Comparison of Different Assembling Techniques Regarding Cost, Durability, and Ecology - A Survey of Multi-layer Wooden Panel Assembly Load-Bearing Construction Elements

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Wood is a pure, sustainable, renewable material. The increasing use of wood for construction can improve its sustainability. There are various techniques to assemble multi-layer wooden panels into prefabricated, load-bearing construction elements. However, comparative market and economy studies are still scarce. In this study, the following assembling techniques were compared: laminating, nailing, stapling, screwing, stress laminating, doweling, dovetailing, and wood welding. The production costs, durability, and ecological considerations were presented. This study was based on reviews of published works and information gathered from 27 leading wood product manufacturing companies in six European countries. The study shows that the various techniques of assembling multi-layer wooden construction panel elements are very different. Cross laminated timber (CLT) exhibited the best results in terms of cost and durability. With regard to ecological concerns, dovetailing is the best. Taking into account both durability and ecological considerations, wooden screw-doweling is the best. These alternatives give manufacturers some freedom of choice regarding the visibility of surfaces and the efficient use of lower-quality timber. CLT is the most cost-effective, is not patented, and is a well-established option on the market today.

Keywords: Sustainable; Multi-layer wooden panel; Load bearing construction elements; Costs; Durability and ecological consideration; Cross laminated timber

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INTRODUCTION

A simple definition of "sustainable development" is to use no more of a material today than can be replaced tomorrow (Rowell *et al.* 2010). A perhaps more complex definition involves the consideration of three dimensions of sustainability: the social, ecological, and economical aspects (Adams 2006). The overlapping portion of these three dimensions represents the region in which sustainable development of society is possible.

The building sector in Europe accounts for approximately 40% of the total material and energy usage, 40% of greenhouse gas emissions, and 40% of the waste generated in Europe (the so-called "40-40-40 rule"). Thus, decisions made by the construction sector are vital to sustainable development (Gluch 2007).

Timber construction, as compared to steel and concrete construction, has a smaller ecological footprint (Bokalders *et al.* 2009). Figure 1, re-plotted using data from Kolb (2008), illustrates the material and energy consumption by each of the four most common structural materials. Energy consumption is nine times higher for steel and three times higher for reinforced concrete than that with wood. Therefore, wood is a very interesting building material (Kolb 2008).

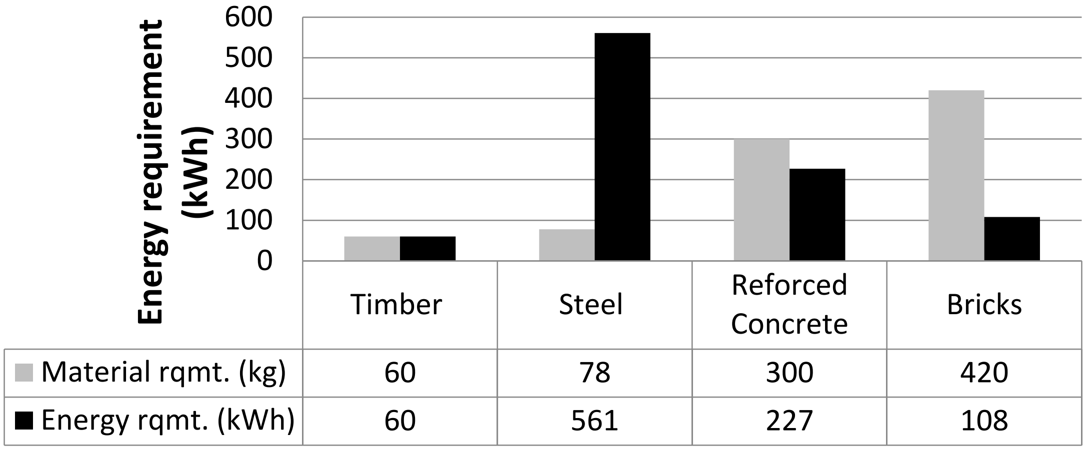

Fig. 1. A comparison of the energy requirements for producing a 3-m-high column

Solid wood exhibits good fire behavior properties (Kolb 2008). Solid wood panels provide good fire retardancy in which the dimensions can be based on one-dimensional charring, unlike unprotected wooden studs, which have larger exposed area and access to greater oxygen supply as a result (Gustafsson and Gustafsson 1999; Östman 2012).

Wood construction systems have a number of advantages over those of steel and concrete. Wood has a higher ratio of load-carrying capacity to weight. Its lower weight reduces soil load by 30 to 50%. The light weight reduces shipping costs of prefabricated elements, and higher volumes can be transported. Lifts are accomplished with smaller cranes and handling is easier, allowing for faster installation. In total, the processing of wooden building materials requires less energy, and wood can be recycled or its energy can be recovered. Increasing the prevalence of wood construction is one strategy for reducing the rate of change to the global climate (Stehn 2008).

However, knowledge about wood construction is lacking. This can create skepticism and preconceptions about the features and costs of wood construction. Development of techniques of assembling multi-layer wooden load-bearing panel elements can be likened to new innovations in wood construction resulting from standardization and increased quality. To achieve full efficiency, several stages, from concept and idea generation to pilot-scale building, are required. Once a technology is proven on the pilot-scale, it is sold to niche markets, and finally, after 25 to 30 years, the mass market. Steel and concrete have had more time to industrially develop (Stehn 2008). The development of these materials is well underway and they have established market positions. Bringing wood construction into greater popularity is challenging (Cigen 2003); as of now, this technology is in the pilot-scale construction phase (Stehn 2008).

In 1994, when Sweden joined the EU, it was allowed to build wood frames more than two floors tall. This had been forbidden for 120 years previously. The new standards are no longer based only on the material, but instead take into account the requirements. The development of modern timber engineering renewed the use of wood as a building material (Fredriksson 2003; Erikson 2007). Given environmental issues, it is becoming increasingly clear that it is important to increase the prevalence of wood structures, which promotes the development of new, sustainable construction solutions (Fredriksson 2003; Erikson 2007).

Competition in the construction industry has driven the development of more effective responses to customer demands. The increasing degree of prefabrication is a factor driving quality improvement, shortening the construction times, and reducing construction cost as per the customers' requests (Fredriksson 2003). Industrial production has prompted the manufacture of multi-layer wooden panels. Based on drawings, panels can be processed *via* computer numerical control (CNC). This approach creates a prefabricated system for a more customer-centered design (Stehn 2008). The degree of prefabrication can be increased by assembling the panels in the factory and installing finished panels, making the final product modular. Prefabrication takes place in a rational, efficient environment and yields better assembled products compared to site-building (Gustafsson *et al.* 2002; Adolfi *et al.* 2005).

Wood construction uses load-bearing systems such as the post-beam system, multi-layer wooden panel system, and stud frame system. These different construction systems can be divided into site-built, prefabricated flat panel elements, and prefabricated modular methods. The choice of material is based on various factors, including the foundation, building design, number of floors, building system, budget, administration of the final product, and functional requirements such as stability, fire behavior, acoustic properties, environmental concerns, product requirements, and the available expertise. Such choices would be easier if clear, structured solutions were available. Currently, these choices are usually based on small studies and made with limited knowledge (Stehn 2008).

In recent years, various techniques for assembling multi-layer wooden panels into construction elements have been developed. These developments have spurred a need for a market comparison to investigate the fundamental differences between the existing techniques. It is unclear which technique, for example, is advantageous for use in residential construction considering production cost, strength, and ecological aspects. Ecological aspects are further divided into the chemical content, renewability, and raw material utilization associated with the technique.

Objective

The objective of this study was to investigate and compare the industrial multi-layer wooden load-bearing panel elements assembling techniques to provide a fundamental basis upon the choice of multi-layer wooden panel elements intended for residential construction. The following techniques for assembling were investigated and compared: laminated, nailed, stapled, screwed, stress-laminated, doweled, dovetailed, and wood-welded. The present survey and analysis will contribute to the understanding of the different techniques of assembling multi-layer wooden panel to construction elements from the perspectives of cost, strength, and ecology.

Review of Different Assembling Techniques for Multi-layer Wooden Panel Load-bearing Construction Elements

Industrial production with a greater degree of prefabrication enables more rational mass-production of multi-layer wooden panel elements. This, in turn, has facilitated the development and introduction of various new techniques for assembling multi-layer wooden panel to construction elements in recent years. Softwood (spruce, pine, or fir) plies or laminates are the raw materials for these elements. Planar elements, serving simultaneously as both load-bearing and enclosing elements, have many applications in walls, suspended floors, and roofs (Kolb 2008).

Panel elements can be assembled together in many ways: in several wooden layers, stacked flat on top of each other, arranged with their wood fibres crossed 90° or crossed 45° relative to those of the neighboring layers, or otherwise. Elements consisting of layers laying on their edges parallel to one another can be stress-laminated. Industrially, techniques including gluing, doweling, nailing, screwing, stapling, stress-laminating, dovetailing, and wood-welding are used for assembling (Mjåland 2004; Kolb 2008; Rubner 2010; Solli and Glasø 2011; Schweigl 2013). A brief description of each system follows.

Cross-laminated timber (CLT)

Cross-laminated timber (CLT) is becoming increasingly common in wooden structures as a pre-fabricated wall and floor element. CLT is a multi-layer wooden panel made of lumber. They are normally stacked on top of each other, glued together, and arranged such that the wood fibres of each layer are perpendicular to those of the neighboring layers. Usually, an odd number of layers is used. This results in a product with high dimensional stability and load-bearing capabilities in more directions than regular sawn timber or glulam (Gagnon and Pirvu 2011).

Panels made of an odd number of layers of cross-laminated timber provide good stability (Fig. 2). In this layered form, the panels do not warp when subjected to moisture and temperature changes. A similar structure is used in plywood (Gustafsson and Gustafsson 1999; Kolb 2008). But plywood is made of rotary cut thin- and wide veneers bonded together. The uneven number of layers allows for strength with a main and side direction. The biggest load is typically placed in the direction parallel to the fibers. More layers correspond to a more homogeneous panel. Lower grades of timber can be used in the inner layers. The thickness of CLT varies between 50 and 300 mm (Kolb 2008).

Fig. 2. Cross-laminated timber (CLT) panels

The cost of the glue used in these panels is relatively high, but it allows good load distribution between the layers (Solli and Glasø 2011). The adhesive provides strong bonding and allows the design to distribute point loads (such as from columns) (Gustafsson and Gustafsson 1999; Gustafsson *et al.* 2002). CLT also has good shear capacity. It allows holes (for doors and windows) to be made in the panel elements and is good for use in the overhanging parts of the building (*i.e.*, a balcony) (Nyberg 2012). In design, it can be assumed, for sake of simplification, that every second layer is subjected to the bending moment and that all layers transfer shear forces between one another (Östman 2012).

Glued OSB panels

A magnum board (glued oriented strand board (OSB) panels) can be obtained by gluing several layers of OSB together, as shown in Fig. 3. These panels have different properties in each direction because the wood chips are glued in specific directions. Much like CLT, glued OSB panels typically contain an odd number of OSB boards. The surface is homogeneous and suitable for coverage with wallpapers or tiles (Kolb 2008).

The chemical content in this type of panel is increased by the glue. The best-quality OSB contains 5% glue (about 29 kg/m^3). OSB boards must, in turn, be glued together to create the magnum board. The glue in bonded structures marketed as formaldehyde-free was replaced, in some cases, with isocyanates, which are now suspected carcinogens. The development of safer glues is ongoing (Thoma 1997; Andrén 2013).

Fig. 3. Magnum board manufactured by bonded 25-mm OSB

Nailed panels

From a production point of view, the nailed panel system is a simple alternative because it requires little previous knowledge and technological resources. The nailed panel consists of crossed boards nailed together like the products sold by the Massivholzmauer (MHM) company. This facilitates processing such as sawing and milling using aluminum nails, which are softer than steel (Gustafsson and Gustafsson 1999; Kolb 2008; Solli and Glasø 2011). Nail-assembled panels are less stiff compared to glued or stress-laminated panels. Lesser load distribution results in lower resistance to concentrated loads in nailed panels (Gustafsson and Gustafsson 1999; Kolb 2008).

Stapled panels

An alternative to aluminum nails is galvanized steel staples. A faster, stapled system exists as compared to the nailed system. The staple back is visible on one side of the layer. Steel staples are harder than aluminum and do not bend easily, even when inserted into wood knots, which are considerably harder than other parts of the wood. Steel staples provide joints with more predictable strength. The manufacture of steel is less energy-intensive than the production of aluminum (Schweigl 2012, 2013).

Screwed panels

Screws provide higher strength and result in smaller gaps between layers because the screw threads pull the layers together more than nails. The screws are visible on one flat surface, like nails (Gustafsson *et al.* 2002; Aarstad 2009).

Stress-laminated panels

Pre-stressed steel bars hold the boards together, as shown in Fig. 4. This system is mostly used in timber bridges. Transverse tension is used as reinforcement, thus reducing the movement caused by variations in temperature and humidity. Transverse tension yields good strength in the transverse direction through the systemic panel effect when steel struts' cohesive stress increases the friction between the slats. This type of panel favors concentrated loads when the load is distributed. To avoid protruding steel fasteners on flat elements, they can be recessed within the outermost layer (Gustafsson and Gustafsson 1999; Tran and Tran 2012).

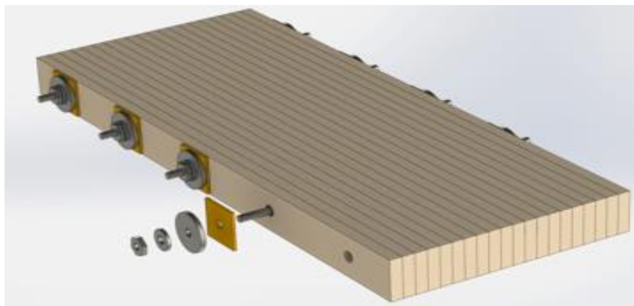

Fig. 4. Stress laminated bridge deck

Widmann (1997) reported regarding screw-laminated timber deck plates, and he compared them with nailed, glued, and stress-laminated decks. He concluded that the glued and stress-laminated decks provide a higher stiffness and a higher load distribution than the screw-laminated slabs, but they all are stiffer than nail-laminated plates. Nail-laminated plates do not provide bending stiffness perpendicular to the laminations.

Dowelled panels

Several varieties of dowelled panels have been developed, inspired by the old craft where wood was joined together with wooden dowels. The elements contain only wood and no glue, metals, or chemicals. In pre-drilled holes, pressed hardwood dowels of beech, oak, or ash are inserted. Wood dowels become securely wedged into the structure when they expand because they have lower moisture content than the rest of the panel material, and thus require no glue (Gustafsson and Gustafsson 1999; Aarstad 2009).

The vertical dowelled system shown in Fig. 5 (Holz100) was developed by Thoma Ervin of Austria.

Fig. 5. Vertical dowelled system (Holz100) (Thoma 2000)

An odd number of boards are placed in a cross-wise or diagonal pattern to increase load distributing ability. Wooden dowels go vertically through the entire thickness of the panel, imparting strength (Thoma 2012).

The horizontal-dowelled system is called Bresta, where a long wooden dowel 25-mm in diameter holds the panel together along its width, as shown in Fig. 6 (left). This system is similar to the stress-laminated system. This type of construction has higher bending stiffness than nailed and screwed structures (Gustafsson and Gustafsson 1999).

Another variant is the diagonal-dowelled system, in which the boards are held together by dowels placed diagonally, as illustrated in Fig. 6 (right). For added effect, dowel flat slat sides have been profiled, but this variant approach is otherwise similar to the Bresta system (Heinz 2012).

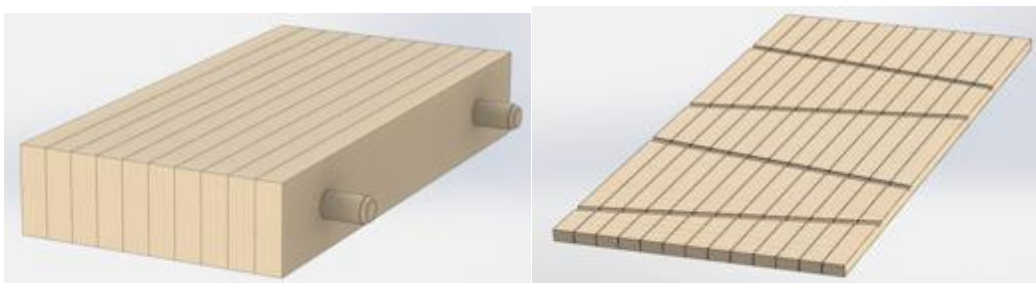

Fig. 6. Horizontal-dowelled system (Bresta) (left) and diagonal-dowelled system (right)

Figure 7 shows wooden screw-dowelled panels bolted together with threaded wooden screw dowels inserted into pre-drilled mounting holes. The threads increase the load distributing ability between layers. Figure 7 shows that a surface can be obtained without any visible screws. Since the threads provide sufficiently high load-bearing capacity, they travel only partially through the outer layer (Lennartz 2012).

Fig. 7. Wooden screw-dowelled system (Lennartz 2012)

According to ETA-11/0338 (2011) and ETA-13/0785 (2013), the internal diameters are 20 mm for both beech screw-dowel and vertical dowel (Holz 100), but the outer diameter of beech screw-dowel is 22 mm due to the thread. The characteristic load-carrying capacity between two cross board layers of wooden screw-dowel is much higher than wood dowel (R_k = 5800 N for wooden screw-dowel and R_k = 3800 N for wood dowel). In the ultimate limit state, the shear modulus between two layers is higher per wooden screw-dowel than wood dowel (K_u = 2400 N/mm for wooden screw-dowel and K_u = 2000 N/mm for wood dowel).

Dovetailed panels

Dovetailing with a dovetail-assembled board is a technique in which wooden strips are used. They cross-wisely hold together the layers in a configuration. The design of the V-shaped strip seam creates durable bonding (Fig. 8). By assembling wooden layers together with dovetails, the design is hidden and has no impact on the visible surface, and the whole system is air-tight. They are assembled more tightly together than the Holz100 (doweled) system, because the wood dowels go through the whole panel's thickness. In a wall construction, the panels stand vertically. This is advantageous because the load is applied parallel to the wood grain. However, the element's weakest point is at the dovetail (Ferk 2002; Rubner 2010) because it can cut the grain.

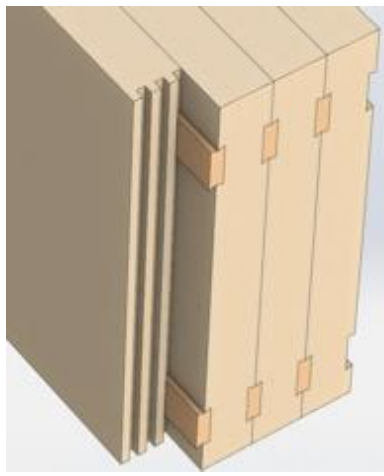

Fig. 8. Dovetailed system

Wood welded plates

Wood welding is a technique by which wood can be assembled without glue using only mechanical friction. Pine is a wood with good water resistance, which depends on the extractives content released from the pine during welding. The strength of this type of assembly can be improved by increasing the proportion of heartwood and the resin coating. A natural composite is formed between the layers at a pressure of 1.3 MPa and friction duration of 1.5 s. This technique is faster and can yield higher strength than adhesive bonding. The development of this technology is at the research level (Vaziri 2011). Figure 9 illustrates wood welding.

Fig. 9. Examples of wood welding (Vaziri 2011)

EXPERIMENTAL

The contacted participants were employees of the companies representative of the multi-layer wooden panel construction element manufacturing industry. They are active in the construction of housing. The companies were selected by searching for their corporate websites online. It was determined which assembling techniques were used in each company. The search was restricted to companies located in the Nordic and Central Europe. In spring of 2013, a total of 27 companies in six European countries were contacted. The various techniques mentioned in the paper were not all represented within a single country. This resulted in a more generalizable market overview, as several companies in different countries were represented.

The structured telephone interview method was used. The quantitatively designed phone interview involved structured questions, and the respondent answered with price indications. The price of a square meter (SEK/m^2) (without tax) of each type of multi-layer wooden panel element, for a customer ordering the material for housing construction with single-sided visible standard quality, was determined. The orders were directly from the business for 120-mm-thick panel elements with a volume of material applicable to frame a standard Swedish villa. These prices would not include transportation, installation, configuration, or any external processing.

Each phone interview lasted 10 to 20 min depending on the respondent's supplementary questions. After the telephone interview, all data gathered, including problems, were sent *via* email to the respondent for review. They were asked to verify the information and then accept, modify, or reject. All information collected from the companies contacted in this study was subjected to a written check.

The collected rates were translated to Swedish Krona per cubic meter (SEK/m^3). The unit prices were calculated using the Equation, ((price schedule from companies including unilateral visible housing quality) • exchange rate on 3rd May) / panel thickness = ((price/m^2) • exchange rate) / 0.12 m = SEK/m^3.

The Oanda Currency Converter was used to convert these currencies to Swedish Krona at the May 3, 2013 rates: 1 Swiss Franc = 6.98094 SEK, 1 Norwegian Krone = 1.12369 SEK, and 1 Euro = 8.53242 SEK. The Euro was applied to pricing from Italy, Austria, and Germany.

The matrix method is suitable for the evaluation and assessment of large amounts of information. This method involves compressed writing. For example, optimization or derivation is used to summarize the writing and highlight the most important facts. Various factors can be clarified and identified using this method. The L-matrix form is the simplest matrix form in which the grid is formed by only two axes (Klefsjö 1999). Matrix diagrams can graphically illustrate the large amounts of information. The processing of information *via* the matrix method is done to summarize the information in each cell. Links between the various elements can be visualized for greater logical clarity. Graphical symbols provide a schematic picture of the various options to facilitate comparisons between the criteria. Matrix analysis is useful for detecting desired customer preferences. The method identifies the weaknesses and strengths of a visual guide aiding in the decision-making process (Bergman and Klefsjö 2012).

The method for producing the matrix involves categorizing the report information into three main categories: cost, durability, and ecology. The assessment was based on the method of criteria evaluation, as summarized in the results. The compilation of the various aspects is graphically visualized *via* positive and negative assessments. Five symbol levels were used in the assessment of the matrix: ++, +, 0, -, and --. The most positive assessment was assigned ++; neutral, 0; and the worst, --. This displays what properties were more or less desirable for each specific technique in assembling multi-layer wooden panels with regard to various aspects of study.

RESULTS AND DISCUSSION

The study results showed that there are different techniques for assembling multi-layer wooden panel construction elements. A comparative study of the cost, durability, and ecology of different multi-layer wooden panel elements has never been published before. In this study, different assembling techniques of multi-layer wooden panel elements were examined, evaluated, and compared finally with respect to three main aspects: price, strength, and ecology.

Unit Prices of Solid Wood Panel Elements

Guideline values are summarized in Table 1, in which 30 prices are shown from 27 companies in 6 European countries. Prices are based on different techniques of assembling wood to multi-layer wooden panel elements. These are the net price of panel elements with 5 layers or on edge wise position with standard dimensions (120-mm thickness) of standard quality (visible, one-sided housing quality). The total material volume was intended to be appropriate for use in the body of a standard Swedish villa. The price is for a customer who orders from the business without shipping, installation, configuration, or other processing or sizing costs. The cost items varied independently of assembling techniques.

Table 1 shows that average prices, from lowest to higher, were Nailed, 4464 SEK; Stapled, 4893 SEK; Glued CLT, 5553 SEK; Glued OSB, 7253 SEK; Doweled, 7461 SEK; Screwed, 8410 SEK; and Dovetailed, 10168 SEK. The price of pre-stressed steel was unavailable since it is used in bridge construction rather than building construction. The difference between the cheapest and most expensive panels was nearly double. The results shown in Table 1 give an idea of the different prices of the multi-layer wooden panel elements made by different assembling techniques. Engineers and end-users have the right to choose which types of multi-layer wooden panels they prefer according to their different characteristics and properties.

Different prices can be ascribed to differences in the manufacturing process. In an automatic production line, dowels are inserted into the pre-drilled holes by a machine. The entire process is more complicated than that of nails and staples, which involve easier, more standardized automatic production lines. In the wood industry, gluing is the most established and well-developed technique of assembling multi-layer wooden panels.

Price, Durability, and Ecology

Table 2 compares the multi-layer wooden panels' price, durability, and ecology. In the first column, assembling techniques are discussed. The next column takes into account how the wood is assembled to the panel element. The other columns report the differences in various customer interests and have been divided into three categories: price, strength, and ecology. The last category (ecology) has been further separated into three subcategories: chemical content, renewability, and raw material utilization. Differences within the categories of the matrix were visually represented with the symbols (+) for positive, (0) for neutral, and (-) for negative. When data was unavailable, it was denoted with the letter "x" in the matrix.

Table 1. Unit Prices of Different Joining Techniques for Solid Wood Panel Element

Assembling Techniques	Price (SEK/m³)	Thickness (mm)	Country	Company
Laminated				
CLT	6167	*120*	Sweden	Martinsons
CLT	6250	*120*	Sweden	David Wettergren Arkitektur
CLT	5333	*120*	Sweden	EBEC Consulting
CLT	5833	*120*	Sweden	AB Fristad Bygg
CLT	6167	*120*	Sweden	Stångebro Bygg AB
CLT	6180	*100*	Norway	Massiv Lust AS
CLT	5105	*117*	Germany	Franz Plank GmbH
CLT	4657	*120*	Austria	NORICA TIMBER Vertrieb GmbH
CLT	5973	*120*	Austria	Stora Enso WP Bad St. Leonhard GmbH
CLT	4344	*120*	Austria	Mayr-Melnhof Kaufmann Gaishorn GmbH
CLT	5725	*117*	Switzerland	Holzuntersander GmbH
CLT	4906	*120*	Switzerland	Schilliger Holz AG
Average	***5553***			
Median	***5779***			
Wood dowels				
Vertical	8500	*120*	Sweden	David Wettergren Arkitektur
Vertical[1]	8579	*120*	Austria	Erwin Thoma Holz GmbH
Vertical	8532	*120*	Germany	Woodcube Hamburg GmbH
Horizontal	6845	*120*	Germany	Riedle & Bader Holzbau GmbH
Horizontal	7155	*120*	Switzerland	Tschopp Holzbau AG
Horizontal	6346	*110*	Switzerland	Sidler Holz AG
Diagonal	5267	*120*	Austria	Sohm HolzBautechnik GmbH
Wood screw dowel	7850	*125*	Germany	Rombach Bauholz + Abbund GmbH
Average	***7461***			
Median	***7503***			
Nail[2]				
Aluminum nail	4000	*115*	Sweden	David Wettergren Arkitektur
Aluminum nail	4600	*115*	Germany	Massiv-Holz-Mauer Entwicklungs GmbH
Aluminum nail	4600	*115*	Germany	Seidelbau Gmbh
Aluminum nail	4654	*110*	Germany	Mayr & Sonntag GmbH
Average	***4464***			
Median	***4600***			
Screw				
Layers on edge-wise	7660	*120*	Norway	Norsk massivtre AS
Layers on flat-wise	9160	*112*	Norway	Norsk massivtre AS
Average	***8410***			
Staple[3]				
Galvanized Steel staple	4893	*143*	Italy	Ligna Construct GmbH
Dovetail				
Dovetailed joint board	10168	*120*	Italy	Reinverbund GmbH
Magnum-Board				
Glued OSB	7253	*125*	Germany	Planungsbuero Christian Stein
Stress laminated[4]				
Steel rod	---		Sweden	Martinsons

[1] Double-sided visible surface quality.
[2] No visible surface quality (nailed).
[3] Less waste through recesses of the wood at the cut-outs. The price includes machining, milling for installations, *etc*.
[4] Used for bridge construction with conditions other than building construction

Table 2. Matrix Overview of Different Assembling Techniques for Multi-layer Wooden Panel Elements in terms of Price, Strength, and Ecology Aspects

		Customer Interest / Material Properties				
		Price	Strength	Ecology		
Assembling Techniques	Lamella Direction			Chemical Content	Renew-ability	Raw Material Utilization
Laminated	Cross	+ +	+ +	-	0	+ +
	OSB	0	0	- -	0	+
Vertical Doweled	Cross	-	0	0	+ +	+
Horizontal Doweled	Edge-wise	-	-	0	+ +	-
Diagonal Doweled	Edge-wise	-	-	0	+ +	-
Wooden Screw Doweled	Cross	-	+	0	+ +	+
Nailed	Cross	+	- -	0	- -	0
Stapled	Cross	+	-	0	-	0
Screwed	Flat-wise	- -	+	0	- -	+
	Edge-wise	-	0	0	- -	-
Dovetailed	Flat-wise	- -	- -	0	+ +	+ +
Stress Laminated	Edge-wise	X	+ +	0	-	-
Wood Welded	Cross	X	+ +	0	+ +	+ +
	Edge-wise	X	+	0	+ +	-

Price

Market differences appeared to contribute to price differences within the same assembling technique, as a function of the country of production and the establishment. The prices indicate to what degree an assembling technique is established in the market. The companies summarized in Table 1 were selected randomly. The number of companies supplying each assembling technique also indicates how established each technique is. Increased establishment facilitates greater access to multi-layer wooden panel elements and thus reduces the monopoly position of the producers.

Another cost factor appears to be whether or not the entire thickness of the panel element is consistently made of the same quality of wood. If not, higher-value timber is only used on the surface, lowering the overall cost of the panel.

Based on this work, CLT is the most cost-effective panel element option. It includes a standard quality of housing construction with a single-sided, visible surface. There is no patent for this technology, and it is the most established alternative available. Wood welding is still at the research level. Stress-laminated wood with steel bars was not included as the economic calculations were not based on the conditions used in housing construction.

Table 2's price column can be interpreted as:

+ + Laminated, cross-layer: Low customer purchase cost and most established market.
+ Stapled: Low customer purchase cost.
+ Nailed: Low customer purchase cost but without clear surface.
0 Laminated, OSB: Average cost to the customer.
- All doweled and screwed on edge-wise: High purchase cost for the customer.
- - Dovetailed and screwed on flat-wise: Maximum purchase cost for the customer.

Strength

The strength was found to be dependent on how the wood assembles together to form a homogeneous structure. The target was to produce predictable-strength assembly and laminations with cross layers, which increase reinforcement of the multi-layer wooden panel construction element.

In multi-story wood construction, wind load becomes more pronounced. Wood has a high load-carrying capacity in relation to its weight as compared to steel and concrete. Panel elements consisting of an odd number of crossed layers (like plywood) have good load-distributing properties. This favors withstanding wind loads of varying directions. The ratio of the vertical load from the weight and the horizontal wind load can cause warping of some panel elements (shear deformations), which is counteracted by the numerous crossed layers.

If strength is critical, it should be noted that the assemblies that are accomplished with nails, staples, or screws do not go penetrate all of the layers. This reduces the load distribution between the different layers, as not all layers are linked together by the same joint. For higher strength, it is better to use steel bars, dowels, or glue. Nowadays, stress-laminated wood is used only in bridge construction, since it is so difficult to tighten in building construction.

The wooden screw-doweled system provides greater strength than the screw, staple, or nails systems. The wooden screw dowels go through all of the layers, and their structures are cross-layers. Further, cohesion is created not only by wooden dowel expansion, but also because the dowels have threads like screws. The threads give the panels a clear surface on one side without visible wooden dowels.

The panel elements can be assembled in parallel or edge-wise, as shown in Fig. 5. On flat-wise crossed layers, higher-value, better-quality wood can be fixed on the outermost layer. Because the whole system works together, it is possible to have an overall higher-wood quality panel. It is beneficial in terms of cost to use low quality wood for the layers that are not visible.

CLT is the most advantageous technique from a strength point of view because the adhesive provides a strong bond with uniform load distribution. Wood welding also provides a strong bond. Some uncertainty, however, exists surrounding the use of wood welded bonds, concerning water resistance. Stress-laminated systems with steel bars that act as load distributors have better point load properties since all layers are linked.

The strength column in Table 2 can be explained as:

+ + Stress laminated, through-bonded: Suited for point loads by steel struts, loading distribution over the entire panel width.

+ + Wood-welded, cross layers: The bond is stronger than glued bonds, although uncertainty exists with respect to its water resistance. The weld around the layers has an even load bearing capacity and can be considered a continuous assembly.

++ Laminated, cross layers: The assembly is slightly weaker than wood welded bond.

\+ Wooden screw-doweled, cross layers: Connections with screws yield strength.

\+ Screwed, flat-wise layers: Non-through connections with screws give strength.

\+ Wood welded, layers edge-wise: Non-through bonds where the bond is not in contact with other bonds.

0 Glued, OSB: The OSB layers have lower strength than the lumber layers because the OSB is glued together and consists of small wood chips.

0 Vertical doweled, cross layers: Through-bonded.

0 Screwed, layers edge-wise: Non-through connections with screws for increased strength.
- Horizontal doweled, layers edge-wise: Through connection.
- Diagonal doweled, layers edge-wise: Through connection.
- Stapled, cross layers: Merging with steel clamps provides more predictable strength as they do not bend; non-through connection.
-- Nailed, cross layers: Non-through connection with aluminum nails.
-- Dovetailed, layers flat-wise: Element's weakest point is at the dovetail, because the fibers have been cut over the full length; non-through connection.

Ecology

In the present study, ecological considerations were restricted to three aspects of multi-layer wooden panel construction element: chemical content, renewability, and raw material utilization. The literature describes different techniques for these three aspects. The results are shown below, as represented in Table 2.

When health issues are the top priority, all types of panels made entirely of wood were best because adhesives contain chemicals that can diffuse into the air and affect residents over time. Some chemicals are suspected to be carcinogenic, and those that are considered safe may be later proven harmful. In some cases, the use of formaldehyde-free adhesives was promoted, but these could also contain other dangerous substances. Expectations are that research will eventually develop healthier alternatives. An entirely multi-layer wooden panel element costs more. However, it should be noted that from an economic perspective, the choice of assembling technique is only a small percentage of the total construction cost.

The non-renewable resources used include screws, nails, staples, steel bars, and glue. The production of aluminum nails requires more energy than that of galvanized steel staples. Steel, as compared to wood or aluminum, is harder and more complicated to alter *via* cutting or drilling.

Dovetailed panel elements are the best from an ecological perspective. The elements consist only of wood and form a sound design in the full scale. The connection is hidden and has no effect on the apparent plane surface. Visible joints can reduce the aesthetic quality of surfaces.

Screw-shaped wooden dowels that joint the crossed wooden layers are the most favorable ecological alternative when strength is a factor. Screw dowels yield high strength because they go through all layers and distribute the load over the whole panel element.

1) Chemical content

The multi-layer wooded panel assembling techniques with glue content, which contain chemicals, received negative results.

0 Doweled, nailed, stapled, screwed, dovetailed, stress laminated and wood welded: No addition of chemicals.
- Laminated, cross layers: The content of chemicals.
- - Laminated, OSB: Elevated chemicals.

2) Renewability

The multi-layer wooded panel assembling techniques with homogenous layers throughout the panel is most beneficial, because it is renewable entirely.

++ Vertical doweled, horizontal doweled, diagonal doweled, wooden screw doweled, dovetailed, and wood welded: Panel elements consist of only wood and thus consist entirely of renewable materials.
0 Laminated: Glue made up in part of non-renewable materials.
- Stapled and stress laminated: Steel content is a non-renewable resource.
- - Nailed and screwed: Content of aluminum, which is a non-renewable resource. Also production of aluminum requires more energy than steel.

3) Raw material utilization

At the utilization of raw materials, it is important how the wood layers are arranged in joining. Panel elements with cross layers jointed on flat-wise is more beneficial than on edge-wise, since it is more probable to have high-value wood on visible surfaces of panel elements and low quality wood in the inner layers. The panel layers are joined at edge-wise with boards that use the same width and thickness. They cannot use different quality of wood.
+ + Laminated and wood welded, cross layers. Dovetailed on flat-wise: Positive utilization of raw materials, clear surface on both flat sides; however, welding results in a visible dark seam between the layers.
+ Laminated, OSB: Positive utilization of raw materials, no visible joint on both flat sides; however, the appearance of glued wood chips is present.
+ Wooden screw doweled, cross layers: Positive utilization of raw materials, the joint is visible on one flat surface.
+ Vertical doweled, cross layers: Positive utilization of raw materials, visible bonding on both flat sides.
+ Screwed, layers on flat-wise: Positive utilization of raw materials, the joint is visible on one flat surface.
0 Nailed and stapled, cross layers: Positive utilization of raw materials, the joint is visible on one flat surface.
- Horizontal doweled, diagonal doweled, stress laminated, screwed and wood welded with layers on edge-wise: No visible bonding on both flat sides except the dark welded joint.

CONCLUSIONS

Different assembling techniques of multi-layer wooden panel construction elements were analyzed and compared with respect to price, durability, and ecology.

1. Cross-laminated timber (CLT) is the best in terms of price and durability.
2. When ecology is the most important consideration, dovetailing is best.
3. Considering both strength and ecology, screw-shaped doweling is advantageous.
4. The numerous assembling options provide freedom of choice as to the efficient use of low quality timber.
5. CLT was the most cost-effective option. The technology is not patented and is the most established alternative available. However, there is still ongoing development of safer adhesives.

6. As opposed to CLT, welded wood is still being developed at the research level.
7. Stress-laminated wood is no longer used in residential construction, as it is difficult to tighten the steel bars.
8. CLT is favorable with respect to strength, since glue imparts strength with a uniform load distribution.
9. Research has shown that wood welding provides a stronger bond than glue. Some uncertainty remains regarding the water resistance wood welding.
10. Wood screw-dowelling is the most favorable ecological market option and yields good strength. The screw-shaped dowels connect all layers. This type of panel element provides a sound design at the full scale; no glue, chemicals, or non-renewable resources are used. Research has shown that pure wood has a positive health effect, as opposed to non-natural materials.
11. The development of various new concepts for assembling wood to panel elements results in a matter of principal for stakeholders who intend to make use of the technology. There, the present study provides basic information. Extended studies may focus on creating detailed documentation aimed at integrating an assembling technique in companies based on their circumstances. Increased use of multi-layer wooden panel constructions can help increase sustainable construction.

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