Log Heating for Veneer Production: A Review of Techniques and Factors

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1 Introduction

Rotary peeling is a process of converting round logs into a continuous thin ribbon (from 0.6 mm to more than 3 mm) of green wood known as veneer (Dupleix 2013). Log conditioning or heating is important for peeling to soften (or plasticise) the wood tissue and ease the cutting process. For almost all hardwood species, heating green wood prior to peeling is necessary to successfully produce high-quality veneer. Hard knots, which, if unheated, may damage a sharp knife. Heating becomes especially important for knotty species, hardwood and frozen wood (Dai *et al.* 2011, Chen *et al.* 2021) as it can decrease splitting and reduce veneer degradation induced by surface roughness (Resch *et al.* 1979). Furthermore, the advantages of heating become more prominent with species of higher densities and when cutting relatively thick veneer (Lutz 1974). The heating of green wood prior to peeling, at the appropriate temperature (and without drying the log), not only softens the wood enough but also improves the peeling process and veneer quality (Dupleix *et al.* 2012).

Heating can also increase the volume and tensile strength of recovered veneer by reducing splitting and breakage during handling and producing tighter, finer veneer with shallower 'peeler' or 'lathe' checks. Conditioning reportedly increased the volume recovery by 3 to 25 percent based on mill study and industrial observation (Resch *et al.* 1979, Steinhagen 2005). It can also reduce consumption of adhesive because the peel is smoother, which reduces the required rate of glue spread. Furthermore, softening can increase production and minimise the power required due to faster peeling and reduce equipment loading. It can also reduce drying time as hot wood is more permeable than cold wood. Some of the advantages and disadvantages of conditioning are listed in previous reports (Resch *et al.* 1979, Steinhagen 2005). However, some disadvantages include fuzzy veneer surface due to overheating, end-checking of logs as when heated in unstaturated steam and change in colour (Resch *et al.* 1979). Resch *et al.* (1979) summarised the possible advantages and disadvantages of heat conditioning of with the reasons which can be applied to log heating for rotary peeling (Table 1).

Table 1. Advantages and disadvantages of block conditioning (Resch et al. 1979)

Advantage	Reasons
Increased volume of recovered veneer	There is less splitting and breakage in handling
Increased quality of recovered veneer from high-quality and frozen blocks	There is decreased splitting and reduced degradation from surface roughness
Reduced knife wear	Knots are softened
Reduced glue spread	Peeled veneer is smoother

Tighter veneer with finer checks and reduced nosebar pressure, especially for checking, thus reducing deep splits thickness above 1 /8 inch	Wood is more plastic and less resistant to fine checking, thus reducing deep splits
Greater tensile strength of veneer perpendicular to the grain	Veneer is tighter and fine, and checks are shallower
Reduced power required for peeling	Softened wood offers less resistance to peeling
Increased production	Faster peeling of softer wood
Reduced drying time with in-line dryers	Some heat is stored in wood, and steamed wood is more permeable
Decreased spinouts	Thoroughly softened wood requires a lower turning force
Disadvantages	Reasons
Increased spinouts	Main block remains cold despite heat-softened ends
Fuzzy veneer surface and tearing	Blocks are overheated (particularly for less dense species)
End-checking of blocks and veneer	Blocks are heated in dry steam resulting in undesirable moisture loss from the log

The optimum temperature and duration for log heating depend on several factors, including the wood species, log diameter, and moisture content. Theoretical analyses, such as measuring the glass transition temperature, can assist in determining the optimal heating temperature for logs. Since heating high-moisture logs is energy-intensive, discovering the optimal temperature becomes critical to optimise energy consumption and time. Various heating techniques are available, such as conventional steam and hot water heating, as well as alternative methods like electrical and microwave heating, which can all be used before peeling. Therefore, the objective of this report was to conduct a literature review of heating temperature and its impact on veneer and composite production. The report also explores the different heating techniques and theoretical determinations of the glass transition temperature, which is the temperature at which materials change from a ‘glassy’ to a ‘rubbery’ state. Finally, the report will provide an overview of the various factors influencing log heating and a brief summary of heating energy requirements.

2 Literature review

Numerous studies have investigated the effect of heating on veneer quality, peeling operation, adhesive performance and engineered wood product (EWP) properties.

Surface roughness plays a critical role in wood bonding. A smooth, flat and free of machining-induced scoring or indentations and irregularities surface is ideal for adhesive application and bond performance. For high-quality bonding, the adhesive must penetrate the wood and form secure mechanical interlocks into the undamaged layer of wood (Frihart 2005, Wykle 2019). Checking, splitting, shedding, and crushing the surface cells during veneer processing can negatively impact the bond performance.

Chen *et al.* (2021) investigated the effect of conditioning temperature on veneer quality for some typical softwood species in North America, including Douglas fir (*Pseudotsuga menziesii*), western white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*) using a roller bar of a 3-inch (76.2 mm) diameter. They found that increasing log temperature increased veneer surface roughness and thickness variation but decreased lathe checks. The optimum log temperatures under the slow-speed laboratory peeling condition were 85 –100°F (29–38 °C). Considering knife wear, lathe vibration and fast peeling speed, the optimum peeling temperatures for typical softwood plywood mills were found to be 85–95°F (29–35 °C) for spruce, 95–100°F (35–38 °C) for lodgepole pine, and 110–120°F (43–49 °C) for Douglas fir. These temperatures were significantly lower than 130°F (54 °C) previously suggested based on a small roller bar. The results of this study have been widely implemented by the Canadian softwood plywood industry with confirmed benefits of energy-saving and veneer quality improvement (Chen *et al.* 2021). In contrast, Dupleix *et al.* (2012) found that low temperatures produce veneers with deeper and more spaced checks than high temperatures when checks are closer and less deep, becoming even more unpredictable, especially in the case of spruce.

Aydin *et al.* (2006) studied the effect of temperature on surface roughness, adhesive wettability, colour variation of veneer, and shear strength of spruce plywood. Veneer samples were manufactured from the logs after they were kept for 3 h and 24 h to reach to average temperatures of 52 °C and 32 °C, respectively. The samples peeled from the logs with a temperature of 52 °C had significantly better roughness values than those of manufactured from the logs with 32 °C. Contact angles of phenol formaldehyde (PF) resin drop on veneers were similar for each peeling temperature while the contact angles of Urea formaldehyde (UF) glue resin on veneers produced from the logs with 32 °C were lower than those of produced from the logs with 52 °C. The highest shear strength value was determined for the plywood manufactured from veneers obtained from the logs with 52 °C by using UF glue.

Xu *et al.* (2017) investigated the effect of softening on cutting forces during veneer slicing. As expected, they found the cutting force increased with increased slicing thickness, however the cutting force was reduced by up to 83.1% when the flitches were steam heated. The cutting force was positively related to the density and hardness of the wood.

Rohumaa *et al.* (2017) studied the effect of heating on lathe check depth, surface roughness, surface integrity of veneer and plywood bond strength. The heating of the logs not only softened the wood during peeling but also caused irreversible changes in the wood material, which subsequently affected the development of plywood bond strength. They found deep lathe checks in veneer significantly reduced the shear strength of PF-bonded plywood, even though these checks are not mentioned in the standard. This finding suggests that reducing the lathe check depth by heating logs before peeling could have a direct benefit in terms of plywood strength by minimising the initiation of mode I bond failure. In a follow-up study, Rohumaa *et al.* (2016) conducted surface roughness measurements using scanning electron microscopy (SEM), surface integrity testing, colour measurements, and wood-adhesive bond testing with an automated bonding evaluation system. The results showed that logs soaked at 70 °C and peeled at 20 °C had roughness, colour, integrity, bond strength, and wetting properties more similar to logs soaked and peeled at 70 °C than those soaked and peeled at 20 °C. In every test conducted, the effect of soaking temperature was greater than the effect of peeling temperature. They conclude that high temperature soaking not only caused softening of the material during the peeling process, but it also caused irreversible changes in the wood material, which affected the veneer surface characteristics and bond strength development.

Although it is easy to control the temperature of steam/hot water heating, the internal log temperature is seldom monitored. Generally, higher target log temperatures take longer and consequently cost more (Resch *et al.* 1979). Therefore, it is essential to find the optimum minimum temperature to reduce operating costs and heating time. The degree of cooling during transfer and the wait time between the heating medium and the lathe should be kept in mind and understood. The manager should be able to weigh the benefits and the associated cost of heat conditioning, and many wood processors believe that the benefits outweigh the cost (Resch *et al.* 1979).

The optimum temperature will depend on species, log diameters and desired time of heating. Even for a given species, no single temperature will be optimum for cutting wood under all conditions (Fleischer 1959, Resch *et al.* 1979).

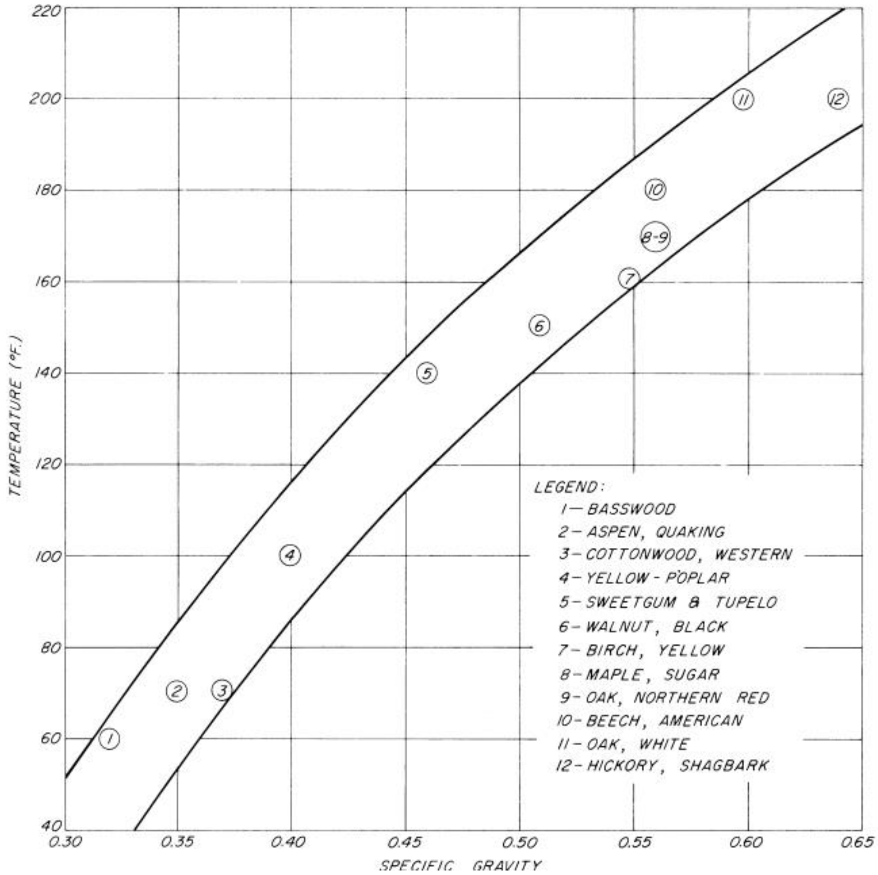

Figure 1. Favourable temperature range (area between heavy lines) for cutting veneer of hardwood species of various specific gravities. Points show favourable temperatures for the individual hardwood species indicated. The data apply to the rotary cutting of veneer Vs inch thick, of straight-grained wood, free of defects such as knots or tension wood ("soft streaks"). (Lutz 1978)

The best temperature for peeling is believed to fall between 120°F (~50°C) and 140°F(~60°C) for most softwoods and is slightly higher for some pines (Lutz 1978). For most softwood species in America, suggested wood temperatures range from m 60°F to 180°F (15°C to 80°C) for peeling 1/8-in (~3mm) (Lutz 1978). Figure 1 shows the ideal temperature range for cutting veneer from different hardwood species with varying densities. The points on the graph indicate the specific temperature range for each species. The data applies to rotary peeling of 1/8 inch thick veneer made from straight-grained wood without any defects like knots or tension wood. Lutz (1978) and Resch *et al.* (1979) presented a comprehensive list of suggested conditioning temperatures for various species for peeling and slicing (Lutz 1978, Resch *et al.* 1979, Steinhagen 2005).

Resch *et al.* (1979) recommended that softwood blocks to be heated to temperatures typically ranging between 50 to 60°C or even higher, as measured at the core (Table 2), when employing the rotary peeling technique. The utilisation of the upper end of the recommended temperature range was found to be advantageous from an economic standpoint (Steinhagen 2005). The temperatures recommended for peeling hardwood blocks, as suggested by (Fleischer 1959), are closely tied to the specific gravity of the wood species. Lighter species, such as *Tilia* sp. and *Populus* sp., can typically be peeled effectively at 20°C. In contrast, denser species, such as *Quercus* sp. and *Carya* sp., may require temperatures as high as 90°C, as measured at the core. In contrast, the temperatures recommended for slicing hardwood are typically 6 to 12°C higher than those for peeling (Steinhagen 2005).

Table 2. Conditioning temperatures suggested for softwood peeler blocks (Resch et al. 1979)

Species	T (°C)	Species	T (°C)
Chamaecyparis nootkatensis	50-60	*Pinus sabiniana*	60-80
Calocedrus decurrens	20-50	*Pinus contorta*	60-80
Chamaecyparis lawsoniana	50-70	*Pinus ponderosa*	60-80
Thuja plicata	60-70	*Pinus lambertiana*	50-60
Pseudotsuga mensiezii	15-60	*Pinus monticola*	50-60
Abies balsamea	20-55	*Sequoia sempervirens*	70-80
Abies magnifica	20-65	*Picea engelmannii*	50-60
Abies grandis	20-65	*Picea sitchensis*	50-60
Taxus brevifolia	180-90	*Abies procera*	20-65
Abies spp.	20-65	**Southern**	
Abies concolor	20-65	*Pinus tadea*	50-70
Tsuga heterophylla	50-70	*Pinus palustris*	50-70
Juniperis occidentalis	60-70	*Pinus serotina*	50-70
Larix occidentalis	60-65	*Pinus echinata*	50-70
		Pinus elliottii	50-70
		Picea sp.	50-60

Much log conditioning research was done prior to 1980 (Hailey *et al.* 1973, Resch *et al.* 1979, Chen *et al.* 2021). Chen *et al.* (2021) mentioned two problems concerning the previous studies: firstly, the recommended temperatures in these reports were based on experience rather than experimental data and secondly, peeling technologies had dramatically changed due to the changes in log supplies. Recently, researchers and industry are aiming to peel various other species, for example, spruce (Aydin *et al.* 2006), birch (Rohumaa *et al.* 2014, Rohumaa *et al.* 2016), beech (Rohumaa *et al.* 2018), Douglas fir (*Pseudotsuga menziesii*), western white spruce (*Picea glauca*) and lodgepole pine (*Pinus contorta*) (Chen *et al.* 2021). However, these results are inappropriate for many commercial softwood/hardwood species in Australia and peeling conditions in Australia. The wood properties from naturally grown, mature native forest trees differ from the same species of fast-grown plantation hardwood trees. Therefore, a proper investigation is necessary to optimise softening, time, and energy consumption for these timbers.

3 Heating methods

Usually, logs are heated in submerged hot water basins with steam or live steam, hot water spray chambers with mixed steam or steam chambers (Resch *et al.* 1979). Some alternative heating methods to hot water or steam also have been used in a small scale or laboratory, such as electric heating (Lutz 1960, Lutz 1974), infrared heating (Dupleix 2013), high-frequency electric heating (Lutz 1974), forcing hot water or steam in the longitudinal direction (Kubinsky *et al.* 1968, Lutz 1974), and heating in steam under pressure.

Resch *et al.* (1979) categorised hot water and steam heating into batch and continuous processes (

Table 3).

Table 3. Methods for block conditioning (Resch et al. 1979)

Method	Process	
	Batch	Continuous
Steam sprayed at low-pressure or high pressure	Above ground chamber (drive-in vaults)	Above ground chamber (conveyor)
Spray or deluge with hot water below 90 ˚C, or superheated or mixed with steam	Above ground or below ground chamber	Above ground chamber (conveyor)
Immersion in water heated by steam coils or live steam or external heat exchanger	Submerged, covered soaking vat	Feed-through soaking vats, above or below ground

3.1 Hot water and steam heating

The two common log heating methods are steaming in a chamber and immersing in a hot water basin. These traditional methods mainly use water or steam as the medium to transfer heat into the bulk wood (Daoui *et al.* 2007, Dupleix *et al.* 2012).

Producers of hardwood face veneer generally prefer hot water vats, while producers of softwood construction plywood generally prefer steam chambers. The heating rate in the two systems is similar (Lutz 1974). In contrast, another source mentioned that steam could heat faster and more evenly than hot water (TLV 2022) as steam transfers heat through condensation at a constant temperature. Others suggest steam can heat wood 5-10% faster than water under the same time and temperature conditions (MacLean 1946, Lutz 1960). In contrast, Feihl (1972) reports that hot water heats as fast or faster than steam. This variation in opinion throughout the literature may be due to the experimental conditions, ambient temperature and target temperature. For example, MacLean (1946) used steam at 212° F (100° C.) and above, while (Feihl 1972) used a steam-air mix at a temperature generally below 200° F (93° C.). Steam and water both also can readily circulate to all surfaces and which can be facilitated by using spacers to create a flow path and promote surface contact with the heating medium (Lutz 1960).

A steam boiler uses more energy to boil the water but uses less energy during heat transfer. On the other hand, a hot water boiler uses less energy to create hot water but more energy during the transfer of heat (Timothy Off Heating & Air Conditioning). Therefore, the advantages and disadvantages of both systems must be assessed before implementing log heating.

The actual temperature throughout the vat can probably be controlled more accurately with water than with a steam air mix (Lutz 1974). However, the control for both systems can be very accurate and depends on the initial capital investment.

There is a possibility of drying when heating with steam-based technology if the relative humidity is not kept high enough. In this context, hot water heating can be beneficial as heating in water vats ensures no drying or loss in moisture content. The steam chambers are potentially safer for operational staff as falling into a hot water vat is generally fatal. The labour cost can be higher as one man with a lift truck can load and unload steam chambers for a large plant, while two or more men are generally needed to operate hot water vats (Lutz 1974). However, continuous operation is possible with hot water vats with a specially designed conveyor system. This would also reduce the risk with hot water vats and heat loss while unloading vats by pumping water to another vat and stopping the logs from floating. Hot water baths may incur higher losses if not appropriately covered. For both systems, various options of fuel can be used, such as woody biomass, diesel, LPG or natural gas.

Usually, the heating temperature for logs is below 100 ˚C. However, some challenges with steam systems is that they can become expensive if additional equipment such as a boiler feed system, blowdown tank, pressure safety system, leak-proof system and boiler license etc. (Kiemen). The boiler for steam generation will also need regular maintenance and service.

Both the steaming and hot water bath technology can be constructed with reinforced concrete. Reinforced concrete can also provide strong supports, longevity and strength for the conveyor system if it exists. Extra layers of insulation can be applied to reduce heat loss. The logs or veneer blocks must be sorted into diameter classes to help achieve temperature uniformity between blocks. In addition, doors rather than curtains can be used with chambers to avoid heat leakage (Steinhagen 2005).

3.2 Heating in steam under pressure

Heating with steam under pressure can shorten the heating time as there is a bigger differential between the starting temperature of the wood and the temperature of the heating medium (Lutz 1974). However, limited laboratory tests indicated that the method gives only a little saving of heating time, and the improvement of veneer quality is not comparable to that obtained by slower steaming at atmospheric pressure (Lutz 1960). Moreover, the high-pressure steam may dry the logs which is not desirable; therefore, water sprays may be needed to help maintain the required high relative humidity to avoid drying and checking.

3.3 Electric Heating

In this method, electrical current is forced through the logs/bolts by means of electrodes attached to each end. This method has been used experimentally to reduce heating time, however, has not been accepted commercially due to non-uniform heating. Since the electrical follows the path of the least resistance, which may be wet streaks, cracks, or mineral streaks in the wood, these areas overheat, and the other parts of the bolt or flitch are underheated (Lutz 1974). Moreover, sapwood heats faster due to higher MC as the current follows the least resistance path. Resistance within heartwood has higher variation (as high as 10 to 1) due to non-uniform moisture content which create variation in the rate of heating (Lutz 1960).

Moreover, the electrical resistance of wood increases as its temperature decreases. Another problem is that dry wood has a very high resistance. Therefore, if the end of the logs/bolts dries below fibre saturation point (FSP), this can create arcing and charring of wood. This method may be utilised as a pre-heating technique to expedite the heating process, subject to a justifiable economic analysis.

A study in 1960 also showed that the duration of heating could also affect the cutting during the peeling process. For example, electrical heating for 1 hour to 140 °F (60°C) did not cut as well as the matched bolt heated to 140° F (60°C) for 72 hours in water (Lutz 1960).

3.4 High-frequency electromagnetic heating

High-frequency technology, such as microwaves, can rapidly heat wood. Microwaves penetrate the material until moisture is located and heats up the material volumetrically. There are two main mechanisms of microwave heating: dipolar reorientation and ionic conduction. Water molecules are dipolar in nature and try to follow the electric field which alternates at very high frequency. Such alternating rotation of molecules produces friction and generates heat inside the material. Ionic conduction is a second major mechanism of microwave heating which is caused by ions, such as those present in salty food, which migrate under the influence of the electric field (Kumar 2015). Similar to electric heating, non-uniform moisture content will generate non-uniform heating using microwave. High frequency has also been used experimentally to heat veneer bolts. As expected, this high frequency tends to overheat the wetter parts of the wood and is much more expensive than heating in steam or water (Lutz 1974).

3.5 Infra-red heating

Dupleix (2013) investigated the feasibility of infrared (IR) heating and found that heating of green wood is unsuitable with IR radiation for the high peeling rates currently in use in the industry due to slow heating by conduction. Therefore, this practice is not commercially adopted.

3.6 Forcing hot water or steam longitudinally through wood

A study by Lutz (1974) found that pushing hot water through short beech veneer bolts produced satisfactory veneer within minutes. However, this method requires the wood to have adequate permeability and a cap to be attached to each bolt. Despite these promising results, this technique has not been implemented commercially, presumably due to the high labour and infrastructure costs of implementing the approach.

4 Glass transition temperature and softening behaviour

The glass transition temperature, T_g, is described as the temperature at which a material changes from a ‘glassy’ state to a ‘rubbery’ state. Heating timber above its T_g softens the tissues, relieves growth stress and improves the peeling process. For example, when the polymeric constituents of timber reach glass transition temperature, the timber achieves a higher softness while relieving internal stress (Kong *et al.* 2017). Understanding viscoelastic behaviour and glass transition temperature is important in many timber processing processes from drying, peeling, pulping and composite manufacturing (Lenth *et al.* 2001).

The evidence in the literature suggests an increased ductility in steamed timber samples caused by the changed viscoelastic properties leading to increased softness in wood (McKenzie *et al.* 2003).

The specific glass transition characteristics of a given timber sample depends on a myriad of parameters (Huang *et al.* 2015). For instance, the species, age and growing conditions. The glass transition temperature of wood increases as the moisture content decreases. The T_g of natural wood polymers has been extensively studied, and it has been shown that the T_g of the primary wood components is relatively high when dry. The glass transition temperature is around 40 °C for hemicelluloses, 50 °C to 100 °C for lignin, and above 100 °C for cellulose (Furuta *et al.* 1997, Lenth *et al.* 2001). When dry, isolated cellulose has a T_g of about 230 – 250°C, the T_g of hemicellulose is in the range of 150 – 200°C and the T_g of lignin is about 130 – 200°C (Salmen 1982, Rohumaa 2016). The glass transition temperature of wood is the same as that of lignin, which is found to be between 60˚C and 200˚C (Lenth *et al.* 2001, Calonego *et al.* 2010, Kong *et al.* 2017).

The presence of moisture will substantially lower these temperatures to a point where the softening of lignin could begin at between 77 and 128°C, and hemicellulose at between 54 and 56°C (Salmen 1982). The Kwei equation has been used by several researchers to describe T_g in wood due to moisture variation (Equation 1)(Kelley *et al.* 1987)

$$T_g = \frac{W_1 T_{g1} + kW_2 T_{g2}}{W_1 + kW_2 + qW_1 W_2} \qquad \text{Equation 1}$$

Where W and T_g represent the weight fraction and glass transition temperature of the polymer (1) and diluent (2). The constants q and k represent adjustable parameters accounting for secondary interactions and free volume considerations, respectively (Kelley *et al.* 1987).

Since glass transition is dependent on many factors, including moisture content, species, and wood composition, it is therefore important that species-specific glass transition temperature should be investigated to find optimum heating conditions. Various tools can be used to measure glass transition temperatures such as Differential Scanning Calorimetry (DSC), Differential Thermal Analysis (DTA), Thermogravimetric analysis (TGA) and Dielectric thermal analysis (DETA) *etc*. Table 4 summarises the softening temperatures reported for wood in the available literature using various tools.

The glass transition temperature is different in hardwoods than in softwood due to the differing amount of lignin content and structure of lignin. Softwoods contain more lignin than hardwoods, and there are structural differences between softwood and hardwood lignin (Hamdan *et al.* 2000, Sehlstedt-Persson 2005). Softwood lignins have higher glass transition temperatures (138–160 °C), while hardwood lignins have a lower Tg range of 110 –130 °C under dry conditions (Sen *et al.* 2013). In addition, hardwood contains a substantially higher content of methoxyl groups than softwood, and the hardwood lignins are less cross-linked than the softwood lignins (Olsson *et al.* 1992, Börcsök *et al.* 2020). Also, softwood lignins are comprised primarily of guaiacyl units while hardwood lignins are typically made up of similar amounts of syringyl and guaiacyl units and to a much lesser extent p-hydroxyphenyl units (Hamdan *et al.* 2000).

The thermal softening of solid wood has been shown to start at between 115 and 145°C (Rohumaa 2016). Steaming or boiling in hot water proved effective in relieving the growth stress via softening the wood (Kong *et al.* 2017). Heating logs to its glass transition temperature reduces the cutting force, limits premature knife damage, and improves surface properties such as roughness, wettability, and integrity. Table 4 provides the softening temperature of some wood species at various moisture content and instruments used.

Table 4. Reported softening temperatures for wood (Lenth et al. 2001)

Refence	Technique	Species	Measurement frequency (Hz)	Moisture content (%)	Softening temperature (T_g) ˚C
Kelley *et al.* (1987)	DMTA	spruce	1	30	60
				20	60
				10	80
				5	115
Salmén (1984)	DMTA	spruce	0.05	Saturated	82
			0.5		85
			5		98
			20		100
Atack (1981)	Torsional Pendulum	spruce	1a	Saturated	85
Becker *et al.* (1968)	Torsional Pendulum	Beech	0.5-3	Saturated	80
				26	85
				20.5	95
Hoglund (1976)	Torsional Pendulum	various	1a	Saturated	80
			10a		110
Sadoh (1981)	Torsional Pendulum	Birch	0.05	Saturated	80
			0.5	Dry	235
Wert *et al.* (1984)	Torsional Pendulum	Spruce	1	dry	132 & 192
Hillis *et al.* (1978)	Static torsion	Pine	N/A	Saturated	80 & 92

Takahashi *et al.* (1998)	Radial Compression	Various	N/A	Saturated	80
Uhmeier *et al.* (1998)	Radial compression	Spruce	N/A	Saturated	85
Funakoshi *et al.* (1979)	DTA	Birch	N/A	dry	210
Irvine (1984)	DTA	Eucalyptus	N/A	25	62
				16	68
				12	82
				7	108
Östberg *et al.* (1990)	DSC	Spruce	N/A	25	60
				20	60
				17	60
				15.5	61
				13	63
				11.5	65
				8	70
				8	73
				7	81
				6.5	86

5 Factors affecting log heating

Factors that influence log heating for veneer cutting include the type of wood, the moisture content of the logs, the temperature of the heating process, size and shape of the logs, density of logs and the heating process.

5.1 Species and density

The species of wood being used can significantly influence the heating and cutting process. Different wood species have varying densities, moisture contents, and hardness, which can affect how they respond to heat and cutting. A combination of trial and fundamental glass transition analysis is recommended to determine the appropriate heating temperature for different wood species accurately. For wood that has significant cross grain or hard knots, it is suggested that the heating temperature should be increased by 20 to 30 degrees (Fleischer 1959).

The net energy required to heat up green wood also varies between species due to their variation in initial moisture content as shown in Table 5 (further discussed in section 5.2).

Table 5. Net energy required to heat green wood (Steinhagen 2005).

Species of varying initial moisture content	Block or log conditions	
	Initially nonfrozen $(kJ/m^3{}^\circ C)$	**Initially frozen** $(kJ/m^3{}^\circ C)$
Pseudotsuga mensiezii (heartwood)	1283	1540
Quercus sp.	2566	3079
Populus sp.	2566	3079

To determine the total net energy demand, one must multiply the unit energy demand values by the total volume input and the total temperature increase over the entire heating range (Steinhagen 2005).

Transverse thermal conductivity of wood increases with density (Yu *et al.* 2011). A 20% variation in density could change conduction by up to 15% in the longitudinal direction at 20°C (Suleiman *et al.* 1999). However, wood with higher density will have a slower heating rate than those with lower density. This is because denser materials typically have a higher heat capacity, meaning they require more heat energy to raise their temperature than less dense materials. As a result, denser materials may require more time and/or energy to reach a given temperature. The cutting force was positively related with the density and hardness of wood.

5.2 Moisture content and temperature of wood

One of the main factors that affect the thermal conductivity and heating rate of wood or logs is their moisture content. The thermal conductivity of water is about 5 times greater than that of dry wood. Therefore, wood with higher moisture content will heat up faster than drier wood. However, Fleischer (1959) mentioned moisture content differences above the fibre saturation point (~25% moisture content) do not significantly impact the heating rate within the temperature range that is typically utilised. The amount of unit energy required by wood varies depending on its moisture content, with woods that have lower moisture content (such as *Pseudotsuga menziesii* (heartwood) requiring relatively less energy, while those with higher moisture content (such as *Quercus* sp. And *Populus* sp.) demanding more energy (Table 5). Additionally, the process of thawing frozen logs (if required) also plays a crucial role in determining the unit energy demand of the wood.

Similar to moisture content, the transverse thermal conductivity of wood increases with temperature (Yu *et al.* 2011). With an increase in temperature from 20 to 100°C, a slight increase in thermal conductivity was observed in both the longitudinal and transverse directions (Suleiman *et al.* 1999). The higher temperature difference between wood and the heating medium will increase the heating rate. It should be noted that a lower initial temperature would necessitate more energy to attain the target temperature.

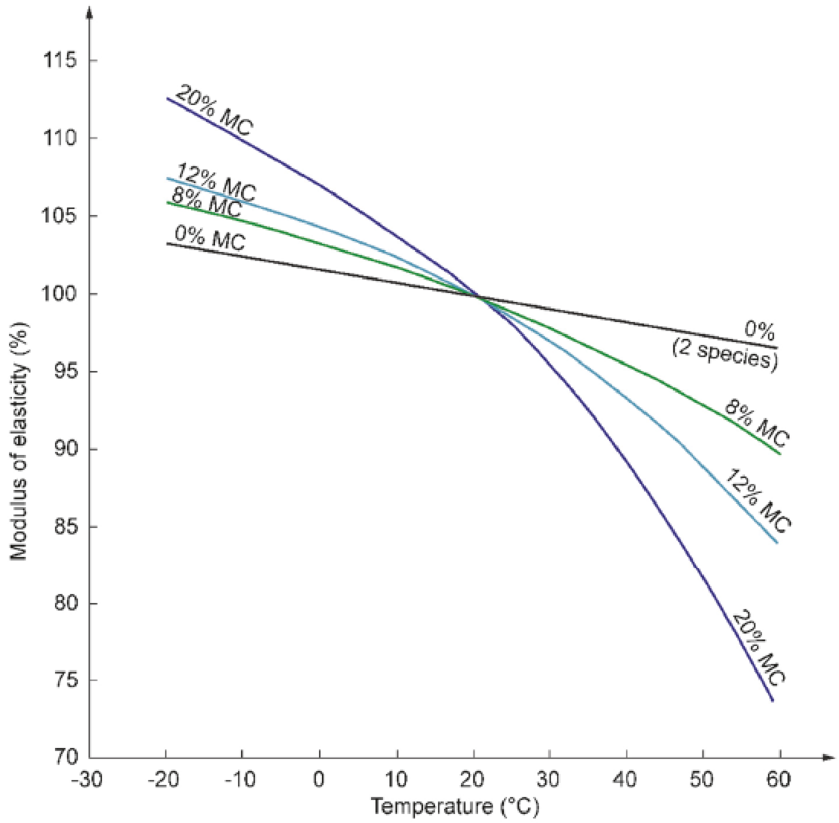

Figure 2. The effect of temperature and moisture content of wood on modulus of elasticity (Sulzberger 1953) (Rohumaa 2016).

Figure 2 shows the effect of temperature and moisture content of wood on the modulus of elasticity. An increase in temperature and/or moisture level tends to decrease mechanical properties, which is indicative of a reduction in cutting force.

5.3 Heating medium

The speed at which logs heat in various mediums is determined by several factors, such as the type of surface contact, the circulation rate of steam or liquids, and the heat of vaporisation (in the case of steam). Water, for instance, generally heats wood at a rate that is approximately 5% to 10% slower than steam (Fleischer 1959). According to tests conducted by the US Forest Products Laboratory, the slowest heating rate was observed when the wood was exposed to low-humidity air, with the heating rate increasing as the humidity of the air increased (Fleischer 1959). As noted in earlier sections, electromagnetic heating has the advantage of rapidly and volumetrically heating up logs from the inside. However, the non-uniformity of the heating and the initial investment costs associated with larger-scale operations have made this method unpopular.

5.4 Log size, grain direction and anisotropy

Achieving the desired core temperature in larger logs takes longer and requires more energy. The temperature of the heating medium and the length of exposure can be adjusted accordingly to reach the desired temperature. However, problems may arise if the heating period is too short, particularly if the logs have not been properly segregated into batches of similar diameter billets (Resch *et al.* 1979).

Figure 3 provides a visual representation of the time required to achieve specific target temperatures for non-frozen peeler blocks that are 8 feet long (~2.4 m) and have a diameter of up to 25 inches (63.5 cm). The target core diameter considered in the figure is 5 inches (~13 cm), with a specific gravity of 0.5 and a moisture content of 100%. If the initial temperature of the block ($T_{initial}$), the target temperature of the block (T_{final}), and the water bath temperature (T_{bath}) are known, the estimated time required to attain the target temperature can be obtained from this figure (Steinhagen 2005). The hours required to achieve specific target temperatures can be adjusted based on certain parameters. For example, if the target core diameter is 4 inches, an hour should be added to the hours given in the figure, while a subtraction of an hour is needed when the target core diameter is 6 inches. If the specific gravity of the material is 0.3, 5% should be subtracted from the hours given by the figure, while an addition of 5% is needed when the specific gravity is 0.7. A moisture content of 50% requires a subtraction of 10% from the hours given by the figure, while an addition of 10% is needed for a moisture content of 150%. Additionally, if the water bath is not agitated, 10% should be added to the hours given by the figure. These adjustments must be taken into account to ensure that the target temperature is achieved within the desired time frame.

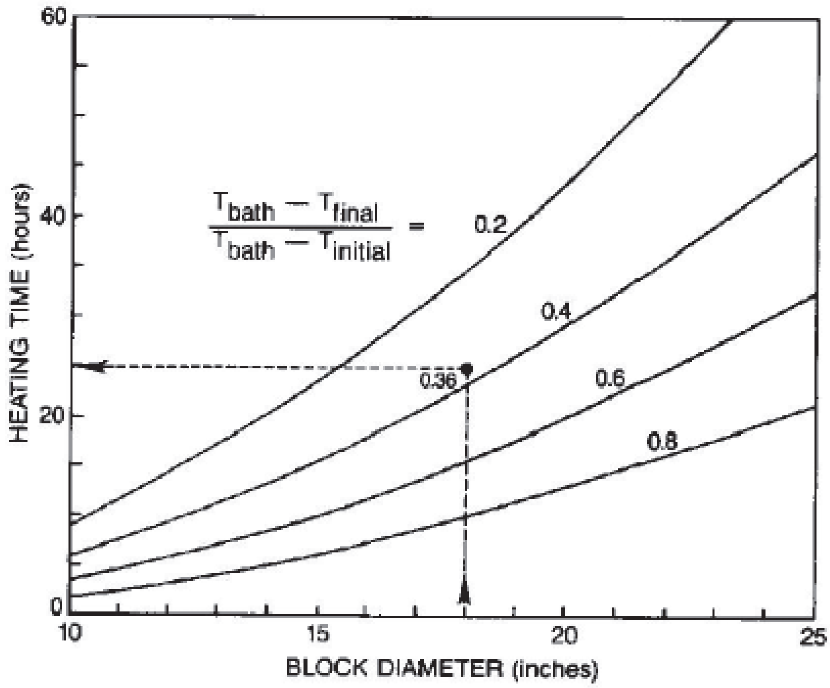

Figure 3. Conditioning time to reach target temperature in a nonfrozen block, given a specific gravity of 0.5, a moisture content of 100 percent, and a target core diameter of 5 inches. The dashed line and data point refer to the example given in the text (Steinhagen 2005)

When heating veneer logs, the most crucial aspect is the rate of heating in the radial direction (perpendicular to the rings), due to the longitudinal direction is much larger than their diameter. As a practical approximation, it can be assumed that, on average, the temperature change along the length of the log occurs roughly 2.5 times faster than the rate of temperature change in the direction perpendicular to the log's axis (Fleischer 1959). The rate of heating is approximately the same in the tangential and radial directions. Faster heating along the longitudinal direction likely results in more rapid heating of knots compared to the neighbouring clear wood. This is advantageous since one of the objectives of heating is to soften the knots to prevent them from dulling or damaging the edge of the lathe or slicer knife (Lutz 1974).

Anisotropy can influence the amount of heat required to adequately soften the material. Woods with a stronger anisotropy will require higher temperatures and longer to achieve uniform heating temperatures.

5.5 Microstructure and porosity

Similar to species and density, wood's microstructure and porosity (proportion of void) affects its thermal conductivity, with the increased presence of voids reduce thermal conductivity. Other factors like rays and cell boundaries could affect conduction, but voids are the dominant factor influencing heat conduction in wood samples. The bulk structure and inherent chemical composition of the samples do not appear to influence thermal conduction other than their unique microstructure (Suleiman *et al.* 1999).

5.6 Dimensional change

When green wood is subjected to heat, it expands in the tangential direction and contracts in the radial direction. This phenomenon has been confirmed by several researchers for both softwoods and hardwoods. The degree of expansion and contraction varies between species. As the temperature of the wood increases, this thermal movement becomes more pronounced, but the rate of increase is gradual until it reaches around 150°F (65°C), after which it increases more rapidly. Therefore, if a particular wood species is susceptible to developing cracks near the core or split when exposed to heat, it is generally advised not to exceed 150°F (65°C) during the heating process (Lutz 1974).

5.7 Growth stress

Most trees develop growth stresses, with the wood in tension in the longitudinal direction on the outside of the tree and in compression near the pith. As a result of these stresses, logs are susceptible to splitting at the ends when crosscut, depending on the magnitude of the stresses and the strength of the wood in tension perpendicular to the grain. In cases where bolts with high growth stresses are heated, the wood at the bolt ends can become temporarily weakened in tension perpendicular to the grain, which can cause radial cracks emanating from the pith at the ends of the bolts due to growth stresses and dimensional changes. Longitudinal growth stresses primarily affect the two ends of a log. Heating the wood to 180°F or higher can relieve 90% or more of these stresses. If the wood is heated while still in long log lengths and subsequently crosscut to bolt or smaller log lengths, the resulting bolt ends are likely to have fewer splits than if the bolts had been cut to length before heating (Lutz 1974).

6 Energy requirement for heating

The energy needed for heating is influenced by various factors, including the quantity of wood to be heated, the heating system's design and efficiency, scheduling and loading procedures, as well as the ambient air temperature. Heating by steam or water is expected to cost less than electrical heating. Calculations related to the energy required for heating wood should account for the specific gravity and moisture content of the wood since the primary energy usage involves elevating the temperature of both the wood and the moisture it holds. The moisture content in the sapwood of conifers is considerably higher than that in the heartwood. Since smaller trees typically have a greater proportion of sapwood, the moisture content in them tends to be higher than in larger, old-growth trees (Resch *et al.* 1979).

The term "sensible" heat refers to the energy required to elevate the temperature of both the wood and the water it holds from the ambient temperature to the desired temperature. Assuming no other energy losses, the minimum energy required for this process can be mathematically expressed as:

$$Q = W_0 \Delta T \left(c + \frac{M}{100} \right) \qquad \text{Equation 2}$$

where Q is the amount of heat (Btu); WW_0 is the oven-dry weight, of wood, ΔT is the temperature rise; c = specific heat of wood; and M is the moisture content (%).

The energy required to reheat concrete structures and offset heat losses rise with increasing heating times for larger logs and decreasing outside temperatures, but it can be reduced by incorporating better-insulated walls and roofs. This information is pertinent to consider while designing and planning heating systems using concrete structures.

In a heat conditioning system, the total energy consumed can be categorised into four components: A) energy needed to heat the wood and water, B) energy needed to heat the cooled-down concrete structure, C) energy losses due to conduction, convection, and radiation, and D) energy losses due to mechanical issues like leaks or malfunctioning heat exchangers or steam generators. An example calculation of energy required for a typical steam heating plant in western Oregon was provide by Resch *et al.* (1979).

In addition to the operating cost in terms of heat and electrical or gas consumption, log heating requires a significant capital investment in steaming chambers, vats or electrical and control equipment. Since conditioning adds to the production cost, a site-specific economic analysis will be necessary to determine the most appropriate infrastructure.

7 Conclusion

In conclusion, this report provided an overview of the background and literature on log softening before peeling and the various heating methods. It was observed that most of the research on log conditioning was conducted before 1980, and the recommended temperatures were mainly based on experience rather than experimental data, making those results less than optimal for many commercial and plantation-grown timbers. Hence, investigations should be conducted to optimise the softening process, time, and energy consumption for any particular target specie. Currently, it would appear that using a hot water bath or steaming chamber is the most effective and economical way to uniformly heat up logs. Although electric heating or electromagnetic methods are faster, the heating is non-uniform and may incur significant additional costs. It is essential to determine the optimal minimum temperature to reduce operating costs and heating time while considering the cooling during transfer and wait time between the heating and the lathe. The glass transition temperature is crucial to understand the optimum heating temperature, which depends on various factors such as moisture content, species, and wood composition. Therefore, it is important to investigate species-specific glass transition temperature to determine optimal heating conditions. Various factors such as density, moisture content, heating medium, log size, among others, affect the heating rate, so the optimum heating time should be determined based on fundamental study, heat transfer modelling, and experimental study. Mathematical modelling of heat can be used to determine the optimum heating schedule to reduce energy consumption and heating time.

8 Reference

Atack, D. (1981). "Dynamic mechanical loss properties of wood." *Philosophical Magazine A* **43**(3): 619-625.

Aydin, I., G. Colakoglu and S. Hiziroglu (2006). "Surface characteristics of spruce veneers and shear strength of plywood as a function of log temperature in peeling process." *International Journal of Solids and Structures* **43**(20): 6140-6147.

Becker, H. and D. Noack (1968). "Studies on dynamic torsional viscoelasticity of wood." *Wood Science and Technology* **2**(3): 213-230.

Börcsök, Z. and Z. Pásztory (2020). "The role of lignin in wood working processes using elevated temperatures: an abbreviated literature survey." *European Journal of Wood and Wood Products* **79**(3): 511-526.

Calonego, F. W., E. T. Severo, A. R. Cunha and D. C. Gaia (2010). "Use of glass transition temperature for stabilisation of board's cracks of Eucalyptus grandis." *Anais da Academia Brasileira de Ciências* **82**(3): 791-797.

Chen, M., G. Troughton and C. Dai (2021). "Optimum veneer peeling temperatures for selected softwood species using big roller bars." *European Journal of Wood and Wood Products* **79**: 1-9.

Dai, C. and G. Troughton (2011). Effect of log conditioning temperature on veneer quality, Technical report, FP Innovations.

Daoui, A., J. Douzet, R. Marchal and A. Zerizer (2007). "Valorisation of Aleppo pine for peeling: Optimisation of soaking." *Bois et Forêts des Tropiques* **294**: 51-64.

Dupleix, A. (2013). "Feasibility of wood peeling assisted by infrared heating."

Dupleix, A., L. Denaud, L. Bléron, R. Marchal and M. Hughes (2012). "The effect of log heating temperature on the peeling process and veneer quality: Beech, birch, and spruce case studies." *European Journal of Wood and Wood Products* **71**.

Feihl, O. (1972). "HEATING FROZEN AND NON FROZEN VENEER LOGS."

Fleischer, H. O. (1959). "Heating rates for logs, bolts, and flitches to be cut into veneer."

Frihart, C. R. (2005). Wood adhesion and adhesives, CRC Press, New York.

Funakoshi, H., N. Shiraishi, M. Norimoto, T. Aoki, H. Hayashi and T. Yokota (1979). "Studies on the thermoplasticization of wood."

Furuta, Y., H. Aizawa, H. Yano and M. Norimoto (1997). "Thermal-softening properties of water-swollen wood. IV. The effects of chemical cconstituents of the cell wall on the thermal-softening properties of wood." *Mokuzai gakkaishi* **43**(9): 725-730.

Hailey, J. and W. Hancock (1973). "Methods and techniques for veneer-peeling research." *West Forest Prod Lab Vancouver Inf Rep VP X*.

Hamdan, S., W. Dwianto, T. Morooka and M. Norimoto (2000). "Softening Characteristics of Wet Wood under Quasi Static Loading." *Holzforschung* **54**: 557-560.

Hillis, W. and A. Rozsa (1978). "The softening temperatures of wood."

Hoglund, H. (1976). "Physical properties of wood in relation to chip refining."

Huang, M., W. Zhang, X. Zhang, W. Yu, W. Li, X. Liu, S. Wang and F. University (2015). "Factors for Phyllostachys edulis timber glass transition temperatures." *Journal of Zhejiang A* **32**(6): 897-902.

Irvine, G. (1984). "The glass transitions of lignin and hemicellulose and their measurement by differential thermal analysis." *Tappi Journal* **67**(5): 118-121.

Kelley, S. S., T. G. Rials and W. G. Glasser (1987). "Relaxation behaviour of the amorphous components of wood." *Journal of materials science* **22**(2): 617-624.
Kiemen, M. (2023). Steam vs. Hot Water- Pros vs. Cons R. C. Inc.
Kong, L., Z. Zhao, Z. He and S. Yi (2017). "Effects of steaming treatment on crystallinity and glass transition temperature of Eucalyptuses grandis×E. urophylla." *Results in Physics* **7**: 914-919.
Kubinsky, E. and M. Sochor (1968). "New softening treatment for beech logs before rotary peeling to veneers." *For. Prod. J* **18**(3): 19-21.
Kumar, C. (2015). Modelling intermittent microwave convective drying (IMCD) of food materials. PhD, Queenland University of Technology.
Lenth, C. A. and F. A. Kamke (2001). "Moisture dependent softening behavior of wood." *Wood and Fiber Science* **33**(3): 492-507.
Lutz, J. F. (1960). "Heating veneer bolts to improve quality of Douglas-fir plywood."
Lutz, J. F. (1974). Techniques for peeling, slicing and drying veneer, Forest Products Laboratory, Forest Service, USDA.
Lutz, J. F. (1978). Wood veneer: log selection, cutting, and drying, Department of Agriculture, Forest Service.
MacLean, J. D. (1946). Rate of temperature change in short-length round timbers, US Department of Agriculture, Forest Service.
McKenzie, H., J. Turner and C. Shelbourne (2003). "Processing young plantation-grown Eucalyptus nitens for solid-wood products. 1: Individual-tree variation in quality and recovery of appearance-grade lumber and veneer." *New Zealand Journal of Forestry Science* **33**(1): 62-78.
Olsson, A. and L. Salmén (1992). Viscoelasticity of in situ lignin as affected by structure: softwood vs. hardwood, ACS Publications.
Östberg, G., L. Salmén and J. Terlecki (1990). "Softening temperature of moist wood measured by differential scanning calorimetry."
Resch, H. and R. Parker (1979). "Heat conditioning of veneer blocks."
Rohumaa, A. (2016). "The impact of log pre-heating on birch veneer surface quality, bond formation and plywood performance."
Rohumaa, A., T. Antikainen, C. Hunt, C. Frihart and M. Hughes (2016). "The influence of log soaking temperature on surface quality and integrity performance of birch (Betula pendula Roth) veneer." *Wood Science and Technology* **50**.
Rohumaa, A., C. G. Hunt, C. R. Frihart, J. Kers, L. Denaud and M. Hughes (2017). The impact of log heating on veneer quality and plywood performance. 6 th International Scientific Conference on Hardwood Processing.
Rohumaa, A., C. G. Hunt, C. R. Frihart, P. Saranpää, M. Ohlmeyer and M. Hughes (2014). "The influence of felling season and log-soaking temperature on the wetting and phenol formaldehyde adhesive bonding characteristics of birch veneer." *Holzforschung* **68**(8): 965-970.
Rohumaa, A., J. Viguier, S. Girardon, M. Krebs and L. Denaud (2018). "Lathe check development and properties: effect of log soaking temperature, compression rate, cutting radius and cutting speed during peeling process of European beech (Fagus sylvatica L.) veneer." *European Journal of Wood and Wood Products* **76**(6): 1653-1661.
Rohumaa, A., A. Yamamoto, C. G. Hunt, C. R. Frihart, M. Hughes and J. Kers (2016). "Effect of log soaking and the temperature of peeling on the properties

of rotary-cut birch (Betula pendula Roth) veneer bonded with phenol-formaldehyde adhesive." *BioResources* **11**(3): 5829-5838.
Sadoh, T. (1981). "Viscoelastic properties of wood in swelling systems." *Wood Science and Technology* **15**(1): 57-66.
Salmen, L. (1982). Temperature and water induced softening behaviour of wood fiber based materials, Department of Paper Technology, Royal Institute of Technology Stockholm.
Salmén, L. (1984). "Viscoelastic properties ofin situ lignin under water-saturated conditions." *Journal of Materials science* **19**(9): 3090-3096.
Sehlstedt-Persson, M. (2005). Properties of solid wood: responses to drying and heat treatment, Luleå tekniska universitet.
Sen, S., H. Sadeghifar and D. S. Argyropoulos (2013). "Kraft Lignin Chain Extension Chemistry via Propargylation, Oxidative Coupling, and Claisen Rearrangement." *Biomacromolecules* **14**(10): 3399-3408.
Steinhagen, H. P. (2005). "Veneer block conditioning manual for veneer and plywood production." *Maderas. Ciencia y tecnología* **7**: 49-56.
Suleiman, B. M., J. Larfeldt, B. Leckner and M. Gustavsson (1999). "Thermal conductivity and diffusivity of wood." *Wood Science and Technology* **33**(6): 465-473.
Sulzberger, P. (1953). "The effect of temperature on the strength of wood." *Aeron. Res. Cons. Comm. Rep. ACA-46, Melbourne* **17**.
Takahashi, K., T. Morooka and M. Norimoto (1998). "< Preliminary> Thermal Softening of Wet Wood in the Temperature Range of 0 to 200℃." *Wood research: bulletin of the Wood Research Institute Kyoto University* **85**: 78-80.
Timothy Off Heating & Air Conditioning Steam Boilers vs. Hot Water Boilers.
TLV. (2022). "Comparing Steam and Hot Water Heating."
Uhmeier, A., T. Morooka and M. Norimoto (1998). "Influence of thermal softening and degradation on the radial compression behavior of wet spruce."
Wert, C., M. Weller and D. Caulfield (1984). "Dynamic loss properties of wood." *Journal of applied physics* **56**(9): 2453-2458.
Wykle, C. J. (2019). Adhesive Bonding of Low Moisture Hickory Veneer with Soy-based Adhesive, Virginia Tech.
Xu, Y., B. Wang, Y. Shen, J. Wu, L. Feng and H. Yu (2017). "Effect of softening treatment on cutting force during slicing the veneers of common fast-growing wood." *BioResources* **12**(4): 7205-7217.
Yu, Z.-T., X. Xu, L.-W. Fan, Y.-C. Hu and K.-F. Cen (2011). "Experimental measurements of thermal conductivity of wood species in China: effects of density, temperature, and moisture content." *Forest Products Journal* **61**(2): 130-135.