A3 (Production stage), A4 Transport from factory to site (Construction stage).

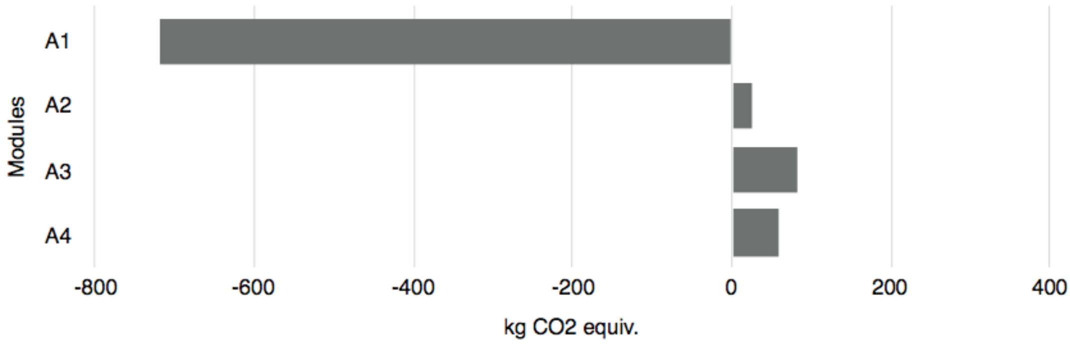


Figure 3.3.3. Global Warming Potential (GWP) of Company 2 for assessed modules A1-A3 (Production stage), A4 Transport from factory to site (Construction stage).

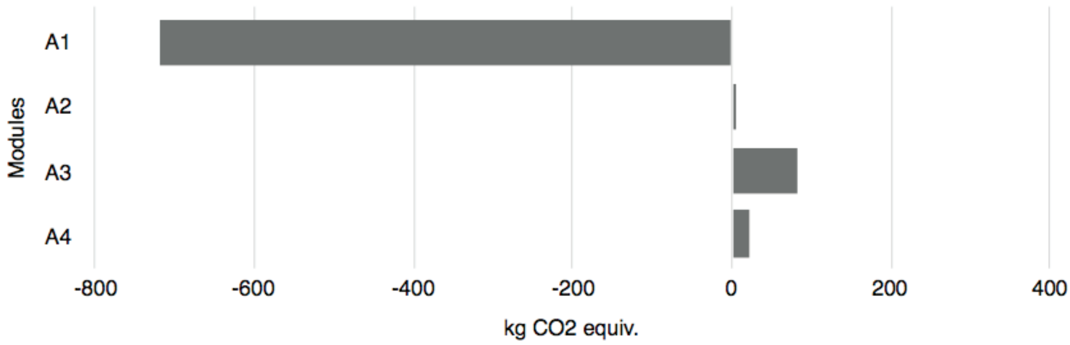


Figure 3.3.4. Global Warming Potential (GWP) of Company 3 for assessed modules A1-A3 (Production stage), A4 Transport from factory to site (Construction stage).

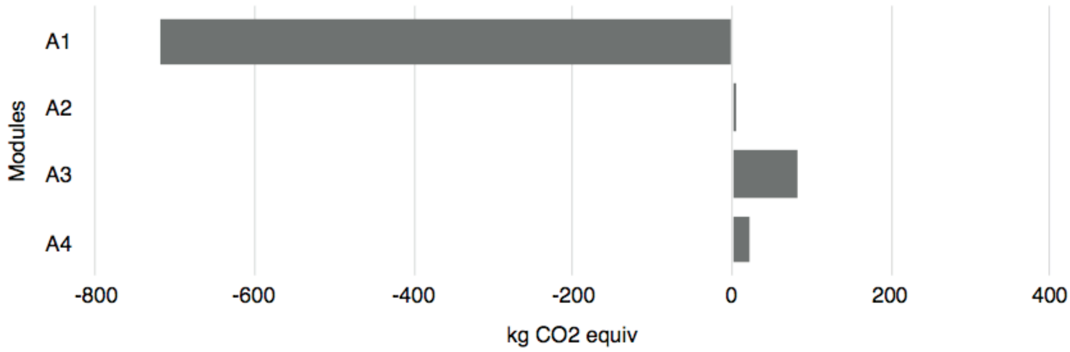


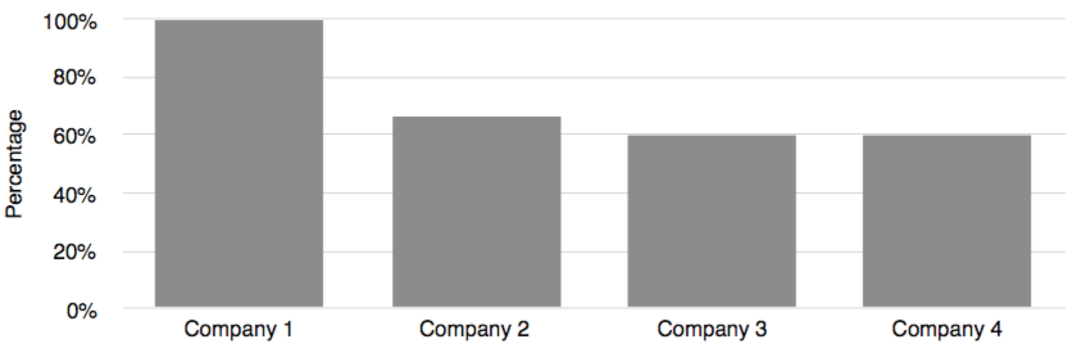
Figure 3.3.5. Global Warming Potential (GWP) of Company 4 for assessed modules A1-A3 (Production stage), A4 Transport from factory to site (Construction stage).

On the other hand, looking at the results from Company 2 (Figure 3.3.3), A3 Manufacturing module is revealed as the activity with largest GWP, whereas A4 Transport module accounts for about two-thirds of the former. However, GWP in A2 Transport module increased five times in comparison to Company 1, precisely as a consequence of the additional lamellae road transportation from the primary processing facility to the CLT manufacturing facility.

Similarly, A3 Manufacturing module also shows the largest GWP in Company 3 and 4 (Figure 3.3.4 and 3.3.5). In contrast, the GWP from the transport modules (A2 and A4) were the smallest among all the cases. In the first case, smaller impact from transportation was due to both the location of CLT manufacturing facilities close to forest resources and the use of ocean freight transport within the range of the Japanese archipelago. In the second one, it was due to more efficient inland transportation owing to the proximity to the final consumer centre in the second case. Altogether, GWP from transportation modules in Company 3 and 4 accounts for less than one-third of CLT manufacturing module (A3).

Considering the aggregated GWP of Company 1 as 100%, the aggregated GWP values of the other two companies were visualised as a percentage (Figure 3.3.6). Company 2, 3 and 4 show 34%, 40% and 40% smaller values than Company 1, respectively, thus attesting the benefits of locally supplied CLT from the GWP point of view.

Figure 3.3.6. Assessed modules' aggregated Global Warming Potential (GWP) of Companies 2 and 3 as a percentage of Company 1 GWP.



Freight costs

Firstly, there is a significant difference regarding the unitary freight costs depending on the transportation modal (Tables 3.3.2 and 3.3.3). This variation is a result of the average load capacity of each means of transport. For instance, whether intercontinental or within the boundaries of Japanese territory, ocean freight is cheaper than road freight, due to its higher load capacity. Likewise, the cost difference between European and Japanese road freight (Table 3.3.3) is a consequence of different freight restrictions in each place, resulting in different average load values, such as 7.4 t/vehicle in Europe (Schade et al. 2006), in contrast to 5.5 t/vehicle in Japanese roads (Statistics Bureau 2016).

Based on the results, Company 1 showed the largest aggregated freight costs of all the four cases. A closer look at Figure 3.3.7 shows A4 Transport module accounted for over 90% of the total freight costs. In detail, ocean freight contributed with more than 20%, whereas road freight transportation through Europe represented around 60% of the freight costs in module A4. In total, weighted freight costs from Austria to Japan would add up more than 30% of the raw material price (Figure 3.3.8).

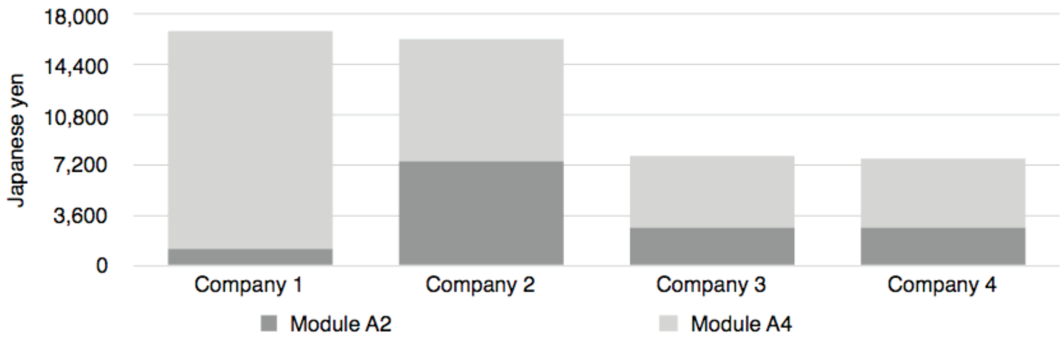
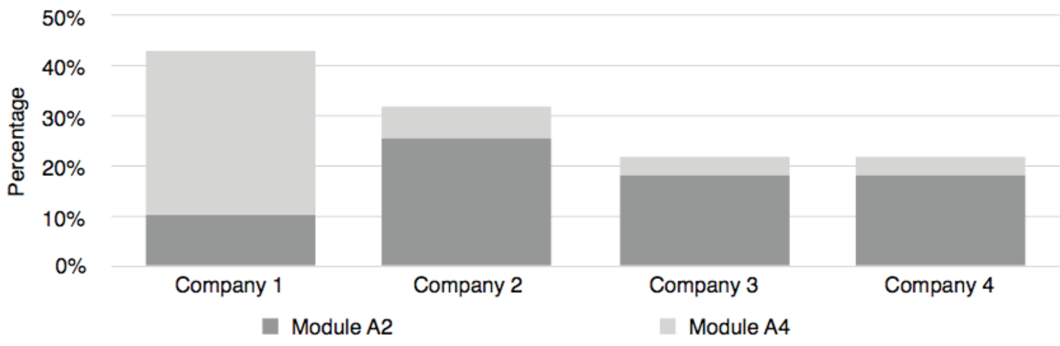


Figure 3.3.7. Freight costs of assessed transportation modules A2 and A4 by CLT supply company.

Road freight costs inside the Japanese archipelago also had a significant influence on the price of domestically supplied CLT cases. Company 2 aggregated freight costs were just slightly smaller than Company 1 (Figure 3.3.7), despite having the shortest transportation distances among all the 3 cases (Tables 3.3.2 and 3.3.3). Moreover, both transportation modules in Company 2 had a similar contribution in absolute terms (Figure 3.3.7). Nevertheless, looking at weighted freight costs (Figure 3.3.8), the results showed A2 Transport module in Company 2 is more than four times higher than A4 Transport module. The reason lies in the fact that transportation during module A2 falls onto less processed, cheaper materials such as sawlog or timber lamella and thus have a larger influence on the price of the material per unit volume. In particular, the transportation of timber lamella from the primary processing facility to the CLT manufacturing facility modelled in Company 2 (Table 3.3.2) was found to be the main contributor to the large weighted freight costs in module A2. In total, freight costs for Company 2 should add up more than 20% of the raw materials price.

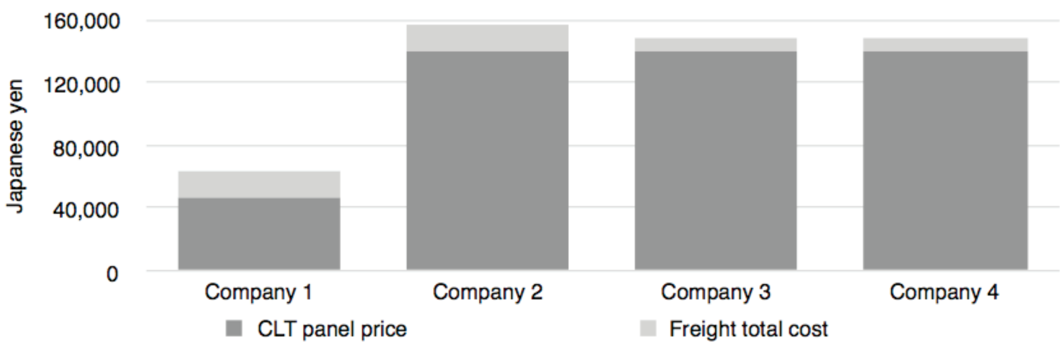
Figure 3.3.8. Weighted freight costs of assessed transportation modules A2 and A4 in the three modelled cases.



The large impact A2 Transport module has on freight costs taking into account the price of the transported material can also be observed in Company 3 and 4 (Figure 3.3.8). However, even though CLT from these Company 3 is transported over a longer distance than Company 2 (Tables 3.3.2 and 3.3.3), the former shows smaller aggregated freight costs than the latter. Lower freight cost in Company 3 is a direct result of the lack of the lamellae transportation phase in A2 Transport module (Table 3.3.2), in addition to the cheaper ocean freight costs from CLT manufacturing facilities to the construction site, in comparison to road freight costs (Table 3.3.3). In the other hand, the lower aggregated freight costs in Company 4 are the result of a more efficient inland transportation, due to the proximity to the final consumer centre

Finally, despite the larger aggregated freight costs, Company 1 presents the most competitive product after adding freight costs from the cradle to the construction site together with the panel price ($1m^3$). In fact, imported CLT will reach around 40% of the price of the other options (Figure 3.3.9), due to the much higher price of Japanese CLT. However, it is worth noting no additional fees such as importing taxes or duties were added to the freight costs of the imported CLT case (Company 1). Hence, a larger impact on the economical aspect of using European CLT in Japan can be expected, depending on the amount of these fees.

Figure 3.3.9. CLT panel cost and freight costs of assessed transportation modules A2 and A4 by CLT supply company.



Limitations of the study
At the time of this study, no specific date on Japanese building products was available on the utilised life cycle inventory. Hence, impacts on A1 and A3 for both domestic and imported CLT were modelled after the average European production. As much as both places may share a similar level of technology development and production steps, there might be different impacts associated with different forestry context and practices in each location which cannot be evaluated by this study. Therefore, the results presented shall be understood as an approximation to the real impacts. Also, it is worth note that no additional fees such as importing taxes or duties were added to the freight costs of the imported CLT. Hence, a larger impact on the economical aspect of using European CLT in Japan can be expected, depending on the extension of these fees.

3.3.1.4 DISCUSSION

From the environmental point of view, the study has found that GWP from transportation modules can easily outnumber the ones from raw material extraction and manufacturing activities (Company 1). Therefore, long distance transportation, even over intercontinental ocean routes, should be reduced as much as possible if one targets the use of low-environmental-impact CLT element. However, for shorter distances such as the range inside the Japanese archipelago, ocean freight transportation show slightly better results than road freight transportation (Company 3) unless inside about 300 km from the final consumer centre (Company 4). On the other hand, from the economic point of view, results showed ocean freight options are more affordable on a tonne.Km basis than road freight transportation. However, as much as it provides a cheaper option, if used for large intercontinental distances costs may add up to 30% of the material price (Company 1). Road transportation showed a negative influence when utilised, especially during the transport of less processed, cheaper materials (Company 2). Hence, the location of CLT manufacturing facilities as close as possible to the forest resources is an important strategic decision for the implantation of new plants inside the Japanese archipelago. Therefore, from both points of view, this study found that a local approach for the supply of CLT in Japan shall be preferred. Especially, in a context where economic impacts may still be more important than environmental ones, decisions which can benefit both parameters may encounter better chances for development. Among the three modelled cases, Company 3 and 4 were the options exhibiting the most efficient multimodal transport combinations from both GWP and freight costs points of view.

Based on the results and aiming to establish a local approach that can be beneficial for both environment and economic, the recommendations from the previous topic (3.2.1) were verified, and improvements can be made in 1) policy making, 2) product manufacturing and 3) marketing strategies. 1) Official policies using evaluation systems based on net carbon emissions to assign financial benefits or penalties on building materials such as CLT, would undoubtedly favour domestic CLT industry and increase the market competitiveness and acceptance of CLT inside Japanese territory. 2) Besides locating new manufacturing facilities as close as possible to forest resources, domestic CLT manufacturers shall also focus on expanding the demand for the product to increase economy of scale of their production lines, thus reducing CLT price per unit volume. 3) Marketing strategies emphasising the greater environmental benefits of locally produced timber products such as CLT as well as its positive effects on the local economy could be utilised to increase domestic CLT diffusion over imported products. Nevertheless, this strategy has to developed concurrently with education initiatives aiming to enhance the awareness of the general public in Japan on the importance of environmental issues.

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3.3.2 Building execution view: cradle to grave study

3.3.2.1 GOAL

The objective of this topic is to evaluate the effect different CLT building elements and combination possibilities for the construction of mid-storey multi-family housing have on the Global Warming Potential (GWP) and material costs from the cradle to the grave.

3.3.2.2 METHOD

Scope and system boundary

This topic presents a multidimensional study, focusing on the economic and environmental impacts of CLT building elements and their combination possibilities in comparison with other timber building systems. Total material cost and Global warming potential (GWP) for the assessed building elements are investigated from the cradle to a hypothetical construction site in Tokyo, Meguro-ward, Naka-Meguro district. Then, considering the end of the service time of the building impacts from the site to the recycling facilities (energy recovery of timber products) or the final disposal locations (other materials) were also included. A functional unit of 1 m^2 of built floor area is used to assess and compare the impacts of modules A1 to A4, C2, C4 and D (Table 3.3.1) for the supply of timber products in two different situations: domestic supplied and imported. Hence, this study is defined as "cradle to gate with options" (Technical Committee CEN/TC 350 2012). Additionally, other indicators such as thermal and fire resistance for wall elements, as well as airborne sound resistance and maximum slab deflection for slab elements were evaluated and evened as much as possible to build comparable models from the technical and functional points of view.

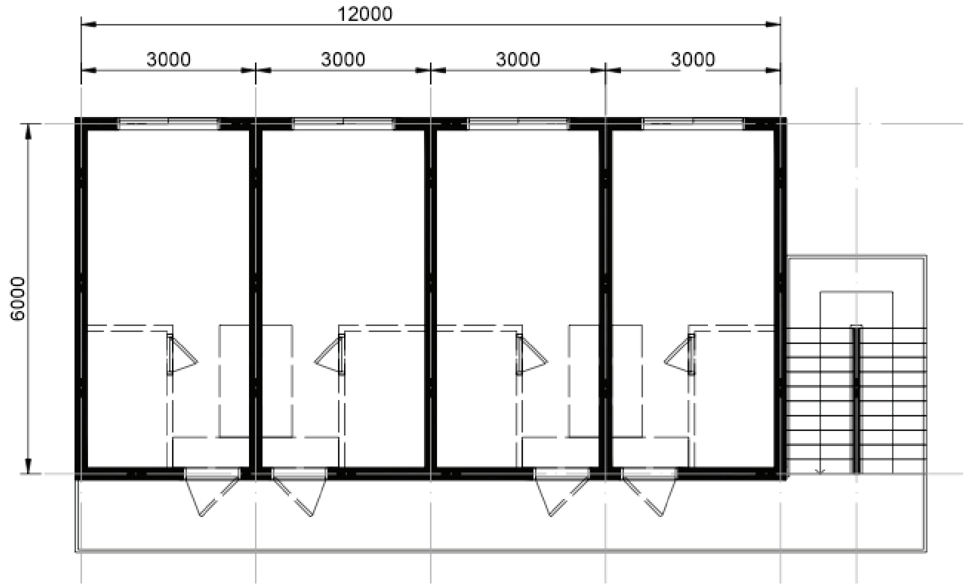
It is worth noting that this work has shown (topic 2.1.2) timber building systems are predominant in Japan inside the range up to three storeys. For this reason, mineral-based building systems were not included in the study. Additionally, the comparison between timber and mineral-based building system was extensively discussed inside LCA field for almost two decades. To name a few, in one of the first published papers on the subject, Cole (Cole 1998) found significant differences regarding primary energy and GHG emissions associated with concrete, steel and wood constructions, with the first one showing larger quantities than the latter two options. Petersen (Petersen and Solberg 2005), found substitution effect regarding GHG emissions between wood and steel is

36–530 kg in the range of CO2-equivalents per m3, whereas between wood and concrete is around 93–1062 kg CO2-equivalents. Gustavson et al. (Gustavsson and Sathre 2006) found materials employed for a wood building shall bear less energy and CO2 balance than an equivalent reinforced concrete building, highlighting the role of energy recovery to achieve that situation. Sathre et al. (2009) found wood buildings are an alternative to climate change mitigation and that if climate change related costs are included, the economic standing of wood-based construction will improve in comparison to a reinforced concrete option. Dodoo et al. (2009) indicated the benefits of energy recovery and recycling of products from timber and steel buildings are superior to reinforced concrete option even taking into account different scenarios for the carbonation of concrete. Robertson et al. (2012) found that a mid-rise laminated timber building has a lower environmental impact in 10 out of 11 indicators than a reinforced concrete option, also highlighting larger feedstock energy contained in the timber alternative as a crucial feature. Nässsén et al. (2012) found the wood framed building has lower carbon emissions than an equivalent reinforced concrete options when wood products are recovered during the end-of-life stage. Nevertheless, the same author warns about the need to address the cost-effectiveness of wood construction options in further analyses. Takano et al. (2014) analysed the influence of material on environmental and economic indicators for a reference building and confirmed the lower impact of timber-based options. However, he also points out that mineral-based systems such as reinforced concrete block are more affordable, hence highlighting the need for a broader interpretation and market development.

Basic project

A hypothetical four-storeys residential building was drawn, based on the trend for multi-storey timber buildings in Japan during the previous decade (Shmuelly-kagami 2010). The project has a total built floor area around 300 m^2 and 16 studio type dwellings, each nearly 18 m^2. The basement floor is executed in reinforced concrete, whereas the remaining three storeys above employ a load-bearing timber structure. External steel staircase and raised passageways fulfil the roles of vertical and horizontal circulation respectively.

Next, wall and slab elements of the upper three storeys of the hypothetical building were drawn using different load-bearing timber systems, namely timber frame, panel and mass timber construction. Furthermore, different combinations of these elements were investigated, resulting in hybrid building elements and systems. On total, eight timber building elements and six different assemblies between wall and slab elements were



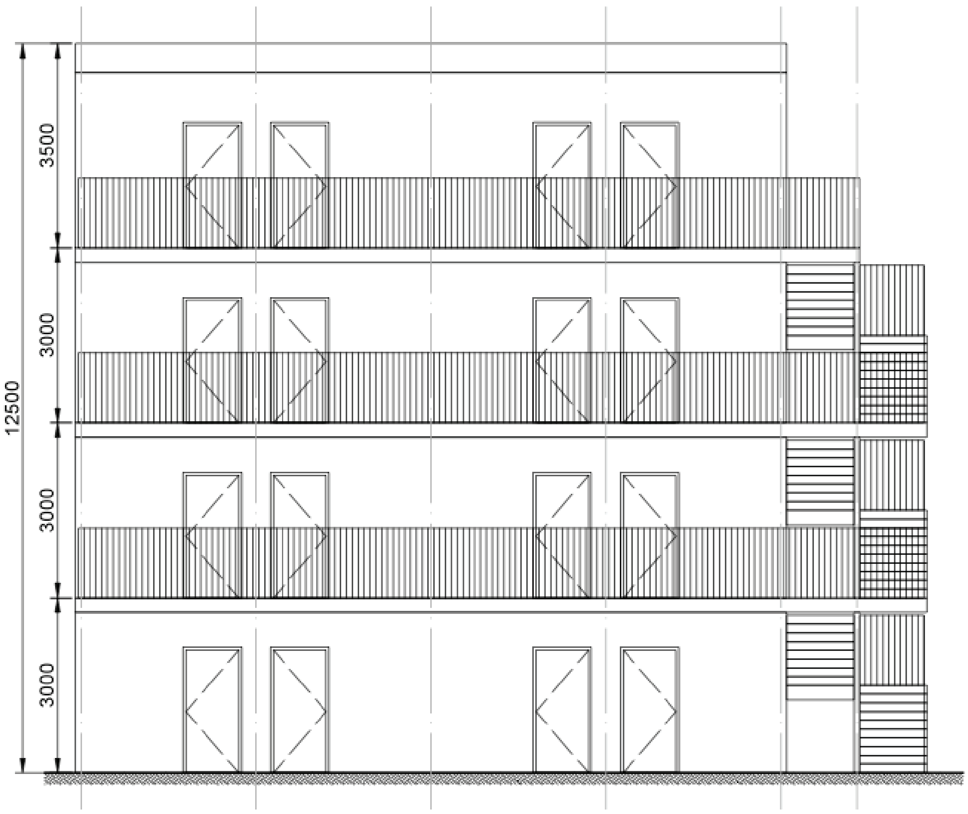


Figure 3.3.10. Assessed hypothetical residential building floor plan and front elevation.

Figure 3.3.11. The flow of different timber building elements and building systems combinations assessed during the study.

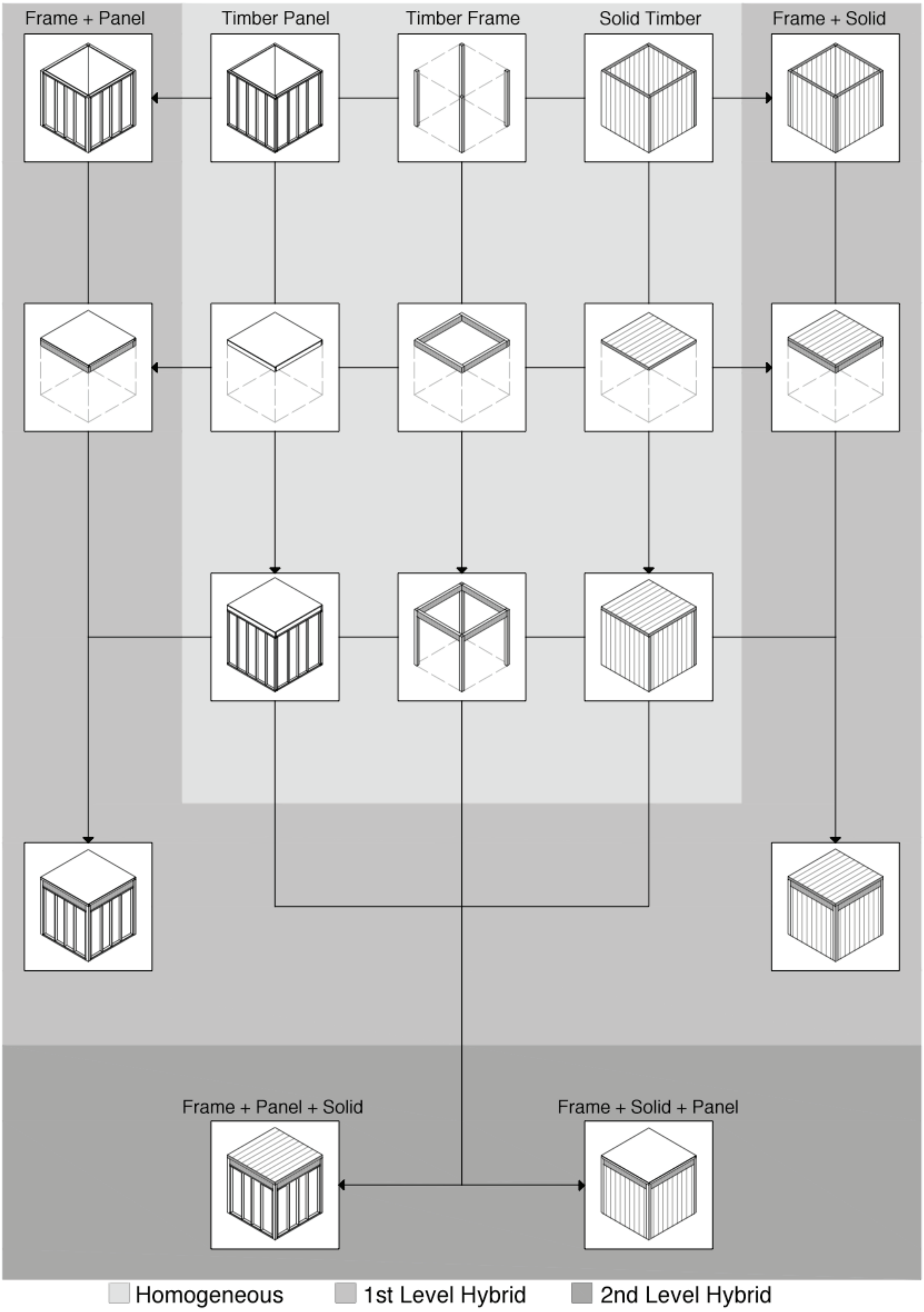


Figure 3.3.11

Assessment of data

Building elements were assessed from six different indicators, two of them for wall elements, namely thermal and fire resistance; two for slab elements, namely airborne sound resistance and slab deflection and the last two for all elements, namely total material cost and GWP. Building fixtures, the concrete basement floor, external steel staircase and raised passageways were assumed to be the same for all options and, therefore, were not assessed during this study. The assessment methods of each indicator are explained bellow.

Thermal resistance

Equivalent thermal resistance was assigned to wall elements. The U-value of solid wall and panel wall elements were calculated using equations 1 and 2, respectively. Components in each wall element were designed to achieve a U-value of 0.51 W/m²k.

$$\text{(Equation 1) U-value}= 1/ Rsi + Rse + \Sigma Rn$$

$$\text{(Equation 2) U-value}= 1/ (Ru+Rl)/2$$

Where $Rn = dn/\lambda n$, $Ru= 1/ \Sigma(F/R)$, $Rl = Rsi + Rse + Rn + 1/ \Sigma(F/Rn)$, $Rsi = 0.13$, $Rse = 0.04$, dn = material n thickness, λn = material n thermal Conductivity.

Thermal conductivity (λ) values for each assessed material are displayed in Table 3.3.4.

Fire resistance

Equivalent fire resistance was assigned to wall elements. One-hour fire resistance was attributed using the encapsulation method, meaning every assessed element was covered by two 12.5 mm thick layers of gypsum board on the inner side of the construction.

Airborne sound resistance

Equivalent airborne sound resistance was assigned to slab elements. Solid slab and panel slab elements in Japan delivering airborne sound resistance of 34 db were retrieved from the experimental results by Murakami et. al (2015) and Kasai et. al. (2015). European CLT airborne sound resistance was retrieved from the technical specification reports provided by one of the main European manufacturers (Stora Enso - Division Wood Products 2016). It is worth mentioning that even though the defined value is insufficient considering the performance standards, 34 db was determined due to the lack of experimental results or public information showing higher performance for Japanese CLT slab elements.

Slab deflection
The maximum deflection of slab elements was calculated for 3 meters span as a one-way girder, using equation 3.

$$\text{(Equation 3) } \delta = 5\alpha L^4 / 384EI$$

Where α= Dead load + live load (N/mm), Live-load= 120 kg/m², L= Span (3m), E= Young modulus (N/mm²), I= Moment of inertia (mm⁴).

Young modulus (E) and density values for each assessed material are displayed in Table 3.3.4.

CLT panels EI values were obtained using shear analogy method as described in the CLT Handbook (2011). Following, as much as possible, structural components in the slab elements were dimensioned to have an equivalent performance without affecting the assigned Airborne sound resistance while clearing the maximum allowed deflection limit of 10 mm (L/300).

Material price
Wholesale prices of most employed timber products were retrieved from the official statistics of the Ministry of Agriculture, Forestry and Fisheries (2016). Prices of CLT panels per unit volume were gathered during interviews with manufacturers. Retail prices for other assessed non-timber building products, namely, rock wool, glass wool and gypsum board were retrieved directly from retailers located inside Japan's main island.

Material prices per unit volume for each assessed material are displayed in Table 3.3.4.

Global warming potential
Based on the quantification of materials from the combination of the parameters mentioned above, Global warming potential (GWP) was calculated according to EN 15978 (Technical Committee CEN/TC 350 2012) for a functional unit of 1 m² of built floor area. GWP unit values for each material are defined as GHG emissions/kg and were retrieved from Ökobaudat's life cycle inventory (Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit 2016) .

Data on GWP during Extraction (A1), Manufacturing (A3), Waste Processing (C3) or Disposal (C4) and Benefits beyond system boundary (D) were assumed the same for each product, regardless of the origin of the building material, due to the lack of specific data about the Japanese products. Transportation modules A2, A4 and C2, were modelled according to the location of specific suppliers. Imported timber products such as sawn timber, glulam and CLT were modelled likewise Company 1 from the previous topic (3.3.1), considering a supplier in Austria (Styria region). Domestic CLT was modelled as if supplied by a hypothetical company located in Tōhōku region, hence modelled after Company 4 from the previous topic (3.3.1). The remaining timber and non-timber materials freight distances were modelled after the location of existent suppliers inside the main island in Japan. Following, transportation distances to waste management and disposal facilities were modelled after the information from Bureau of Environment (Bureau of Environment, Tokyo Metropolitan Government 2008).

Aggregated freight distances for each assessed material are displayed in Table 3.3.4

Table 3.3.4 Properties and characteristics of accessed building materials.

Material	Density (Kg/m3)	MOE // (N/mm2)	Conductivity (W/mk)	Av. price (yen/m3)	Road freight (Km)	Ocean freight (Km)
Jap. Cedar sawn-timber	400	5000	0.12	58,200	250.5	0
Spruce sawn-timber	450	11000	0.13	70,100	780.5	17500
Jap. Cedar Glulam	400	5000	0.12	68,000	250.5	0
Spruce Glulam	450	11000	0.13	78,800	780.5	17500
Jap. Cedar CLT	400	5000	0.12	140,000	300.5	0
Spruce CLT	500	11000	0.13	60,000	780.5	17500
Japanese Plywood	660	NA	0.16	61,000	450.5	0
Rock wool board	160	NA	0.043	85,000	270	0
Rock wool	30	NA	0.038	15,000	270	0
Glass wool	24	NA	0.038	21,500	270	0
Gypsum board	800	NA	0.22	46,150	120	0

Comparison

Besides the absolute values of the six indicators mentioned above, all the results were presented normalised to a scale from zero to one (Equation 4), to facilitate the comparison between different elements and systems.

(Equation 4) Normalised Indicator X = (Ix - Min Ix) / (Max Ix - Min Ix)

Where “Ix” = value of accessed indicator X.

Table 3.3.5. Absolute values of assessed indicators for wall elements, slab elements and wall + slab combinations.

	Building system	Origin	Timber use (m3/m2)	Price (yen/m2)	GWP (kg CO2 equiv.)	Thermal resistance (W/m^2k)	Fire resistance (min)
Wall elements	Panel	Domestic	0.067	9,018.84	6.60	0.50	60
	Panel	Imported	0.067	9,374.66	10.15	0.50	60
	Frame + Panel	Domestic	0.073	9,078.44	4.08	0.50	60
	Frame + Panel	Imported	0.075	9,780.00	9.07	0.50	60
	Mass Timber	Domestic	0.167	32,611.70	-1.33	0.51	60
	Mass Timber	Imported	0.176	19,788.13	22.46	0.51	60
	Frame + Mass	Domestic	0.148	29,288.14	-7.98	0.51	60
	Frame + Mass	Imported	0.162	19,483.20	12.84	0.51	60

	Building system	Origin	Timber use (m3/m2)	Price (yen/m2)	GWP (kg CO2 equiv.)	Airborne sound resistance (db)	Slab deflection (mm)
Slab elements	Panel	Domestic	0.058	4,868.05	-8.02	34	0.89
	Panel	Imported	0.046	4,516.10	-1.46	34	0.72
	Frame + Panel	Domestic	0.089	7,063.63	-12.63	34	0.62
	Frame + Panel	Imported	0.053	5,174.44	-1.54	34	0.77
	Mass Timber	Domestic	0.210	29,400.00	-48.52	34	0.75
	Mass Timber	Imported	0.100	6,000.00	-0.90	34	0.03
	Frame + Mass	Domestic	0.260	34,078.59	-39.65	34	0.61
	Frame + Mass	Imported	0.117	7,331.22	-1.83	34	0.53

	Building system	Origin	Timber use (m3/m2)	Price (yen/m2)	GWP (kg CO2 equiv.)
Wall + Slab assemblies	Panel	Domestic	0.125	13,886.89	-1.42
	Panel	Imported	0.113	13,890.76	8.69
	Frame + Panel	Domestic	0.162	16,142.07	-8.55
	Frame + Panel	Imported	0.129	14,954.43	7.54
	Mass Timber	Domestic	0.377	62,011.70	-49.85
	Mass Timber	Imported	0.276	25,788.13	21.56
	Frame + Mass	Domestic	0.408	63,366.73	-47.63
	Frame + Mass	Imported	0.279	26,814.42	11.01
	Frame + Panel + Mass	Domestic	0.299	40,959.86	-29.22
	Frame + Panel + Mass	Imported	0.188	16,783.37	7.53
	Frame + Mass + Panel	Domestic	0.237	36,351.77	-20.61
	Frame + Mass + Panel	Imported	0.215	24,657.64	11.30

Figure 3.3.12. Building elements and wall+slab combinations results normalised to a scaled from 0 to 1.

3.3.2.3 RESULTS

The results of the study are presented bellow divided into wall, slab and wall+slab combinations. The absolute results of each assessed indicator are displayed in Table 3.5 and the normalised values for comparison are shown in figure 3.3.12.

Wall elements
All assessed wall elements were equalised by thermal and fire resistance performance. From the total material cost point of view, wall elements employing panel system are more affordable than Mass timber wall systems, regardless of their origin. In contrast, domestic Mass timber wall element is over three times more costly than panel options, whereas imported Mass timber wall is two times more expensive. The 1st level hybrid combination of frame + mass system contributes to lower the cost difference to three times for domestically supplied materials but is not significant for the imported version. Additionally, the 1st level hybrid combination of frame + panel does not present any significant cost difference in comparison with the homogeneous panel element.

From the GWP point of view domestically supplied wall elements containing CLT panels are the only options presenting a negative GWP value, outnumbering all other assessed elements. Particularly, the 1st level hybrid combination of frame + mass shows the smallest GWP, over six times smaller than domestic homogeneous mass timber wall element on the second place. On the other hand, imported homogeneous mass timber wall element showed the largest GWP of all options. Overall, wall elements which have imported timber materials showed larger GWP than domestically supplied elements.

Slab elements
All assessed slab elements were equalised by airborne sound resistance and partially evened by maximum deflection, except by imported mass timber slab, which showed a much smaller deflection than the other elements. Nevertheless, from the total material cost point of view, slab elements employing panel systems are more affordable than slab systems containing domestically supplied CLT. In particular, domestic mass timber slab element is four to six times more expensive than options containing panel system. Moreover, the 1st level hybrid combination of frame + mass for domestically supplied timber products further increased the cost difference to nearly seven times. On the other hand, imported solid slab or 1st level hybrid frame + mass combination are only slightly more expensive than homogeneous panel system options.

From the GWP point of view domestically supplied mass timber slab elements containing CLT panels outnumber all other assessed elements. On the other hand, mass timber slab elements containing imported CLT panels showed the largest GWP of all options, despite having less than half of material volume compared to the domestic version. Overall, slab elements which have imported timber materials show larger GWP than domestically supplied elements.

Wall + slab combinations

By using the previously assessed homogeneous building elements and combinations, six different assemblies of wall and slab elements were modelled for domestic and imported timber products, resulting in two homogeneous and four hybrid options. From the total material cost point of view, homogeneous and 1st level hybrid combinations containing panel systems are the most affordable options, regardless of their origin. In contrast, domestic homogeneous mass timber wall + slab assembly is the most expensive option, over four times higher than homogeneous panel options, whereas imported homogenous mass timber wall + slab assembly is circa two times more expensive. The 1st level domestic or imported hybrid of frame + mass assembly does not show a significant cost difference in comparison with their respective homogeneous solid assembly. However, domestic 2nd level hybrid assemblies show 30% to 40% lower material costs than homogeneous domestic mass timber assembly

From the GWP point of view wall + slab assemblies with domestically supplied CLT panels outnumber all other assessed elements. In particular, domestic homogeneous mass timber or 1st level hybrid frame + mass assemblies showed over 30 times lesser GWP than assemblies containing panel system. Furthermore, 2nd level hybrid assemblies with domestically supplied CLT panels are situated in the medium range, showing slightly higher GWP than former assemblies but still lower values than all other assemblies. On the other hand, imported homogenous mass timber wall + slab, 1st level hybrid frame + mass timber and 2nd level hybrid assemblies show the largest GWP values. Overall, combinations with domestically supplied timber products showed negative GWP, whereas imported timber products assemblies presented larger positive GWP values.

3.3.2.4 DISCUSSION

The study demonstrated how a multi-dimensional analysis could be used to clarify value generation possibilities and limitations of CLT building system, thus signalising the choice of determined solutions based on the expected value outcome.

Considering the results of individual building elements from the material cost point of view, it could be noted that homogenous or 1st level hybrid combinations employing panel system, regardless of supply origin, are the most affordable options mainly as a result of their lower relative timber mass (0.05 ~ 0.08 timber m^3/ built m^2). After, homogeneous or 1st level hybrid combinations employing imported CLT panels present two times higher material costs in comparison to panel systems. Nevertheless, as the latter elements also show double timber utilisation rates (0.1 ~ 0.12 timber m^3/ built m^2) the cost increase can be understood as proportional to timber mass addition. However, homogenous or 1st level hybrid combination employing domestic CLT panels show a much larger material cost increase than timber volume addition (0.1 ~ 0.21 timber m^3/ built m^2). The disproportional cost increase strengthens previous findings (Topic 1.2.3), which revealed the overly high price of domestic CLT panels as the result of an idle production capacity. Moreover, based on the results, domestic manufacturers would need to cut CLT price by at least 1/4 of its current value, to be competitive with the panel and imported CLT option, which is highly unlikely to happen given the price of domestic sawn timber. Hence, the urge to develop and establish an initial demand, while forwarding new value concepts into the construction field, in order to create a qualified demand for CLT-based building systems, as described in the previous chapters (3.1 and 3.2).

As a matter of fact, an opposite trend was observed when evaluating individual building elements from the GWP point of view. Overall, building elements which employ imported timber materials show larger GWP than domestically supplied elements, owing to the additional greenhouse gas emissions during intercontinental transportation. In contrast, elements employing domestic CLT panel performed better than any other assessed elements, due to its large timber mass in addition to effective freight route, thus reducing the transportation-related emissions. On these grounds, using evaluation systems based on net carbon emissions or embodied energy to assign financial benefits or penalties to build materials or systems, would undoubtedly favour domestic CLT-based building systems. Accordingly, this could offer a different possibility to increase the market competitiveness and acceptance of CLT inside Japanese territory.

Finally, the assessment of wall and slab assembly options showed similar results to individual elements for homogeneous and 1st level hybrid options. However, domestic 2nd level hybrid assemblies provided intermediary choices from both material cost and

GWP points of view. Particularly, Frame + Mass (wall) + Panel (slab) presented lower total material cost, while Frame + Panel (wall) + Mass (slab) showed slightly better results for GWP indicator. The former could be employed for the retrofitting of existent buildings as reinforcement for conventional timber frame structures. The primary use as a structural material could help to associate Japanese CLT with "Direct" values and contribute to its diffusion in an initial stage of implementation. The second assembly could be an option to introduce CLT in the multi-family housing construction, taking advantage of the know-how and cost-effectiveness of timber frame and panel structures, nevertheless introducing "Indirect" value concepts by the use of a CLT slab element

Limitations of the study
At the time of this study, no specific date on Japanese building products was available on the utilised life cycle inventory. Hence, impacts on A1, A3, C3, C4 and D modules for both domestic and imported elements were modelled after the average European production. As much as both places may share a similar level of technology development and production steps, there might be different impacts associated with different forestry context and practices in each location for instance which cannot be evaluated by this study. Therefore, the results presented shall be understood as an approximation to the real impacts. Also, it is worth note that no additional fees such as importing taxes or duties were added to the freight costs of the imported CLT. Hence, a larger impact on the economical aspect of using European CLT in Japan can be expected, depending on the extension of these fees.

Also, the lack of experimental data about Japanese CLT performance indicators, particularly regarding sound insulation, limited the design of slab elements to one option. Hence, even when it was not necessary to use a seven-layered panel for structural purposes (1st level hybrid), the thickness was kept for the sake airborne sound resistance, thus hindering the real potential of domestic frame + mass elements. Therefore, execution laboratory tests followed by the development of basic performance catalogues by the manufacturers would not only enable more precise comparison between system but also offer practitioners crucial information to choose CLT over other materials and use it in more effective ways.

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3.4 Section 3 conclusions

The chapter pointed out that a pact between main groups involved in CLT implementation should be established, defining the main concepts for present and future CLT value generation concepts in construction, according to the Japanese context. Leading actors from each group shall work towards developing better conditions for the implementation and diffusion of CLT buildings in Japan in their respective field but towards the same goals. Arguably one of the crucial task in the long-range, concerning the continuation of Japanese CLT as an entirely domestic product, is to provide the conditions for a secure supply of enough quantity of quality timber for CLT manufacturing. In contrast, one of the major issues to be solved currently is to establish an effective knowledge transfer. It is crucial for the successful implementation of CLT in Japan that the main related actors can reach a consensus about present and future value generation concepts so that a collective effort can be made in the middle-to-long range, to increase of domestic CLT utilisation and create a qualified building demand for the product.

Also, the study demonstrated how a multi-dimensional analysis could be used to clarify value generation possibilities and limitations of CLT building system, signalising the choice of determined solutions, based on the expected value outcome. From the environmental point of view, Japanese CLT panels and building systems showed better results than any other of the assessed options, due to its large timber mass in addition to potentially effective freight route. Particularly, ocean freight transportation showed slightly better results for shorter intercontinental distances than road freight transportation. From the economic point of view, road transportation showed a negative influence when utilised, especially during the transport of less processed, cheaper materials. Therefore, the location of CLT manufacturing facilities as close as possible to the forest resources was confirmed as an important strategic decision for the implantation of new plants inside the Japanese archipelago. Furthermore, results showed homogenous or 1st level hybrid combinations employing panel system, regardless of supply origin, are the most affordable options, followed by homogeneous or 1st level hybrid combinations employing imported CLT panels. In contrast, homogeneous or 1st level hybrid combination employing domestic CLT panels show more costly options. Hence, the urge to develop and establish an initial demand, while forwarding new value concepts into the construction field, thus creating a qualified demand for CLT-based building systems.

Nevertheless, as a matter of fact, domestic 2nd level hybrid assemblies provided intermediary choices from both environmental and economic points of view. Frame + Mass (wall) + Panel (slab) presented lower total material cost, whilst Frame + Panel (wall) + Mass (slab) showed slightly better results for GWP indicator. The former could be employed for the refurbishment of existent buildings as reinforcement for conventional timber frame structures. This could help to associate Japanese CLT with “Direct value Concept” and contribute to its diffusion in an initial stage of implementation. The second assembly could be an option to introduce CLT in the multi-family housing construction, taking advantage of the know-how and cost-effectiveness of timber frame and panel structures, nevertheless introducing indirect value concepts by the use of a CLT slab element

4.0 Conclusions

Abstract: this section presents the original results of the thesis. The section is divided into three chapters. The first chapter synthesises and discusses the main findings obtained throughout the study. The second presents the future view for the utilisation of CLT mass timber system in Japan. Finally, the third one assigns topics for further research on the theme. The results showed that to forward the implementation process of domestic CLT in Japan and improve its value generation possibilities three tasks need to be accomplished. 1) To reach a consensus and communicate the value generation possibilities of domestic CLT through the chain of production. 2) To develop social awareness about environmental issues and forward the idea of environmental impact evaluation into the building industry. 3) To promote the forestry sector to guarantee an abundant supply of quality material in the long range and increase the technical performance of domestic CLT panels and assemblies. Ultimately, the idea of impermanence, usually associated with wood and wood-based products must evolve into an idea of permanence, particularly for mass timber elements. That means the understanding of timber products for mass timber construction such as CLT has to change from the idea of a "building material" to the idea of an "asset". This new approach would determine once a high-embodied energy CLT panel is produced, and its service time is extended as long as possible. Further studies include analysing the benefits of CLT construction for stakeholders, to develop comprehensive information about CLT panel and mass timber building systems functional performance and to develop studies evaluating the feasibility of the energy recovery of CLT elements after a building is dismantled as well as its environmental impacts.

4.1 Discussion

This thesis investigated what improvements are necessary to forward Japanese CLT implementation process from the manufacturing and utilisation points of view. The proposed measures aim to improve value generation possibilities of CLT-based building systems inside the local context by using a multidimensional approach. The approach includes the simultaneous assessment of dimensions from technical, function economic and environmental aspects of construction.

The research scope was defined including the main stages of CLT production chain from the forest resources to the finished buildings to investigate Japanese CLT implementation process. The reason for defining a comprehensive scope lies in the concept most of "mass timber", frequently associate with CLT building elements and construction. In fact, mass timber panels category, in which CLT is included, are the only wood-based engineered products that can simultaneously constitute structural and enclosure systems, without the addition of other products. Hence, mass timber systems are characterised by the intense use of timber per area unit of construction. Owing to the timber intensive characteristic of mass timber systems and therefore higher burden for the supply of raw timber material, it requires an in-depth examination of the forest situation. Furthermore, timber intensive characteristic acts as a multiplier of the employed mass timber panels main features, meaning both of its strengths and weaknesses are magnified when utilised. Therefore, it is crucial to evaluate how different options and rates in which CLT panels could be utilised in construction impacts final value generation possibilities and threats.

After the research scope was defined, two primary production activities contained in it were identified, and an analytical model for the thesis was proposed. The model allocated four main fields of study, and two production activities (from cradle to factory gate and from factory gate to construction). At the top general inputs for timber construction were set (timber resources and buildings demand) and at the bottom, specific outputs for CLT (CLT manufacturing and CLT building) were placed. The general fields were briefly analysed by statical data, while the specific fields were analysed in depth by related literature, case studies, questionnaires and interviews. Next, general recommendations and an action plan were proposed and detailed based on the analysis of the main fields of the research scope, targeting to improve value generation possibilities for CLT-based building systems inside the local context within a maximum time range of 50 years, accounting for the average rotation time of Japanese planted forests. Finally, a series of lifecycle assessments evaluated the impacts of CLT panels and CLT-based building systems from a multidimensional view, considering different possibilities for value generation.

The thesis aims to provide information to decision-makers, indicating primary issues to address through policies, product development, architectural design and education strategies. The results showed the leading valuation strategy for CLT panels and buildings is focused on stressing technical (statics) and environmental (climate change mitigation) subjects. That means CLT should provide optimal load bearing capacity, both in- and out-of-plane, combined with low environmental impact, thus being referred as a climate change mitigation option. To generate the technical value of CLT mentioned above it is crucial to have sufficient offer of quality timber supply. Furthermore, an abundant supply is required, due to timber intensive characteristics of CLT utilisation in mass timber systems. Likewise, the high timber mass of CLT-based building systems provides a high feedstock energy potential that if recovery at end-of-life stage will generate a net carbon surplus, thus attenuating the environmental impacts of the construction. However, at the time of this research, Japanese CLT is still not able to generate the same values. Firstly, the lower properties of the currently available Japanese Cedar supply limits the technical value of domestic CLT. To make matters worse, finite forest resources in Japan cannot guarantee the provision of quality material in the long range. Second, building industry regulations and general public awareness about environmental issues are still in an initial stage of development in the country. Therefore, Japanese CLT cannot generate value from the environmental point of view either. Under these circumstances, the study concluded that to forward the implementation process of domestic CLT in Japan and improve its value generation possibilities three tasks need to be accomplished. 1) To reach a consensus and communicate the value generation possibilities of domestic CLT through the chain of production. 2) To improve the social awareness about environmental issues and forward the idea of environmental impact evaluation into the building industry. 3) To promote the forestry sector to guarantee an abundant supply of quality material in the long range and increase the technical performance of domestic CLT panels and assemblies.

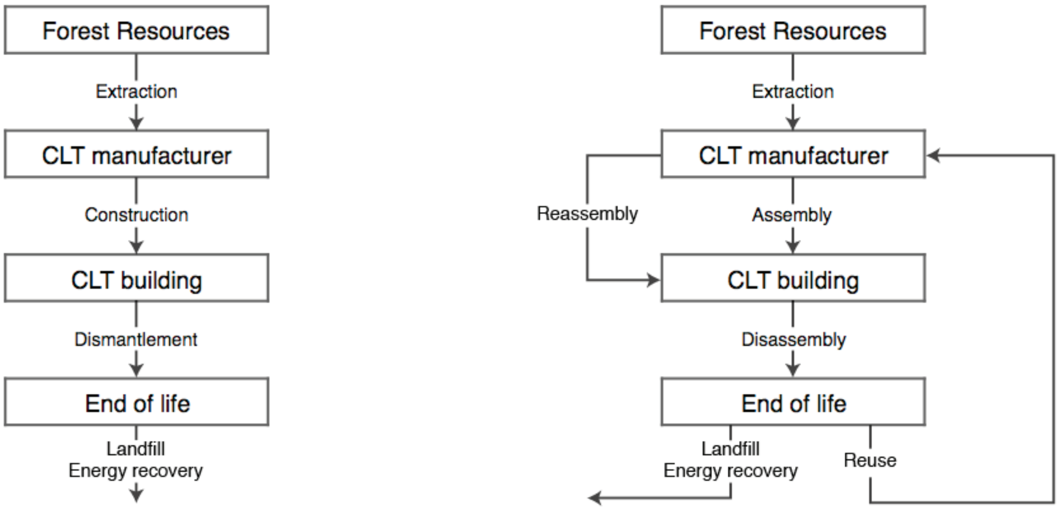
The study contributed to the field of CLT construction in three ways. 1) It proposed an original method to evaluate the chain of production of Japanese CLT from the forest to the finished building, based on the TFV theory of production. The proposed method could be used in Japan or different locations at any stage of CLT implementation, aiming to maximise its value generation possibilities. 2) It demonstrated the potential of combining various dimensions from different subjects to comprehend and facilitate the development of measures that can be beneficial considering the whole chain of production of CLT. Additionally, it also provided a way to increase the political relevance of lifecycle-based environmental impact studies. 3) It proposed and detailed an action plan that, if followed by the leading actors from CLT chain of production, would be able to revert the threats and weaknesses found throughout the research, within a time range of 50 years.

4.2 Future of CLT

By using an LCA methodology, the study confirmed the significance of the energy recovery strategy for CLT mass timber systems to achieve a positive environmental evaluation as pointed in other studies from the same subject (topic 3.3.2). Nevertheless, the assumption of energy recovery of CLT elements during the end-of-life stage of construction is still highly theoretical. Owing to the recent history of CLT, real case studies which can prove the feasibility of the energy recovery of panels and studies demonstrating the net negative carbon balance are missing. Additionally, environmental benefits of timber utilisation such as energy recovery and carbon fixation are assumed based on the conditions of a growing forest stock or equilibrium between timber resources consumption and regeneration. Therefore, based on the information analysed throughout this research, Japan presents an adverse context for the environmental performance of CLT, due to the short lifespan of constructions, smaller than the rotation time of Japanese forests, worsened by lack of a growing young forests stock. Hence the need for a broader multidimensional approach such as proposed in this study that can take into account the specificities of the local context.

Based on the findings of this study, the author believes that the understanding of timber products for mass timber construction such as CLT has to change from the idea of a "building material" to the idea of an "asset" for companies and society as a whole. In other words, the idea of impermanence, usually associated with wood could evolve into the idea of permanence, particularly for mass timber elements. This new approach determines that once a high-embodied energy CLT panel is produced, its service time is extended as long as possible. To accomplish that goal, optimised mass timber building systems, designed prioritising the reuse, recycling and finally recovery would allow to cascade CLT panels, while generations of forests are grown and used as necessary. Ultimately, the concept of CLT panels as an asset would lead to an improved lifecycle model and a new business opportunity. That is, in a scenario which emphasises the re-utilisation features and extended service time for mass timber building elements, CLT manufacturers could lease their products or solutions, instead of selling the product to the clients. Especially, the continuous reuse of the limited Japanese forest resources would be an efficient and sustainable method to allow for the revitalisation of domestic forestry and timber industry, assuming an increase in the demand in the next decades. Furthermore, customers would not need to worry about the construction and demolishing processes, as even considering the culture of a short average lifespan of residential constructions in Japan, buildings could be disassembled by the manufacturers and the elements reused for other buildings. Although it may sound extreme for the timber products industry, the concept is employed for steel frame disaster relieve constructions. A domestic developed building system application designed for reuse could even employ the stronger and more affordable imported raw-timber or CLT panel as its extended lifespan and cascading effect would be able to offset the initial emissions from transportation and manufacturing.

Figure 4.1.1. Present (left) and foreseen (right) lifecycle model for CLT buildings.



4.3 Topics for further research

First, to deepen the comprehension about the possibilities of CLT implementation in Japan would require a more detailed research on the inputs, i.e., forest resources and building demand. By analysing the potential benefits of CLT construction to stakeholders such as forest owners, designers, developers, builders and also end-users could contribute to developing a method to assess the merits CLT construction from a social point of view, subject not dealt throughout this thesis.

Second, to develop comprehensive information about CLT panel and mass timber building systems concerning acoustic performance, vibration, airtightness, moisture transfer, durability and so on. A compendium of the properties mentioned above would facilitate knowledge transfer across the chain of production, as well as enable an easier understanding of other value generation possibilities, associated with the functional performance of the construction.

Third, to develop studies evaluating the feasibility of the energy recovery of CLT elements after a building is dismantled. Furthermore, comparison of energy recovery options with cascading options for reuse and recycling of CLT could offer insight into the extent of the benefits the later ones could have from economic or environmental points of view. In this cases, it would be crucial to define different land use assumptions for the forest land use and include the assessment of different rotation time ranges.

Fourth, to develop an open national lifecycle inventory would allow for more precise assessment of the environmental impacts of CLT in Japan.