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# Cross Laminated Timber as Sustainable Construction Technology for the Future

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<p>The purpose of this final year project was to investigate and analyse the sustainability performances of cross laminated timber (CLT) construction technology. First the availability of the raw material (timber) was studied comparing the systems of Northern Italy and Finland. Second, the manufacturing process and application of CLT in construction was compared to other traditional construction systems. A central part of the study was the environmental impact of the adhesive used in the production, with a special focus on the emissions in the production, application and disposal phases. Further studies were conducted on how to treat CLT waste material and how to improve and optimize the manufacturing process to reach a complete sustainability of the product.</p> <p>For the Bachelor's thesis, the disposal of the timber and wood adhesive in CLT were studied. With the support of the collected data, it was possible to propose four technical solutions to the problem of the disposal of waste come from the CLT. It was concluded that CLT can be advertised as a completely sustainable material for construction.</p>	
Keywords	Cross Laminated Timber, sustainability, construction technology

## Contents

### Abstract

1	Introduction	1
2	Timber in constructions	1
2.1	Utilization of the forest in Northern Italy	2
2.2	Utilization of the forest in Finland	3
3	Cross Laminated Timber technology	4
3.1	Manufacturing CLT	4
3.2	Benefits of using CLT	6
3.3	Construction technology	7
3.4	CLT application in Italy	10
3.5	CLT application in Finland	12
4	CLT and traditional construction materials	15
4.1	Building technology	15
4.2	Construction times	17
4.3	Job site safety	17
4.4	Costs	18
4.5	Sustainability	19
5	Environmental impact study	20
5.1	Polyurethane adhesive glue	20
5.2	Emissions	22
5.3	Disposal and recycle of the material	23
6	Analysis and discussion of the results	26
6.1	CLT overall sustainability	27
6.2	Reuse and recycling of the wastes from CLT	28
6.3	Optimization of the production	31
7	Conclusions	34
	References – Bibliography	35

## 1 Introduction

In the beginning of the 20<sup>th</sup> century with the industrial revolution, all the construction focused on the development of reinforced concrete. Reinforced concrete was a stunning invention that has revolutionized the world of construction, due to its adaptability to every field of construction. [1.] Concrete enabled the construction of buildings with complex shapes and geometry that with the traditional materials and technologies, was not possible to achieve. Nowadays concrete is the most widely used construction material, but thanks to the recent concerns about the climate change, other sustainable materials are entering the market. [2;3.] One of these new technologies entering the global construction market is Cross Laminated Timber also known as CTL or Xlam. [4.]

This final year project is supported by the Italian company Xlam Dolomiti, leader in the CLT production for Italian and south European market. The study project aims to study and compare the efficiency and sustainability of concrete and Cross Laminated Timber in construction. A special focus is paid on the composition and recyclability of the polyurethane glue used in the production of the CLT panels, which the producer sees as a possibly critical aspect in ecological terms in the manufacturing process of Cross Laminated Timber.

## 2 Timber in constructions

The Alpine area and Finland, are both covered with a wide forests. So it seems reasonable to take advantage of such a great product, timber, to construct residential buildings thanks to the availability and sustainability of the raw material. However, in neither of the areas is timber a common building material. Even a simple few storeys high building is constructed with concrete. However, timber is one of the oldest construction materials and has incredible structural properties. The idea of an intense use of this resource and the danger of deforestation has limited its use and created a sort of dislike in the use. [1;5;6.]

As presented by Dr. Mahter from the Agricultural University of Norway [6], Europe has actually experienced a reforestation phase. This means that there are more forests growing than were cut. [6.] This phenomenon is well supported by the Forest Certification eco-labelling PEFC, it ensures a sustainable management of forests by controlling that new trees are planted whenever others are cut. In the Italian Alps (Trentino Alto-Adige) and Finland, this forest governance covers the majority of woods and related management activities. [7.]

## 2.1 Utilization of the forest in Northern Italy

Trentino Alto-Adige is the Italian site where Xlam Dolomiti head quarter and production facility is located and mainly operates. [8.] Since there are similarities in the wood commerce and governance with Finland, it was a natural choice as a comparison in this thesis. [7.]

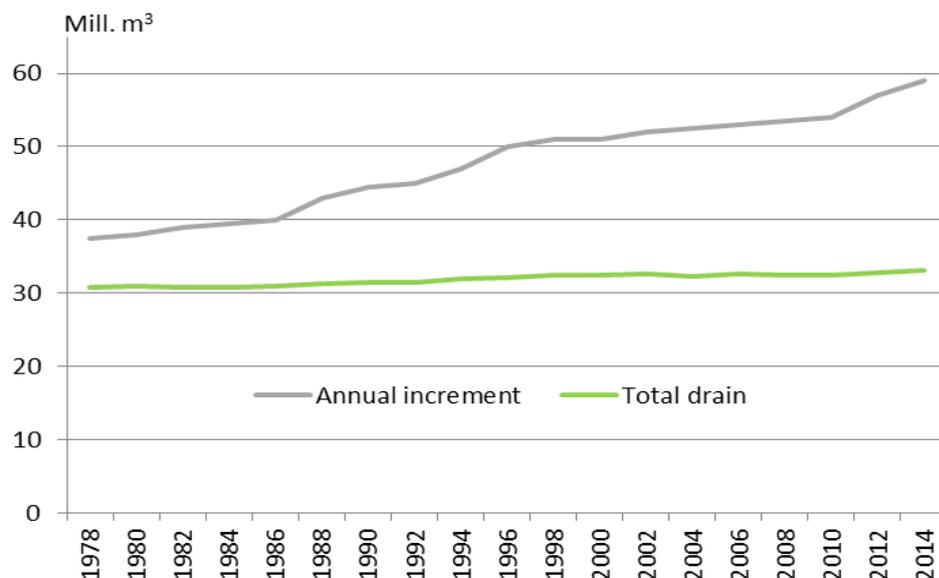


Figure1. The growth of Trentino Alto-Adige's forests per year [9.]

The latest available report on the conditions of the woods in Trentino shows that the amount of forest cut per year is lower than the growing one. In figure 1, the trend is clearly shown. Thanks to the management and control by the wood institute, the available raw material for timber is growing constantly. During the recent years, the rate has been about two trees planted for each one cut. [8;9.]

## 2.2 Utilization of the forest in Finland

Comparing Finland with Trentino Alto-Adige seems inappropriate because of the difference in size and location. However, as reported in figure 2 below, it is possible to find many similarities in the territorial management. The graph shows the trend of annually grown and cut forest. As it was in the Trentino area, as discussed in chapter 2.1, the trend is on favour to the growing of new forests. In Finland the rate of growing is slightly lower than in Trentino but approaching the rate two new trees for one cut.

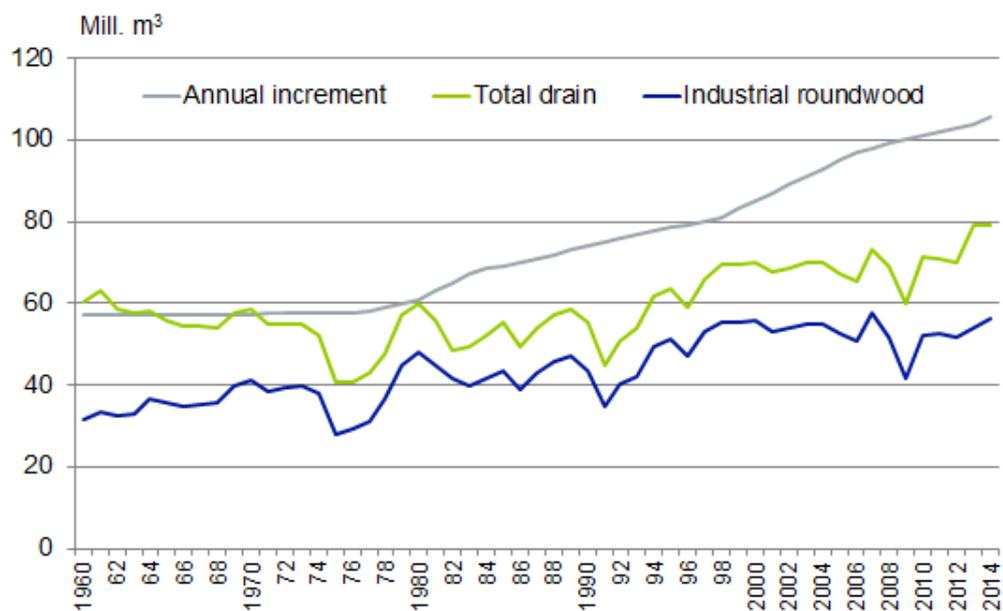


Figure 2. The growth of Finnish forests per year [10.]

In both cases, the raw material seems not to be an issue. The data in both figure 1 and 2 about forest management shows that both areas are directed to a policy of reforestation. [6;9;10.]

### 3 Cross Laminated Timber technology

In the beginning of the '90s, what is now known as Cross Laminated Timber was developed by a timber manufacturing company in Austria. However, it took several years for the product to enter the construction market, mainly due to the lack of technical knowledge in the field. It was still unknown how exactly to apply Cross Laminated Timber also known as CLT to the residential constructions and the standard structural resistance still had to be studied in detail. After intensive studies on the performance of CLT and a new focus on the sustainability of buildings, CLT gained popularity in Europe. [4.] The intense use of this construction technology began around the year 2000 and is growing exponentially due to it being easy to handle and prefabricate. [11.]

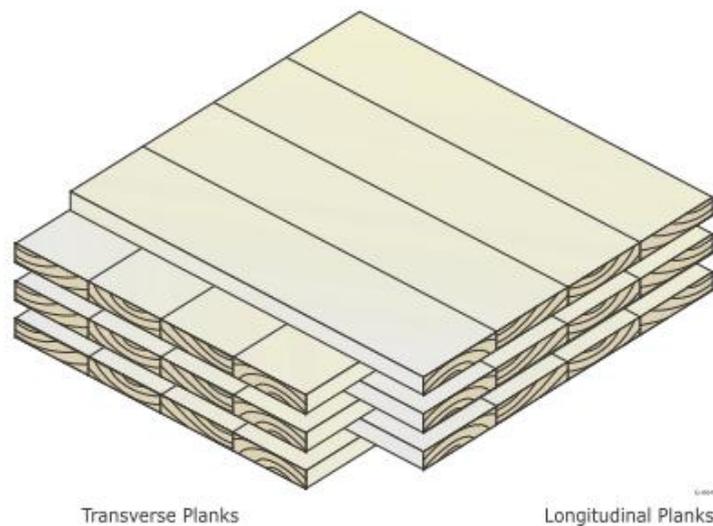


Figure 3. Cross Laminated Timber configuration [11.]

Cross Laminated Timber panels consist of several layers of timber boards with different orientation, some of them longitudinally and others transversally as shown in figure 3. The basic CLT element is made up of at least three layers glued together in order to provide a substantial structural response to the structural stresses. [11.]

#### 3.1 Manufacturing CLT

Cross Laminated Timber can be said to be a simple product. It is obtained simply by assembling two basic raw materials: lumber and adhesive glue. What makes the product efficient is not only the quality of the raw materials, but also the design and manufacturing process itself. [11.] The type of timber boards used in the production of Cross

Laminated Timber modules depends essentially on the manufacturing company. A key factor in the raw material choice, in the case of Xlam Dolomiti, is the importance of a product coming from an eco-labelled, certified forest PEFC (Programme for the Endorsement of Forest Certification) as shown in figure 4. In many cases, this assures the quality of a controlled purchased raw material. A PEFC label assures that the timber is cut from a forest that follows the reforestation standards and respects the environment by planting new trees whenever others are cut. [12.]



Figure 4. Timber boards' delivery from PEFC certified forests [13.]

Once the timber boards arrive at the production site, they are quality controlled before being transported into the manufacturing area. In Xlam Dolomiti production, each piece of lumber arrives already cut into a shape; 200mm wide, 22mm thick and 5000mm long. [13.]

The initial phase of the manufacturing consists of the planing of the board surface to remove possible impurities, to refresh the wood to reduce oxidation, and to improve the gluing efficiency. [11;13.] A standard CLT panel has a size of 13.5x3.5m, i.e. after the planing, each 5m long longitudinal board needs to be extended to cover the full length of a panel. Every longitudinal board is loaded on an automated milling machine that creates finger joint connections and glues two boards together. The final product is a solid one piece lumber with a length of 15m composed of three boards. The second

manufacturing phase is the adhesive application: first the boards with the same length must be grouped side by side to form a layer with an even surface. A moving arm runs over the so formed timber board surface and applies an even layer of adhesive glue over the top face of the boards. The process continues by adding several layers of timber boards stacked crosswise. A cross-section of a CLT element has at least three glued layers of boards placed in orthogonally alternating orientation to the neighbouring layers as shown in figure 3. [11-13.]

There are three main wood adhesives used for Cross Laminated Timber production: PRF (phenol-resorcinol-formaldehyde), EPI (emulsion polymer isocyanate) and PUR (one-component polyurethane). [11.] Xlam Dolomiti uses PUR, produced by the Swiss company Purbond. [12;14.] The product had been chosen due to its gluing strength properties and the absence of formaldehyde. The formaldehyde-free composition makes PUR a safe product to handle and use. [12;15.]

Once the wood adhesive is applied and the desired number of layers are laid in place, the entire module is sent into a wood hydraulic press. The Cross Laminated Timber panel is left into the press for about 10 minutes, extracted and laid to rest horizontally for another 10 minutes in order to let the PUR adhesive dry. [11;12;14.] After a quality check, to make sure that the manufacturing process has been successful and that the adhesive is dry, the module is loaded on the last automatic machine in the production chain. This phase is also known as the bottle neck of the production because of it is slow. The panel is conveyed to a multi-axial numerically-controlled machine that cuts out the openings for windows and doors and other required parts in the panel according to the architectural design. [11;13.] The production is finalized by marking, packing and loading the CLT modules. They are ready for direct installation on site or for assembly in a prefabrication factory. [11;12.]

### 3.2 Benefits of using CLT

Constructing a building with solid timber can have several advantages. Solid timber has a great comfort impact, it is a sustainable material and it has very good structural properties. However, building with Cross Laminated Timber seems to have an even higher potential. It has better structural, energy saving and insulation properties, fire resistance, as well as fast and easy prefabrication. [4;5;11.] Without a doubt, it can be said that wood is one of the best construction materials in terms of carbon footprint and

sustainability, basically because it is possible to recreate it by planting new trees. The LCA study by L. Mahelle, et al, showed that Cross Laminated Timber has a total negative GWP (global warming potential). This means that it not only compensates its emissions, but it actually fights the global pollution. [11.] However, a certain level of uncertainty is attached to the adhesive glue used in the production and its effect on the environment. [12.] This topic is analysed in more detail in chapter 5 about the glue's behaviour when used and disposed, of together with the possibilities to recycle the product.

Another important aspect mentioned previously is the possibility of assembling panels in the factory, creating real prefabricated house boxes ready to be installed on the jobsite. This not only reduces constructing times but also the risk of accidents on the job site area due to small numbers of on-site workers and the simple equipment needed for the installation. [16;17.] The single CLT module can be applied for many uses and many different types of building structures. Customizing panels according to the designer's requests is a surplus, nowadays there are no limitations on the use of CLT except for the height of the unit we want to construct. [11;12;16.] A final aspect that might not be essential for Finland, but that is instead one of the main concerns in the rest of the world is the seismic resistance of a building. After a direct test performed at FPInnovation's laboratory in Vancouver, it was possible to conclude that Cross Laminated Timber has an excellent behaviours and resistance to earthquakes. What differs from the traditional concrete or brick buildings it is the elasticity of the raw material, timber in fact prevents the structure to collapse in case of seismic actions. The only consequence registered was localized at the connections of the panels where screws and nails were untighten but had still the ability to keep the structure together. [11.]

### 3.3 Construction technology

The final manufacturing product of the Cross Laminated Timber is a plane 2D panel that is the basic starting point for many CLT construction systems. Being so simple has the advantage of a lower price that incentives a customer to use it in the construction of a CLT building. [12;16.] Constructing a building with 2D panels is very simple, once the truck arrives to the site, panels are simply lifted as shown in figure 5. The connectors installed on each panel allow to lay them in place, and then tight them together with wood screws or nails.



Figure 5. Cross Laminated Timber roof installation [18.]

The 2D panel construction method allows having 20% shorter building times compared with the traditional concrete constructing technique. To prevent damages, connections between panels are usually sealed to be waterproof to reduce the acoustic transmission. A simple 2D module system forms just the building shell and it requires some further external and internal works. For outdoor areas it is necessary to install the insulation, vapour and moisture barriers, together with the external cladding, windows and doors. The internal spaces are finalized with electrical, heating and plumbing system, and walls, floors and ceilings levelling and painting. [8;16.]

A second possibility is to take the 2D element a step further creating a 2D equipped module. It is a basic CLT panel but with already some features built-in to reduce the amount of work to perform at the job site. Instead of taking the panel straight to the construction area, it is transferred to a prefabrication factory unit where some qualified workers install windows and doors, insulation, moisture barriers and the final cladding on the CLT panel. Basically the set of works that are traditionally performed on the site, are instead done in a more safe, controlled and protect manufacturing area with increased productivity thanks to an assembly line. [16;17.]



Figure 6. Cross Laminated Timber 2D equipped module installation [17.]

The 2D equipped module is then delivered to the job site, lifted as illustrated in figure 6 and installed in the same way as the 2D simple element. What remains to do is to finalize the interior works. The 2D equipped module constructing times are about 30% shorter than with more common concrete building systems. [16.]

The most recent construction technology using CLT available on the market it is a 3D or box module. The prefabrication phase in this case is used to create a functional living block already in the factory to be then transported on site. The manufacturing field now takes care of not only of the installation of external features like insulation, windows and cladding, but also creating a 3D module. This module is equipped with all the systems already built-in, internal walls, floors and ceiling completely finalized, the 3D module can be realized in such detail that it is complete for about 90% and needs only to be taken to the site. [16;17.]



Figure 7. Cross Laminated Timber 3D modular construction [17.]

An ordinary apartment building is composed by two of the 3D modules lifted and assembled together as shown in figure 7. [17.] The ready-made structure produced in a factory allows having a high quality check on the construction method, higher work safety compared to a normal job site and short manufacturing times. In terms of construction times, the 3D module technology ensures a 50 to 70% saving on construction times if compared to what it takes to build the same structure with for example concrete. It is clear that a more sophisticated technology requires a higher initial investment, but in most of the cases this cost is compensated with a higher quality of the product and a benefit in time saving. [16.]

#### 3.4 CLT application in Italy

With the European Union pushing the construction market in a more ecological direction, with the target of a 20% energy reduction by the year 2020, many designers and constructors are getting interested in new sustainable technologies. [3.] Digging into the Italian market, a suggestion comes from the Italian engineer Albino Angeli, general manager at Xlam Dolomiti, who states that the motivation of their Italian customers to use Cross Laminated Timber is because of a marketing trend, the efficient construction times, energy saving and the convenient payback time. These are the causes that drive customers to choose Cross Laminated Timber and especially Xlam Dolomiti. In Italy, the construction of modular wood houses was imported from Austria thanks to the company Rasom in the year 2005. [12;19.] Later also the big international company Rohto Blaas started to focus on CLT making it become one of their specialties and

strength. [20.] These two companies invested a consistent amount of effort and resources to advertise the CLT construction technology, making it trendy and also important for sustainability. [12.]

Time saving is generally taken into consideration by those customers that want to construct, renovate or expand their buildings in a relatively short timeframe. This category is primarily represented by the hoteliers who have just a limited time to expand or renovate a part of their hotel and for this reason they need a time-efficient construction method and therefore, they use CLT. A construction field where Cross Laminated Timber is most commonly used and that is growing quickly is the renovation of residential buildings. It consists of recovery and converts old spaces, usually located in the historical centre, into new residential units. [12;18.]



Figure 8. Renovation of a residential building with Cross Laminated Timber in Bologna [18.]

In the case showed on figure 8, the structure is located in the centre of Bologna (Italy) and a key necessity there was to have the shortest construction time possible in order to dismiss the job site as soon as possible to limit the problems that a job site in a city centre can cause. This saving in time for the construction balanced the initial higher investment for a CLT solution. The gains, compared to a traditional construction style,

are from a shorter renting period of vehicles, lifting equipment, and scaffoldings, lower number of workers and lower municipality fees. [12;16;18.] With building expansion and renovation increasing in popularity, the necessity to reduce the greenhouse gases and the 20% energy saving European margin standard, it is now possible to see more and more CLT constructions around Italy. [3;21.]

### 3.5 CLT application in Finland

Finland is well known internationally for its huge amount of forests. [10.] Despite its availability, timber is not the favourite material in the construction in urban areas. It is used in single family houses where almost 80% of the new units are built with timber structure, but in the construction of blocks of flats or row houses the percentage is very low. At the moment, no more than 5% of the multi-residential units are built with CLT in Finland. The major reason why it is not so well integrated in the market can be the shortage of CLT producers and specialists. [16.] It is just a little bit over one year ago that CrossLam (the first Finnish “real” producer of CLT panels) was established in Kuhmo. [22.] Previously the Cross Laminated Timber was managed by the pulp and paper manufacturer Stora Enso. [17.] Matti Mikkola from Puutuoteteollisuus Oy suggests that although getting no financial support from the European Community, the Finnish construction market is rapidly going to focus on new and more sustainable building solutions that achieve the EU 2020 target. He continues underlining the big potential that such construction technology has in the terms of ready-made prefabrication, which is not reachable by any other building system. [16.] The reasons why CLT is used in Finland are very much similar to the Italian ones. Constructing with CLT panels is in fact very fast, sustainable, safer and virtually mistake less. [4;16.]

One problematic aspect in the Finnish construction system is connected to the adverse weather conditions during the year. Even if each construction company has a certain experience and system to protect the construction site from the bad weather, it is difficult to perform a mistakes-free on site structure. It was studied that even in best cases, there are always some building infiltrations or small faults in the application of the insulation membranes on site. [23.] From this perspective, the possibility of prefabrication in the factory that Cross Laminated Timber offers of not only a 2D module (produced also for concrete) but the unique opportunity of a 3D module is a great innovation. Production in a prefabrication facility means basically working in a protect and safe environment that allows for an increase in the production rate, the safety of the staff and mini-

mize the probability of construction mistakes, due to a constant checking process. [16;17.]



Figure 9. Manufacturing of a 3D module in the production plant [25.]

Figure 9 shows an intermediate stage of the production of a 3D module for the first building ever built with such a system in Helsinki area. The building located in Pukimäki, was produced by Stora Enso's 3D box module and built by SRV Oy. [24;25.] When the 3D Cross Laminated Timber modules left the production facility, they were already equipped with all the necessary systems, even part of the furniture. The 90% ready structure was then delivered to the job site where just six on-site workers lifted it and finalized the construction as shown on figure 10. [25.]



Figure 10. Lifting and installation of a ready-made 3D module [25.]

The total construction was 30% faster than building the same structure with concrete. [25.] With shorter construction times and fewer workers on site, the safety level at the job site is improved significantly. [4;16.]

According to the timber expert Matti Mikkola from Puutuoteollisuus Oy, the knowledge of the designers and the workers in Cross Laminated Timber technology is very low at the moment, but the general trend and interest is growing fast and the technology as well. CLT is a resource that has a huge margin of improvement and in the near future it is going to be used more and more often. [16.]

## 4 CLT and traditional construction materials

Concrete is the single most widely used construction material in the world. In the last decades it was used in almost in all buildings with complex structure. Its mixture is easy to prepare with Portland cement, water and aggregate, the rest is done by a chemical reaction in the mixture. The problem is that the world produces and uses so much concrete that it is responsible for 5% of the annual global CO<sub>2</sub> emissions.

For this reason the construction market is investing and searching for other solutions. This concern forced the major concrete producers in the world to agree in the investment in further research on concrete. [2.] For the first time since the massive production of concrete in the 20<sup>th</sup> century, this material seems obsolete for certain type of constructions. Thanks to massive advertisement and a lot of studies on its benefits, timber seems the solution. Many experts agree that timber will probably never become more common than concrete, but it has the potential to steal a good part of the residential building market. [4;16;18.]

To understand and evaluate the advantages and disadvantages of constructing with concrete or timber, especially CLT, better it is possible to use a break-down structure. The break-down means that similar residential constructions are analysed with respect to five major fields, building technology, construction times, job site safety, costs and sustainability. The aim is to compare the technologies to understand which aspects one technology excels over the other.

### 4.1 Building technology

A basic residential building can be realized in concrete with cast in-situ or precast system. [1.] Cast in-situ or in-place means that the whole structure is built directly on site. It usually requires labour intensive work to prepare the formworks, place the reinforcements and then pouring the concrete. After 28 days it is possible to remove the formworks and the structure is solid. Cast in-situ is the best known and most used construction technology nowadays. Precast concrete usually involves the prefabrication of a part of the wall (2D structure) in a factory. This reduces the work load on site, but due to the weight of the concrete it is not possible to prefabricate big elements. Usually prefabrication involves just the structure and the insulation. [26;27.]

In chapter 3.3, while talking about the Cross Laminated Timber technologies, it was possible to find three construction systems, 2D module, 2D equipped element, and 3D or box module. A 2D module is the simplest possible element. It can be made on a production line. It is then transported to the site, installed and later all the finishes are applied. [4;8;11] Despite the basic process needed, not many companies on the market are trained in, or have a know-how about this system. [12;16.]

The 2D equipped element is manufactured a little bit further, adding some features to the single panel. This process is performed in a specific factory where, the external insulation, the moisture barrier, the cladding and the windows or doors are already mounted on the panel. As for the 2D module technology, the 2D equipped element is delivered to the site, lifted and installed. In this case the lack of know-how in the installation is summed to the small number of CLT prefabrication facilities. [4;16-18.]

A more innovative CLT construction solution is the 3D module. It consists, as the name suggests of a real prefabricated box with walls, floor and ceiling completed and ready for the users. The basic residential unit is composed of two 3D modules (living room, kitchen and bedrooms) lifted as an entire block due to the light weight of the structure and assembled together. The majority of the work is done at the prefabrication factory and what is left for the job site workers is the installation of the modules and their connection. [17;25.] The technical challenges for this system are found at the prefabrication plant because only few CLT companies are able to perform a 3D box module solution at the moment. [16;17.]

Looking into the construction technology field, it is possible to notice that CLT has an advantage on the prefabrication side, because it can offer a ready-made system to the customers. On the other hand, concrete is a material that has now been used for more than a century and can be handled by most of the companies. The same is true for designers and structural engineers. The group of specialists in the Cross Laminated Timber is very restricted at the moment but it is expanding due to the interest in the technology. [12;18.]

## 4.2 Construction times

The curing process for concrete takes approximately 28 days during which the structure needs to be continuously supported with frame works. Only after this longer time the concrete element is ready to serve its purpose. The same curing time is also required for a precast element in a factory because the type of concrete and the technology used are the same. When building with modules they can be cast during the preliminary phases of construction and transported to the job site once they are needed. [26.]

The production of a CLT 2D panel in a normal production facility takes about one day, and the panel is ready to be used already the following day. When construction with CLT 2D modules is compared with concrete construction, the CLT saves about 20% in construction time. [16;18.] For a 2D equipped CLT element, the time spent in the factory is longer, because of the additional features installed, but the time is well balanced with the time saved in the on-site working activities. Similarity to the precast concrete element, it is possible to manufacture the 2D equipped module in advance. Compared with the concrete building technology, the time saved in this case is about 30%, thanks to the possibility to install not only the insulation on the panel but also the windows, doors and cladding on the single module. The most sophisticated Cross Laminated Timber system, the 3D box module, requires a longer production time in the factory in order to reach a 90% level of prefabrication. However, the longer time is well balanced with the construction time savings between from 50 to 70% compared to the more commonly used cast in-situ technology. [16;17.]

## 4.3 Job site safety

Construction prefabrication is a concept introduced during the second industrial revolution in the beginning of 1900. It was considered a stunning innovation because it reduces the construction times and man-power on the job site, encouraging the more efficient on-factory assembly line. [1.] Has been established that the number of workers operating on a job site is proportional to the risk of accidents that can occur. Increasing the number of onsite workers creates a higher hazard risk and vice versa, less people working and interacting means lower accident probability. Other aspects such as the equipment in use, the composition of the site, the organization and conditions are also

responsible for a lower or higher risk probability. However, studies show that accidents are very much dependent to the workers and their skills. [28.] In a prefabrication process, the majority of the work is done in a factory. The factory is considered a safer environment compared to a job site area. The factory is not affected by weather conditions, the indoor environment can be controlled in temperature, ventilation and air quality, the work is supported by machinery and checked constantly. The potential of a prefabrication assembly line is the remarkable know-how and skill of the single worker. This helps to prevent accidents and results in higher manufacturing efficiency. [29.]

The higher job site safety demonstrates how an innovative solution as the CLT 3D module which needs no more than 5 or 6 onsite workers, due the substantial prefabrication, reduces the hazard risk significantly. A well organized and managed residential building job site generally requires from 40 to 50 on site workers, this means that the risk of an accident is 10% higher than having 6 of them operating in the same area. [18;28.]

#### 4.4 Costs

Construction is a delicate business not just on the technical side but also on the economical one. In a tender procedure the winning bid is the most time/cost effective one. The easiest way to save economical resources during a construction is to use cheap construction solutions and materials, or to balance the higher investment with a shorted construction time. [30.] Comparing concrete with a CLT building solution, the latter is more expensive in terms of initial investment, but the savings in time makes it almost equal to the concrete one. [18.] The reason why an easy solution such as CLT, which involves some sets of timber boards glued together, results in a high initial cost was explained by Mr. Matti Mikkola from Puutuoteteollisuus Oy. He claims that all the costs are caused by poor knowledge of the technology in the construction in general. During his studies, he found out that there are three major factors influencing the expenses of the CLT, namely lack of design knowledge, cost of the fire protection, and extra water sprinklers installation. [16.]

These three factors influence the price of a CLT solution by an additional 300 €/m<sup>2</sup>. [16.] Clearly, with the future development of the Cross Laminated Technology and accurate research on the field, it will be possible to lower these costs or even adjust them to the same level with other building technologies.

## 4.5 Sustainability

Over the past years, ecological and sustainable ideas have entered the market and are getting general acceptance. It has been shown that the massive CO<sub>2</sub> emissions and greenhouse gases from the industry are destroying the planet. [3.] For example the massive worldwide production and use of concrete causes 5% of the annual carbon dioxide emissions in the atmosphere. Actually, the production of structural concrete itself is more environmentally-friendly than the production of for example steel or bricks, but its wide use increases the total quantity of carbon dioxide emitted and raises it to such a high value. [2.]

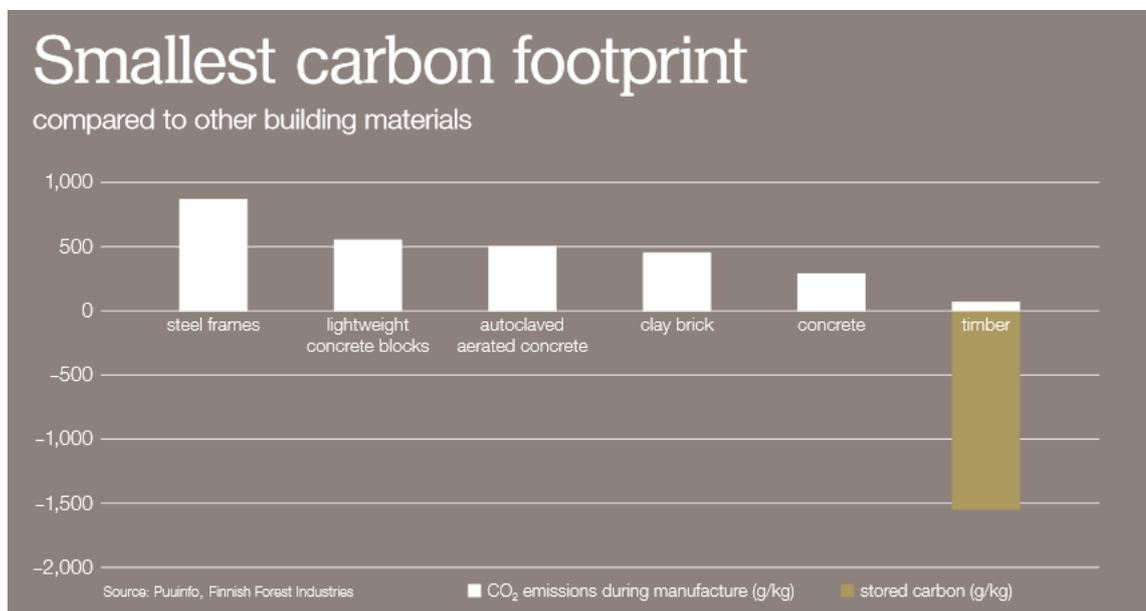


Figure 11. The carbon footprint of different materials [25.]

For this reason, timber starts to be considered as a replacement. Timber is a great choice because it can store CO<sub>2</sub> and its carbon footprint can be recovered as illustrated in figure 11, because it is possible to plant new trees. [25.]

## 5 Environmental impact study

Timber is certainly an ecological material that has no impact on the environment and that can be reused and recycled. This is well known by many producers, companies and supported by numerous studies on it. [4;11.] What is not really known is the behaviour of timber and an adhesive glue together. Basically what is not clear is whether it is possible to consider Cross Laminated Timber as a 100% sustainable product with the possibility to reuse or recycle it once dismissed. Typically on the manufacturing plants, the waste from the production of Cross Laminated Timber is sent to a treatment plant where the material is burnt in an incinerator. [4.]

The Italian company Xlam Dolomiti started to wonder instead if it is possible to recycle the parts. To be sure the properties of the adhesive glue used in the production process were studied. This study set out to analyse the polyurethane wood adhesive, its properties and the possibility to dispose and recycle it. This would allow the company to improve their knowledge on the material and the possible applications of it. [8.]

The global wood adhesive market for CLT is dominated by three major products PRF, EPI and PUR. PRF (phenol-resorcinol-formaldehyde) is a dark coloured formaldehyde based adhesive, well-known for structural use in timber application for North America. EPI (emulsion polymer isocyanate) is a liquid two-component wood glue with light colours, used for I-joists and timber lamination. PUR (one-component polyurethane) is a white solvent and a formaldehyde free adhesive used commonly in Europe for CLT. [11.]

### 5.1 Polyurethane adhesive glue

What Xlam Dolomiti uses for their production is PUR wood glue, produced by the Swiss company Purbond-Henkel AG. [12;14.] Purbond's product had been chosen thanks to its gluing strength properties and absence of formaldehyde in the composition; this makes it a safe product to handle and use compared with PRF and EPI. [15.] Formaldehyde is a volatile organic compound (VOC) that is suspected to cause irritation to eyes, nose and respiratory tract. Therefore it is a great advantage to limit or reduce its use and contact with humans.

During the application of a wood adhesive such as PRF, the amount of formaldehyde emitted varies by the mixture ratio. According to the law, the maximum concentration on the work area must be lower than 0,37mg/m<sup>3</sup>. [31.] Whenever PRF is handled, the workers must be extremely aware of the toxicity and equipped with personal safety and respiratory equipment. Using a formaldehyde free product like PUR means that there are no harmful pollutants in the air and the workers can handle the material safely. [32.]

Purbond wood adhesive is produced like all commercial wood glues. The raw materials are mixed together, heated up and some chemicals are added as binding to the mixture. In the case of polyurethane, the two main components, the methylene-diphenyl-diisocyanate and the polypropyleneglycol are mixed together in equal parts. The materials are heated in a so called reactor with a small amount of other additives. After some time, the adhesive is ready and can be cooled and packaged. Changing the amount of components in the mixture, the produced adhesive has different properties. [32;33.]

Table 1. Characteristics of wood adhesives [11.]

Item	Units	Adhesive		
		PRF	EPI	PUR
Cured adhesive colour		Dark	Light	Light
Component		Liquid, two components	Liquid, two components	Liquid, single component (isocyanate pre-polymer)
Solids content	(%)	50	43	100
Wood moisture content (MC)	(%)	6 - 15%	6 - 15%	> 8% optimal 12%
Target application rate (single spread)	(g/m <sup>2</sup> )	375 - 400 (75 - 80 lb/msf)	275 - 325 (55 - 65 lb/msf)	100 - 180 (20 - 35 lb/msf)
Assembly time	(min)	40	20	45
Pressing time	(min)	420 - 540	60	120
Applied pressure	(psi)	120	120	120 - 200

Table 1 shows a comparison of PUR adhesive performances with the other two CLT gluing solutions. [11.] It is possible to notice how properties of PUR are not the best compared to other adhesives on the market, but it was chosen by Xlam Dolomiti for its higher safety and zero formaldehyde emissions. [12;32.]

## 5.2 Emissions

Even though Purbond products are formaldehyde free, this does not automatically mean that PUR is sustainable. To analyse the effective impact in terms of emissions in the atmosphere it is necessary to investigate three phases, i.e. the production of the adhesive, the application to produce CLT, and the disposal of the product. During these three steps in the material's life, the adhesive might emit different substances because of the diverse uses of the product. [32.]

Producing the PUR wood adhesive involves high temperatures, fossil fuel based raw materials (methylene-diphenyl-diisocyanate and polypropyleneglycol) and other chemical additives. [33.] The study was performed on 1kg of PUR wood glue product with 100% solid content. As a result, emissions were found. They could be divided into three groups: fossil depletion with 200mPt, ecosystem emissions with 75mPt, and human health emissions with 175mPt. [32;34.] Fossil depletion emissions mainly refer to the production of raw material and in that sense are not directly derived from the manufacturing of the adhesive. Emissions to the ecosystem are a consequence of the heat required in the production. This heat is generally produced by electric resistances and the production of electricity has a CO<sub>2</sub> impact on the environment. The third group of emissions, the health emissions are caused by the chemicals added to the mixture in order to complete the process and assign some specific strength characteristics to the wood adhesive. In total, the emissions were calculated to be about 450mPt (mill points). It must be specified that these values refer to the pure production process of the adhesive. In the CLT manufacture, the adhesive product arrives packaged and the CLT producer has no control over the PUR manufacturing phase. For this reason any improvements in the Cross Laminated Timber sustainability production, have no effect on the production of PUR adhesive. [32-34.]

CLT functions due to the adhesive. In the case of Purbond, the product is simply poured over the timber boards and then a second layer of boards is laid on top. [11;13.] During this phase, the hardeners in the glue are activated and in the study it was noticed that this produces some emissions. However, these emissions are very small and they are classified as Human health emissions and Environmental emissions. For every square meter of Cross Laminated Timber produced, the human health emissions are  $3.06 \cdot 10^{-14} \text{ g/m}^3$  in a day and the environmental emissions are  $8.8 \cdot 10^{-8} \text{ g/m}^3$  in a

day.[32;34.] They can be considered not harmful because of the extremely low concentrations compared to the legal limit value of  $2 \cdot 10^{-5} \text{ g/m}^3$  per day. [32;33].

Generally, the CLT panels and the manufacturing waste material are disposed by burning. The material is collected on a truck that takes the glued timber parts to an incinerator where they are burnt. In this case there are two setups for the incinerators plants, one where the materials are just destroyed, and another where heat or electricity can be produced from the combustion. [4;12.] According to Mr. Forlanelli (marketing development manager for Purbond Italy), it is possible to consider the emissions equals to zero in the case of the incinerator, thanks to the high-tech filters installed in the plants. [35.] However, it was calculated that burning Cross Laminated Panel with PUR adhesive will produce an embodied carbon (CO<sub>2</sub> emitted during the whole process) amount of 1192 tCO<sub>2</sub>eq. If the less common landfill disposal is used, the emissions in the atmosphere are created by the degradation of the glued timber and the breakdown of the components in the soil. It was calculated that the embodied carbon for CLT disposed in a landfill would be 1013 tCO<sub>2</sub>eq. [32;36.]

It is important to consider that a certain part of emissions must be accounted for the transportation of the material and the disposal works as well. The transportation value strictly depends on the location of the production plant or the building that is going to be dismissed. The collected average data shows, however that the emissions are relatively small if the transportation is local. The total carbon emissions are 12 tCO<sub>2</sub>eq. Generally, the disposal of CLT involves demolition on site. The environmental effect is calculated to be 22 tCO<sub>2</sub>eq for embodied carbon emissions. [36.]

### 5.3 Disposal and recycle of the material

From the collected data emissions data from the adhesive glue, it is clear that the end life of Cross Laminated Timber is a problematic phase in terms of sustainability.

Companies such as Xlam Dolomiti are in that sense interested in a possible alternative solution to this issue. [12.] It is already possible to find bio-based wood adhesives on the market. They are bio resins obtained from plants and animal wastes or wax. The benefit of using a bio-based adhesive is the same as using timber in the construction, i.e. they can be recycled and they have no carbon footprint. The reason why none of the CLT producers uses them is because of the weak adhesive strength and the higher costs. It was, however calculated by the researchers of the BRE (Building Research

Establishment) in Great Britain that in approximately five to ten years, the development of this field, it might be possible to use bio-based adhesives in CLT. [37.]

An efficient way to use waste parts or disposed modules of CLT could be for indoor residential heating. The waste parts can be sawed or chopped into wood chips to produce pellet fuel. This technique is widely used all over the world and the majority of the waste wood originating from different manufacturing processes is turned into pellet fuel. Pellet fuel is then burnt in a residential heating unit to produce both heat for the spaces and domestic hot water. [38.] Timber glued with PUR adhesive can only be used in such a way if the percentage of glue is less than 5%. Otherwise, according to the experts at Purbond labs, the emissions could be harmful for humans and the environment. [35.] Unfortunately, on average the adhesive content in the CLT is slightly higher and therefore, it does not allow such use. So Cross Laminated Timber can only be used as a heating source in an incinerator plant, where the sophisticated filters and high temperatures ensure the destruction of any possible pollutants. [34.]

Burning CLT for heating purposes in big incinerators may seem a feasible solution but it actually wastes precious material. On a more sustainable view, it is possible to think about other solutions that would recycle or reuse the waste material. To recycle CLT, it would be necessary to split each lumber layer and extract the glue from them. After that the wood could be recycled or composted and the glue eventually cleaned and reused. The problem is basically that the process would not only take a lot of time and resources but also there are no technologies that could carry out the process in a large scale. [32;35.]

A more feasible and ecological solution is to convert the CLT waste into construction products. It was established that processes such as sawing and chopping of the CLT panels have no impact on the emissions from the PUR adhesive. [32.] With this process wood chips are produced. [38.] According to the size of the wood chips, they can be used for different applications in the construction. Wood chips are the base material of wood fibre insulation, chipboards and wood bonded panels. [39.] Each of these products is widely used in the construction and they represent undoubtedly an optimal way to reuse the CLT.

Tests performed on the life-cycle of the CLT showed that at the end of the expected life time (usually 50 years), part of the structure can still be used. Mr Albino Angeli from Xlam Dolomiti stated that if the structure is constantly checked and maintained properly during its lifetime, about 80% of it can be reused. This means that the majority of the elements still have conserved all the structural properties. Theoretically, removing the unsuitable 20% of the panel, the module can be reinstalled in a new construction. [11;12.] The problem with this solution is that not many customers want and are willing to buy an old material for their residential construction. An additional issue is that CLT was introduced as a construction material in the 90's and it means that the oldest buildings are no more than 25 years old. Therefore, only experimental results are available and they are, perhaps, less reliable than empirical data. For this reason it is more probable and feasible to reuse Cross Laminated Panels for secondary structures like storage places or garages. [12.]

Table 2. Embodied carbon in tCO<sub>2</sub>eq for CLT with different end of life scenario [36.]

	Re-use	Re-engineering transformation	Incinerate	Incinerate with energy recovery	Landfill
<b>Absorbed by the timber</b>	-1100	-1100	-1100	-1100	-1100
<b>Demolition</b>	22	22	22	22	22
<b>Transport</b>	12	12	12	12	12
<b>Construction</b>	45	45			
<b>Manufacture</b>		10			
<b>Combustion</b>			1192	1192	
<b>Energy from combustion</b>				-628	
<b>Emissions from landfill</b>					1013
<b>Total</b>	-1021	-1011	126	-502	-53

Emissions and environmental benefits were calculated for each of the disposal and reuse solution technologies. Table 2 compares the gains and losses according the embodied carbon (CO<sub>2</sub> emissions during the entire process) for the different end of life scenarios. [36.] The basic starting value -1100 is the absorption of carbon dioxide by the timber. This is a value calculated on the ability of the timber in the growing phase and during its use to store and produce oxygen. It has a negative value because is not contributing to the global warming. Another negative value that needs to be explained is the one for production of electricity through combustion. This allows getting energy as heat and electricity from the burning process, which without the waste material would require more ecologically hazardous and pollutant source such as fossil fuels to produce it.

## 6 Analysis and discussion of the results

Building with timber has countless advantages and the technology in this field is growing rapidly. In a few years it will be possible to see more and more Cross Laminated Timber residential units built around the world. At the moment the companies producing or dealing with this construction technology, like Xlam Dolomiti, are investing a lot on the research on CLT. They aim to gather knowledge about the technology in order to be able to offer a product that is completely ecological and competitive in the market. The scope of this study is in fact to recognize the critical points in the CLT and suggest some alternatives. The final result is a series of possibilities to improve the production and the use of the product in order for it to be considered emissions free and 100% sustainable. [8;12.]



Figure 12. Sustainability life cycle [3.]

With the possibility of an ecological raw material and manufacturing process, an emission free usage of the product and a sustainable plan of using the disposals it is possible to achieve the goal of complete sustainability as shown in figure12. [3.]

### 6.1 CLT overall sustainability

CLT is advertised and chosen for its remarkable ecological properties. As discussed in chapter 4.5, timber is an incredibly good material that can store CO<sub>2</sub> and planting new trees helps to reduce the global warming impact as shown previously in figure 11. Timber is also the only construction material that can be created by nature and not a limited resource that is mined until all of it is used. [6;25.]

Instead, the crucial point is the adhesive used to glue the timber board together to produce CLT. At the moment it is not possible for the CLT producers to utilize bio-based resins in the production because of the weakness of the adhesive. Ecological adhesives have just entered the market and their resistance when glued to the timber has been proved to not be strong enough to match the legal requirements. [37.] For this reason, the CLT producers like Xlam Dolomiti use synthetic-based adhesives that are able to achieve the minimum requirements for structural resistance. [11.] Between the three most common adhesives on the market, PRF, EPI and PUR, Xlam Dolomiti decided to use PUR (produced by in Switzerland by Purbond) because it is formaldehyde free. [12;13.] Having a formaldehyde free material to handle is a great advantage in terms of personal safety because formaldehyde is a volatile organic compound that can cause irritations and respiration problems to the users. [31.] However, PUR is a synthetic material and it was shown to have some heavy health and environmental emissions in the production. Producing the adhesive is, however, a field that does not concern the CLT product or producers. However, it does affect the production phase of the adhesive and the manufacturers of it.

The observed emissions show that CLT is emission free during the application. The emissions in during the application were measured to be not more than  $8.8 \cdot 10^{-8} \text{ g/m}^3$  per  $\text{m}^2$  of CLT produced in a day, when the limit value is  $2.0 \cdot 10^{-5} \text{ g/m}^3$ . [32-34.]

This means that the maximum possible emission is 0.44% of the limit value. The disposal of the CLT is a more delicate topic, however. The material to be disposed comes, on one hand, from the shaping of the CLT panels in the manufacturing process and on the other, from demolished structures. At the moment the Cross Laminated Timber

producers are using two possibilities for the waste disposal, that is incineration and landfill disposal. [12;32.] It was seen that in both cases the PUR adhesive emits greenhouse gases. Burning Cross Laminated Timber produces 1192 tCO<sub>2</sub>eq for embodied carbon, but in most of the cases the process is performed in industrial incinerators that thanks to their sophisticated filters and high temperature, can capture the pollutants. In the most advanced incineration plants, the burning phase is also used to produce heat or electricity. A landfill disposal is less harmful compared to incineration because it does not directly emit CO<sub>2</sub> in the air in a short time. The emissions are caused by the breaking down of the material causing an embodied carbon (emission from all the process) of 1013 tCO<sub>2</sub>eq. In this case though, the material is buried and it is not possible to get any benefits from the material. [32;36.]

Table 2 shows that incineration can be seen the better of the two options, but none of them is really sustainable. The efficiency of the energy recovery from the incineration is strictly connected to the type of plant. The value reported in table 2 is estimated according to the most common incineration technology, this means that the collected data is not a strict standard value but can vary. [36.] To achieve a complete sustainability of a product it is necessary to be able to reuse the waste material and transform it into raw material for other products.

## 6.2 Reuse and recycling of the wastes from CLT

Recycling CLT means separating the timber part from the adhesive and recycling each component individually. This procedure is available in laboratories on micro scale, but there are no machines or procedures to handle large quantities of CLT material. [34;35.] For this simple reason, it is more convenient to reuse the waste material. Tests demonstrated that chopping CLT into smaller parts, also called chips, do not activate the chemicals in the PUR adhesive. Thanks to a stable condition of the product, there are no hazardous emissions in the air. [32.] Wood chips are widely used in the wood manufacturing process to produce wood composite panels. [39.]

This makes it possible to reuse Cross Laminated Timber wastes for the production of chipboards, wood bonded panels, and wood fibre insulation panels. The raw material each of this three construction products is made of is either virgin or recycled wood chips. [39.] Mr Joseph Gabriel (Technical director of Henkel-Purbond in Switzerland)

claims that it has already been proved that wood chips composed of timber and PUR adhesive can be used in the production of other wood construction materials. [32.]



Figure 13. Chip board for construction [18.]

To produce chipboards, also known as particle board shown in figure 13, the raw material is graded in a rotating machine to create different sizes chips. Bio-resin or wax is added and a mat is created by pushing the mixture through a series of wheels. To bind the wood chips together, the mat is hot pressed, forming a solid panel. Once the boards are cooled and cut on size, they can be packaged to be sold. This material is very much appreciated by the constructors thanks to its good mechanical performance that is equal along and across the panel. Chipboards are generally used as floor decking or on the surface of walls and roofs. [18;39.]



Figure 14. Wood bonded panel for construction [40.]

Wood bonded panels are slightly more complex to produce than chipboards but they are widely used in construction as fire protection boards. They are produced by chopping the wood chips in a hammermill to obtain small wood flakes. The wood flakes are mixed with bio-cement and the mixture is then pressed for about 7 hours until the cement is dry. Before shipment, the panels are further dried in a heated chamber at 70 to 80°C. Thanks to the high content of cement, this type of panel reacts very well against fire and has a good thermal insulation value. [5;39.]



Figure 15. Wood fibre insulation panel for residential buildings [18.]

Wood fibre panels are generally used as thermal insulation for residential buildings as a sustainable alternative to mineral or rock wool insulation. Manufacturing of insulation panels is quite simple and fast thanks to a fully-automated process. The production process starts by loading the wood chips into a refiner that transforms them into a wood fibre pulp. The pulp is then mixed with water and a binder (usually wax or latex) and the mix is pumped in a forming module. The long continuous fibre mat created is pressed and dried in an air drier. The panels are then cut to size and packaged. Nowadays, wood fibre insulation technology has developed a lot. This has resulted in products with the same thermal transmission property as synthetic insulation panels have. [18.]

Chipboards, wood bonded panels and wood insulation are an excellent way to reuse CLT wastes. In fact each of these building materials is an additional material to the CLT. Chipboards are used for roofs and floors, wood bonded panels as fire protection required by the law, and to insulate the building it is possible to use wood fibre panels.

[18.] Compared to the incineration, although the base material is a waste product from the manufacturing or disposal of a structure, the reuse of the glued timber as wood chips raw material gives new life to it. By reusing the waste and disposal material to produce new construction materials, the sustainability cycle concept shown in figure 12 is complete. It is possible to consider Cross Laminated Timber and its production 100% sustainable.

### 6.3 Optimization of the production

Beyond the reuse of the waste form the manufacturing and disposal of Cross Laminated Timber, it would be better to reduce the waste produced. [12.] To achieve that the only possible way is by developing and optimizing the production. At the moment, the manufacturing process is supported by the use of automatic machines during all the phases. The production setup adopted by Xlam Dolomiti is similar to what most of the other producers have and it has six main parts:

- Planing and joining of the timber boards
- Polyurethane adhesive application
- Panel lay-up
- Assembly pressing
- CLT on-line cutting and finishing
- Product marking, packaging and shipping [13.]

Wastes from the production are coming from the on-line cutting and finishing process. During this phase, the already formed CLT panel is conveyed to a multi-axial numerically-controlled machine. This automated machine cuts and shapes the panel according to a 3D computer model elaborated on the base of the architectural designs of the building that will be constructed with CLT modules. The result is a panel with the openings for windows and doors and other required parts such as beams or trusses support elements. This process slows the production process because the mill producing the openings needs to drill the CLT panel and then slowly cut off the parts. The cut off parts are actually the wastes from the production. [12;13.]

Optimizing the previous phases of the production, it would be possible to reduce the amount of waste material significantly. As illustrated in figure 16, it was found out that an additional manufacturing phase in the production can reduce the waste, the work

load on the on-line numerical cutting machine and, consequently, reduce the overall production time. [13;16.]

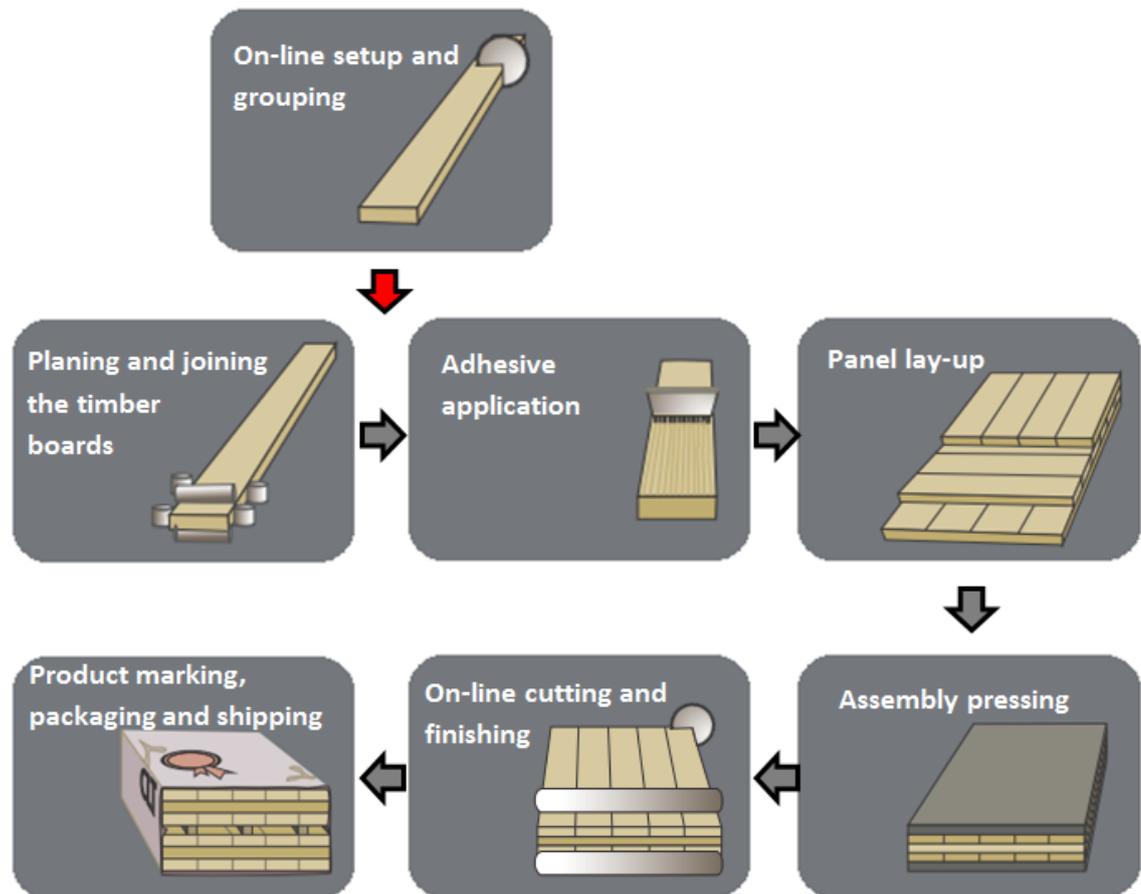


Figure 16. Optimized Cross Laminated Timber production [11.]

The benefit of this idea is the possibility to use the 3D computer module not only during the cutting of the material but also in an early stage of the production. A multi-axial numerically-controlled machine could be used right before the PUR adhesive application. The machine could elaborate the electronic model to calculate and arrange the lumbers according to the specific design of the single panel. Longitudinal and transversal timber boards could be positioned so that the openings on the single panel would already be on place. The adhesive application stage could proceed without any substantial changes. CLT on-line cutting and finishing process would receive panels with already roughly made openings and the multi-axial mill should only complete and round off the openings. [12.]

Introducing such machinery in the production process it is possible to reduce the work load on the on-line cutting, the amount of waste material in the manufacturing of CLT, and optimize the producing times. In terms of waste material reduction from the production, the effective value varies a lot according to the design of each specific Cross Laminated Timber panel. With a rough estimation, it is possible say that at least 30% of the waste material is saved per each panel. As explained by Matti Mikkola from Puuto-teteollisuus Oy, such a machine is under development and not yet available on the market. None of the Cross Laminated Timber producers, continues Mikkola, is equipped with this technology, but having regard to the possible benefits of it; in the next few years it will be for sure added to the production lines. [12.]

## 7 Conclusions

Cross Laminated Timber is a fast growing building technology that is revolutionizing construction, and offering a more sustainable alternative to the typical building systems. Not only the building characteristics and structural performances of CLT will play an important role in the coming years, but also its unique seismic resistance is going to be the key for safer buildings around the world. To be competitive in the construction market, Cross Laminated Timber producers must focus in developing the further researches in the field and advertise how the higher initial costs of the technology are well covered and balanced by the shorter construction times, structural safety, high product quality and excellent sustainability. [12.]

The study, done in cooperation with the company Xlam Dolomiti, into the sustainability performance of CLT proved that it is not only an excellent product for its structural and building resistance but also for its environmental-friendly character. The study showed CLT to be the only construction material to have a negative carbon footprint; it means that the CLT technology reduces the emissions of greenhouse gases both during the production and the disposal phases. [18;25.]

Xlam Dolomiti, adapting a policy of reuse of the waste from Cross Laminated Timber production, can successfully advertise their product as 100% sustainable. With the development of technologies in the field, Xlam Dolomiti can introduce an additional automation step in the production. Then, the amount of total waste is going to be reduced and the manufacturing process is optimized.

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