Thermally modified hybrid aspen –
Adding value to fast growing broadleaved species in Northern Europe

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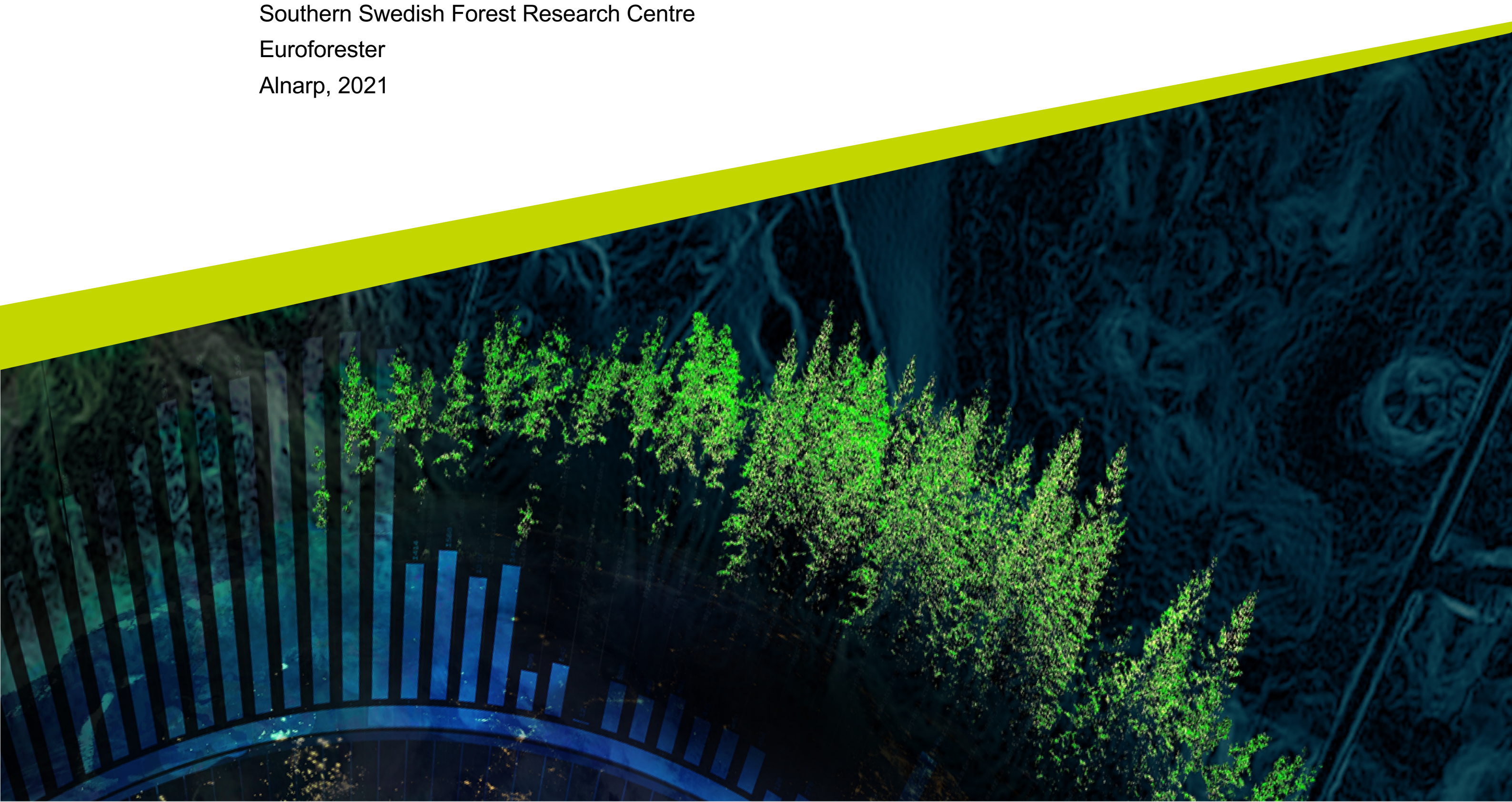

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Abstract

This thesis is focused on thermal modification of hybrid aspen (*Populus tremula* L. x *Populus tremuloides* Michx.), its mechanical properties, wood defects and potential use in construction. In the recent years, wood as a building material has become increasingly popular. It is preferred because of its aesthetic appeal; it is renewable and substitutes fossil-based energy consuming materials. However, greater use of wooden products can also put more pressure on our natural forests.

The main problems discussed in this paper were: mechanical characteristics after intense thermal modification and overall quality characteristics of thermally modified hybrid aspen.

The present thesis conducts an empirical research of harvesting model trees, band sawing them into boards and kiln-drying, in order to prepare samples for thermal modification. Specimens were prepared for compressive strength, bending strength and wood density testing. Mechanical tests were carried out following the standards of ISO 13061-17, ISO 13061-3 and ISO 13061-2, accordingly. Furthermore, thermally treated sample boards from hybrid aspen (*Populus tremula* L. *x Populus tremuloides* Michx.*),* were evaluated according to 14 predetermined quality characteristics.

Thermally modified hybrid aspen showed lower wood density and lower bending strength, but higher compressive strength in comparison with untreated hybrid aspen material. Wood quality evaluation showed that hybrid aspen had almost two times more wood defects compared to European aspen. Thermal modification process had statistically insignificant effect on measured wood quality.

As a result, it can be said, that despite the decrease of some mechanical properties, thermally modified hybrid aspen still has a potential in areas where load bearing abilities are not so important, for example sauna interiors and interior panelling.

Keywords: Thermally modified wood; wood quality; short-rotation forestry; Hybrid aspen, European aspen, *Populus tremula x tremuloides*

1.Introduction

1.1 Issue and background

Hybrid aspen (*Populus tremula* L. × *Populus tremuloides* Michx.) is one of the fastest-growing hardwoods in Europe (Rytter, 2006; Tullus et al., 2012). Due to prevailing demand the establishment of intensively managed forest plantations or more commonly known as short-rotation forestry (SRF) has spread from the southern regions to the northern regions of Europe. During the last decades, over 4500 ha of land has been cultivated with hybrid aspen in Baltic states and Nordic countries. Large areas of abandoned agriculture land in Baltic region can be used for planting stands of fast-growing decidious tree species (Lutter 2017; Tullus et al., 2012). Hybrid aspen is considered to be one of the most promising tree species for SRF in the Baltic region (Rytter, 2018).

Greater utilization of hybrid aspen plantations is mainly driven by three factors:

- The need to absorb and store atmospheric CO2 and mitigate climate change (Sustainable development goals 2030)
- Pressure to reduce timber harvesting operations in natural forests of boreal and temperate zones (Brockerhoff et al., 2008)
- The need for natural resources (Barua et al., 2014; McEwan et al., 2020).

Plantations take up a relatively small area of total forested land, but they give a very considerable proportion of world's timber production. The area of cultivated semi-natural forests in 2015 was 7% of the total forested area and it has been steadily increasing by almost 5 million hectares every year on average (FAO, 2010; FAO 2015).

Forest plantations and more importantly hybrid aspen plantations have the potential to produce a large proportion of the world's wood needs (Siry et al. 2005). Hybrid aspen is suitable for producing large amounts of renewable biomass in short rotations and it is one of the most favored species in forest plantations on abandoned agricultural lands (Hjelm & Rytter, 2018). Often the plantations of hybrid aspen are aimed at intensive production of bioenergy and pulpwood (Tullus et al., 2012; Pleguezuelo et al., 2015).

Due to a similar heating value compared to other fast growing tree species, aspen is mainly used for producing pulpwood, but a large share is also used for energy production. Heating value of three-year-old hybrid aspen shoots is 18.608MJ kg^{-1} (Hytönen et al, 2018 ; Hytönen, 2018). Compared to more widely used *Salix* spp., hybrid aspen gives similar results in heat energy and ash content (Klašnja, 2013), but it has an advantage over other energy crops as it can be used for pulpwood production in case the bioenergy market is low.

Both European aspen (*Populus tremula* L.) and hybrid aspen are ideal as a raw material for paper industry, because their wood has good fibre properties (Tullus et al., 2012). Aspen wood stands out because it has high content of cellulose and low content of lignin (Sable et al., 2017).

Despite this, the growing population of people do not only require pulp, paper and bioenergy,they also need wood as a building material. Demand for round-wood is predicted to reach six billion cubic meters by year 2050 (Barua et al., 2014). This means that the pressure on our forested lands will grow tremendeously, especially for natural and semi-natural forests (Barua et al., 2014). In the last years, private forest owners have become more interested in producing good quality round wood for sawmills, to earn price premium for sold material. Some of them think that poplar wood can be used as a lumber to produce long lasting products (Arlauskas, 2020).

Hybrid aspen seems to be a good solution to withstand many challenges of our inevitable future. In this thesis I am trying to answer one question, that has has been left unanswered: „How does thermal modification change the properties of hybrid aspen wood?".

1.2 Sustainable development of hybrid aspen plantations

Plantations can't replace social and environmental aspects of natural forests, but both plantations and natural forests can have many common functions. Incorporating plantations across spatial scale and creating mosaic pattern of landscape has had big effects in enhancing ecological footprint in many parts of the world (Payn et al., 2015). Establishing plantation forests on degraded forest lands, abandoned mining areas and low quality agricultural lands can make a huge difference on the livelihoods of people living in third world countries, potentially helping them out of poverty (Assirelli et al., 2016 ; FAO, 2010). Well managed, plantations can offer a substantial amount of ecosystem services and allow more areas to be left out of management for conservation purposes (Silva et al., 2018).

Plantation forestry is often seen as something negative, especially from a biodiversity and species richness standpoint. However it doesn't have to be that way, when forest owners take into account environmental impacts of plantations and try to balance and improve forest management. Problems such as soil nutrition loss and decreased biodiversity can be avoided with proper forest management (Freer-Smith et al., 2019).

There are multiple actions forest owners can take, in order to maximize economical and social returns and at the same time avoid irreversable environmental impacts. Some of them involve:

- Reduction of clear-cut area or creation of mosaic pattern over a larger spatial scale helps to stop the loss of nutrients through erosion or surface runoff.
- Choosing seasons of mechanical intervention, in order to minimize negative effects of timber harvesting, wood transport and road construction on sensitive soils.
- Establishing plantations on abandoned, marginal and contaminated lands to protect the land necessary for food production.
- Using a mixture of species when creating plantations to make them more resilient to changing climate conditions.
- Planted species have to match with local conditions in order to minimize possible pest and diseases outbreaks while reducing susceptibility to abiotic disturbances.
- Acknowledging wide array of stakeholder perceptions and making an effort to bring them together is important for making plantation forestry acceptable among the general public (Cristan; et al., 2016; FAO, 2010; FAO, 2015; Freer-Smith et al., 2019).

Fast growth of plantation forestry improves carbon sequestration and therefore mitigates climate change (Arlauskas, 2020). Agriculture systems have a bigger impact on the land then intensively managed forest plantations. This is mainly due to the amount of fertilizers and pesticides used in farming different crops (Freer-Smith et al., 2019). Furthermore a well developed root system in poplar plantations shows a promise to act as a filter and purify polluted water (Christersson, 2010).

Forest plantations can have a positive impact on sustaining or enhancing local biodiversity in some areas (Kanowski, 2005). Due to greater structural diversity and tree species complexity, hybrid aspen stands can support relatively high levels of biodiversity (Lindbladh et al., 2014). Compared to spruce monocultures, studied hybrid aspen plantations held a greater abundance and higher species richness in avian biodiversity (Lindbladh et al., 2014). Likewise the undergrowth of second generation of hybrid aspen plantations is diverse. In a study carried out in hybrid aspen plantation in Estonia, 71 vascular plant species, 21 moss species and 24 lichen species were found (Tullus, 2018).

1.3 Challenges and opportunities of thermally modifying hybrid aspen and European aspen

Using thermal modification for improving the mechanical properties of wood is not a recent development, first research on this topic was done almost a century ago (Candelier et al., 2016). Thermal treatment is based on the idea of polymer changes under increased temperatures. It has to be done in a chamber with poor oxygen access to prevent the material from burning. In return, environmentally friendly material which has increased biological durability and dimensional stability, while having reduced hygroscopicity, can be produced (Candelier et al., 2016). This result is obtained without any additional chemicals, only heat, steam and water are used in the process of thermal modification. Thermal treatment induces a darker coloration of wood which enhances the appearance of less attractive wood and can make it more desireable among customers (Chen et al.,2012). It is one of the most advanced methods on the market with a high economic importance (Gérardin 2015).

Multiple disturbances can endanger our forests and in the worst case scenario timber stocks might be insufficient to meet the future demand of forest industry. When this happens, fast growing species like hybrid aspen can become important for filling the gap. For example hardwoods such as European ash (*Fraxinus excelsior L.*) are commonly used for thermal modification (Stachowska et al., 2020), ash has proved to give desired look and good durability in demanding weather conditions. However when European ash is compared to hybrid aspen, it can be seen that they have completely different mechanical properties. These species can't replace each other, however European ash population is severely declining due to ongoing pandemic of ash dieback. It is one of the most serious problems in European forests and threatens keystone species on a continental scale (Agan et al., 2020).

Same applies to coniferous tree species commonly used for thermal modification. For example Norway spruce (*Picea abies* Karst.) stands are not in a good shape at all. Bark beetle (*Ips typographus* L.) is causing severe damages in Central Europe, more then forest owners can possibly cut.

One of the possible advantages with thermally modified hybrid aspen is that its low biological durability can be improved. Thermal treatment could enable us to use hybrid aspen in a broader array of application. By lowering the hygroscopicity, thermally modified wood can possibly be used in temporarily humid areas such as sauna interiors or facades (Lahtela, 2021).

On the other hand thermal modification also has its own challenges, some of them include weaker bending strength and lower wood density, which can make thermally modified wood too weak to be used for load bearing applications.

Wood is not a homogeneus material at all, therefore it is almost impossible to predict how thermal modification process affects its quality. Thermal treatment has an inclination towards creating wood defects, common problems include cracks, splits and fissures. Often these imperfections are the result of tensions in the wood (Heräjärvi & Junkkonen, 2006). There is a clear correlation between the density of wood and tension induced problems. Denser wood usually means that wood holds more tensions, which cause problems during thermal modification. This brings us to a good opportunity of thermally modifying hybrid aspen. Aspen, especially hybrid aspen, has a low mean density of around 400 kg/m^3 according to Heräjärvi & Junkkonen, (2006) and a weak cellular structure. Meaning that in theory it can be treated with less errors, since the wood doesn't have so many tensions. Wood species of lower densities generally adapt more easily to thermal treatment than those of higher density (Candelier et al., 2016).

What if it is possible to make more out of our fast-growing broadleaved tree species, other than just pulpwood and wooden chips for bioenergy? What if long lasting products that also help with carbon sequestration, could be made from fast growing broadleaved tree species?

Study aims

The aim of the study is to find out if hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) can be used to produce good quality thermally modified wood.

The research questions are:

- Is it possible use thermally modified hybrid aspen in construction, the same way as untreated European aspen?
- To what extent does intense thermal modification affect compressive strength, bending strenght and wood density of hybrid aspen?
- Is low density the key element of producing straight thermally modified wood?
- Does hybrid aspen sawn material have more knots compared to European aspen?

2.Materials and methods

2.1 Site description

The trees were cut at an experimental site located in Nõgiaru, Nõo Parish, Tartu County, Southern Estonia (coordinates N58° 326487 ” E26° 555084). Particular hybrid aspen plantation was established in the year 2000 on a fertile land that was formerly used for agriculture. There are two reasons why I chose this site for collecting samples. Firstly because this stand is well studied and there is plenty of scientific information available. Second reason was more practical, the site is very close to the wood laboratory of Estonian University of Life Sciences and this simplified further processing of the logs.

According to the measurements of Tartu meteorological station the length of the growing season in Nõgiaru is 188 days year^{-1} (B.Viru, 2014). Annual mean temperature and minimum temperature are 6,3 °C year^{-1} and -32,4 °C year^{-1}. Mean annual precipitation is 673mm with snow covering the ground 110 days year^{-1}. Data has been obtained from Tartu-Tõravere weather station (Ilmateenistus 2020) . Figure 1 shows a map of Estonia with the study area marked in red.

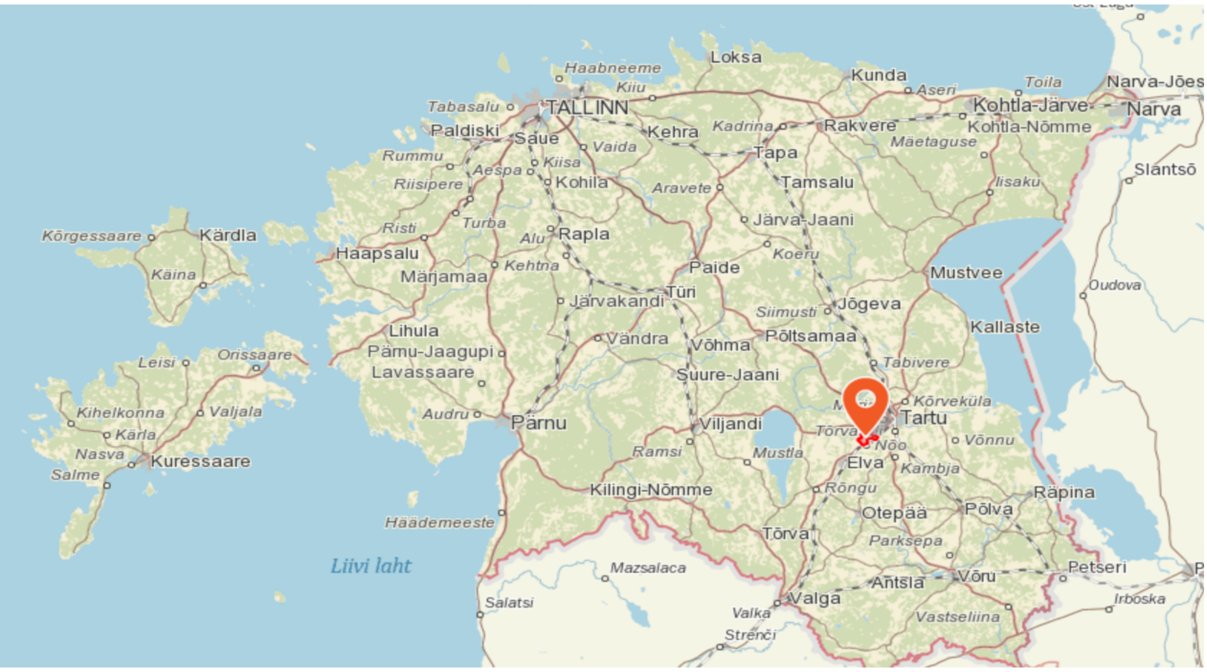

Figure 1. *Map of study area in Nõgiaru, Southern Estonia. Red polygon marks the location of Nõgiaru village.*

Soil characteristics on the site are very fertile, first layer of humus reaches the depth of 24-26 cm. Second layer consists of small granite pebbles (moraine) in the diameter of 1-10cm, mixed with sandy-clay. Third and the last layer is bedrock which is sandstone (Maa-amet, 2021).

Volume of rocks over the diameter of 20 cm, is between 5-20m3/ha. According to national land office maps this stand is growing on one of the most fertile soils in Estonia (Maa-amet, 2021).

Prevailing soil type in this region is Automorphic (well-drained) Luvisol (Soil Atlas of Europe, 2021). Site properties have to be taken into consideration when planting *Populus* sp. (Mc Carthy, 2016).

2.2 Description of the first generation stand

Nõgiaru hybrid aspen plantation was established in the year 2000 with 1 year old seedlings and this year it will make the stand 22 years old. 27 Finnish origin bare rooted clones (C05-99-8 until C05-99-34) were used as a planting material. Mean planting density for the stand was 1300 plants per hectare and the trees were planted in rows with spacing of 2-2,5 x 3-3,5 m. Clones were planted randomly across different experimental plots. On average one experimental site consists of 15 different clones (R.Lutter, 2015).

Whole-area or strip ploughing site preparation methods were used before planting. (R.Lutter, 2015).

2.3 Management of the first generation stand

All hybrid aspen sapplings were protected after planting with 0.3-0.6 m biodegradable plastic tubes to protect trees from rodents and hare (*Lepus* sp.*)*. Study area is not fenced and has no protection from game damage (Tullus et al., 2007).

No thinning or pre-commercial thinning regimes have been carried out in the study area. Experimental site has not been fertilized and no additional irrigation has been used. Trees have not been pruned, lower dead branches are still attached and affect the quality of sawn wood.

Pruning enhances wood quality of hybrid aspens, but it has to be done early when the branches are small to minimize the possibility of developing discoloration and rot (Rytter L., Jansson G., 2009).

2.4 Sampling methods used in choosing trees for the experiment

Simple random sampling was used for choosing the trees to produce samples for the experiment. Total selection size for the experiment was 4 rows of 25 trees each, 100 trees in total. The rows were taken from the middle of the experiment to avoid edge effects.

In order to extract our sample trees from the selection list, a random number function (1) in Microsoft Excel was used.

$$\begin{gathered}\mathbf{=INT(RAND()*100)}\\ \mathbf{P=1- N-1/N.N-2/N-1\ldots.N-n/N-(n-1)}\\ \mathbf{Cancelling=1-N-n/N}\\ \mathbf{=n/N}\\ \mathbf{=4/100}\\ \mathbf{=2{,}5\%}\end{gathered} \tag{1}$$

This gave a random whole number that was equal or greater than 0 and less than 100. Meaning that every tree had a equal probability of inclusion in our selection with a chance of 2,5% to be chosen for the experiment (H.Taherdoost, 2016).

2.5 Origin of the dimensional lumber used for comparison and control

Thermally modified samples for comparison group (B), were produced using the exact same method (recipe) and in the same oven, but together with a different batch of material. Please see section 2.9 for description of sample groups (A-D).

Dimensional lumber for comparison group (B) and control group (C), was chosen from 3246 untreted European aspen (*Populus tremula*) packages stored in Thermory AS warehouses. Packages were first filtered by the origin, which had to be local (Estonian). Local origin was important for lowering the possibility of big genetical differences. 1132 packages fit into this selection, a total of 2 packages were chosen for comparison group (B) and control group (C) out of the selection list. Exactly the same simple random sampling method was used as described earlier in this research paper (Section 2.4). Following two numbers were obtained using the random sampling method: 1019 and 827.

Thermal modification was done to 80 sample boards out of the 87 samples (Section 2.7.2), which came from the drying-kiln. 7 boards were taken out to make Control group (D) – untreated hybrid aspen for wood density comparison.

Dimensional lumber for testing was obtained from Thermory AS, together with a possibility for thermal modification. This company was chosen, because it is currently the largest thermally modified wood producer in the world and it holds great practical knowledge on thermal modification. Thermory AS has been operating in this field for the last 20+ years (Thermory AS, 2021).

2.6 Felling of the sample trees

Following four numbers were obtained using the random sampling method: 75,26,33,30. Based on the numbers trees were cut, shown on Figure 2.

Figure 2. *Felling of selected sample trees for the experiment, in Nõgiaru, Tartu County (04.02.2021)*

Since the main purpose of this research is to evaluate quality of the wood, it is important to note that the risk for possible sampling error was very low. This is because plantation forests have very homogeneous stand characteristics (Mc Evan et al., 2020). Measurements of the trees used for the experiment can be found in *Table 1*.

Table 1. *Measurements of the selected Finnish clones.*

Tree number	Genotype	Mean diameter (cm)	Mean height (cm)
75	C05-99-8 until C05-99-34	33,0	25,7
26	C05-99-8 until C05-99-34	31,7	26,1
33	C05-99-8 until C05-99-34	29,2	26,5
30	C05-99-8 until C05-99-34	34,2	24,3

Trees were felled in -26 °C degrees Celsius and the ground was covered with 40-50 cm of snow. Other than the origin, it is not known exactly which clones were used in the experiment.

2.7 Prepearing of dimensional lumber for the experiment

Dimensional lumber from hybrid aspen Finnish clones (C05-99-8 until C05-99-34) was produced in the wood laboratory of Estonian University of Life Sciences. Total of 87 samples (2500mm x 100mm x 32mm) were obtained from four sample trees. In this part of the experiment, stem was used in 2500mm lengths, all the way to the top. Logs with diameter of 14 cm or less (measured from the smaller end) were not used. Preparation of dimensional lumber can be seen on Figure 3.

Figure 3. *Sawing timber into dimensional lumber in wood laboratory of Estonian University of Life Sciences*

The logs were first sawn in half from the pith (commonly known as the „**breaking cut**“) and then into 32mm thick slabs. Edges were removed on a table saw manually.

2.8 Kiln-drying and thermal modification of the samples

2.8.1 Drying process

Sawn and edged boards were bundeled together (See Appendix B for Photos of sample preparation), in order to be sent into a drying kiln. Total of 87 boards were stacked to form a bundle.

A wooden stick was placed between every layer of the boards to ensure uniform air movement during the process. Moisture content of the „green“ boards was 34-39 % and it was brought down to 10-12% for thermal modification. Drying process took 15 days in total.

2.8.2 Thermal modification process

Hybrid aspen and European aspen samples were both treated in the exact same open system thermo-oven in Thermory Loo factory, simplified graph of the process can be seen on Figure 4.

Thermal modification process took a total of 62.4 hours to complete. The recipe for thermal modification differs among tree species, this test was done with the parameters specially made for 32mm x 100mm dimension European aspen. Material in this dimension is normally used for sauna bench boards.

Sample boards that came from the drying kiln where not re-stacked in any way before thermal modification process, only the straps that held the bundle together were changed from plastic to metal. During this process 7 boards from the top layer were taken out, for measuring wood density.

Most commonly aluminium sticks are used between boards instead of wooden sticks. This is mainly due to two reasons, aluminium lasts longer and it doesn't take water in. When the moisture content is higher in the wooden sticks compared to the material, it can leave deep discoloration on the wood.

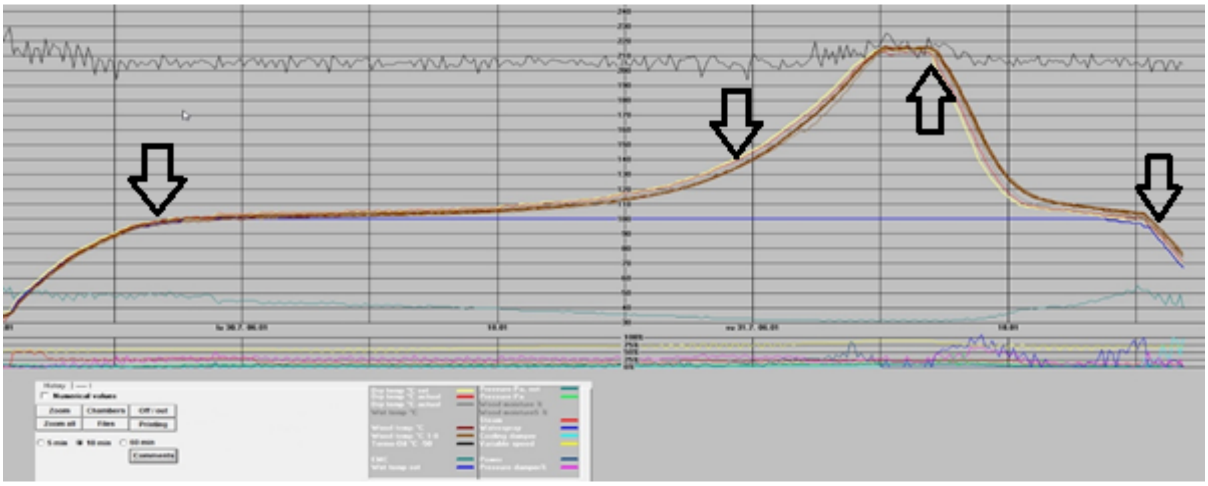

Figure 4. *Simplified process of producing thermally treated wood. Brown and yellow lines show the temperature inside thermo-ovens, 8 lines indicate thermometers that are used to ensure uniform temperature. The arrows coincide with the points below, accordingly (Modified from source: Thermory AS 2021)*

The process of thermal modification can be dividend into four different phases.

- Removing of the water from the wood by heating it to 100°C degrees Celsius.
- Extractives, which include terpenes, fats, waxes and phenols evaporate from the timber, temperature is slowly increased from 100°C degrees Celsius to 190°C degrees Celsius. Thermowood achives its characteristic brown color in this stage.
- Moisture content is increased to 4-7% by adding steam and water, timber is left to equalize.
- Last is cooling and stabilization of the boards, this phase is important, because too fast changes in temperatures may cause cracks and fissures in the wood.
-

No chemicals are used in the production of thermally modified wood, only steam, water and heat are used in the manufacturing process (Lahtela, 2021).

Thermal modification ovens that were used, hold between 30-40 m3 of wood and are very expensive to run. Most commonly natural or biogas is used to heat the ovens. Wood based material can’t be used since it doesn’t ensure the consistency of heat. Gas is more controllable in order to achive desired and consistent temperatures.

2.9 Comparative experimental design and statistical analysis of sample quality

Prepared dimensional lumber samples were 2500mm long, 100mm wide and 32mm thick. The sample quality experiment consisted of three treatments:

Group (A) - Thermally modified hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.)

Group (B) – Thermally modified European aspen (*Populus tremula* L.)

Control group (C) – European aspen without thermal modification

Control group (D) – Hybrid aspen without thermal modification (used only for density comparison)

Groups (A), (B) and (C) consisted of 80 samples each. Group (D) consisted of 7 samples.

The experiment was made up of two thermally modified tree species, European aspen (*Populus tremula*) and hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) and untreated

European aspen for control. This is a multiple factor design, with three treatments (A, B and Control).

Factors measured in the design are as follows: spike knot, edge knot, broken knot, dead knot, bark knot, knot hole, end split, checks, fissures and shakes. This means that every single board was evaluated multiple times to find defects, one defect at a time.

Factors such as: insect holes, blues stain, mechanical damages, wane and feed-roller marks were left out of the experiment, beacause they are irrelevant in measuring quality coming from the actual differences of the wood. These factors arise only in the poor processing, handling or managing of the wood.

Geometrical values such as spring, bow, twist, and cup were also counted as defects, when they were not in accordance with values stated in Thermory AS grading rules (Figure 5). Measuring was carried out according to the standard EN 1611-1 (See Appendix. A for detailed description).

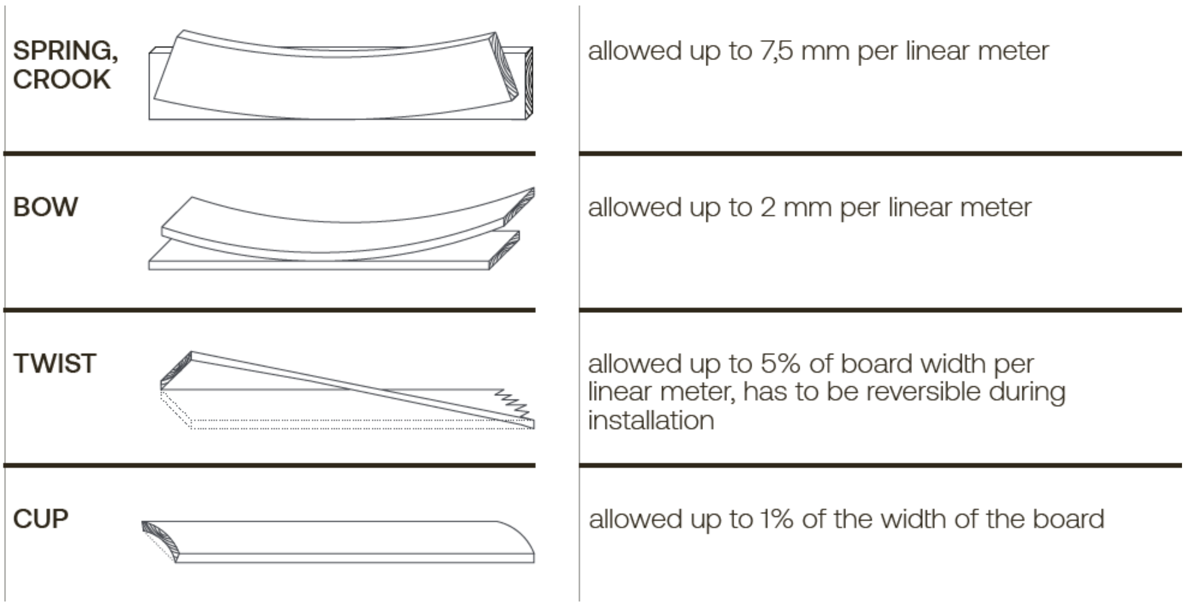

Figure 5. *Excerpt from Thermory AS grading rules (Thermory, 2021)*

Every measured defect mentioned before raised the score for the board by 1 point. Multiple defects of the same factor were still counted as 1. Maximum score for one board could be 14 and minimum 0. This score will be called wood defects index.

Control part plays a key role in ruling out any major qualitative changes, which might happen during thermal modification of the dimensional lumber.

Thermally treated sample groups (A) and (B) with sample size n=80 in both groups, were compared to each other and then to a control group (C) with n=80. This was done using a single factor analysis of variance (ANOVA).

After finding significant differences between groups, Tukey's HSD was used for performing a post-hoc test. A *p-value* of <0.01 was used as a cut off for significance level. Statistical calculations were performed in Microsoft Excel.

Additionally, all the knots on the better face of the boards in groups (A) and (B), were counted.

2.10 Measuring mechanical properties of thermally modified hybrid aspen

The following mechanical properties were measured in the study: compression strength, bending strength and wood density. Testing was done as stated in standards ISO 13061-17, ISO 13061-3 and ISO 13061-2, accordingly. All of the specimens that were used in the mentioned tests, were obtained from the same starting material with a cross section of 20 mm x 20 mm. Specimen were only cut from clear wood (no defects was allowed).

For compression tests, samples with 20 mm x 20mm cross-section and 30 mm height were prepared. Bending tests required samples with 20 mm x 20 mm cross-section and 300 mm height.

Both compression and bending tests were made using testing system INSTRON 3369 (Instron Corp., Norwood, MA, USA). For flexural testing INSTRON load cell capacity of 50kN and testing speed of 1400 ± 150N/min was used. Compression tests were done with testing speed of 1-3mm/min and with force of 25000 ± 5000N/min (Kask, 2015). 25 samples were used for both tests. The mechanical testing was carried out with air-dry moisture content of 8,8%. Strength properties change together with the moisture content of wood (Roszyk et al., 2020).

In order to measure oven-dry wood density, 27 pieces from untreated hybrid aspen and 27 pieces from thermally modified hybrid aspen. Samples with dimensions of 20 mm x 20 mm x 30 mm were measured with electronical caliper and weighed on a scale with an accuracy of

0,001 grams. Following equation (2) was used in Microsoft Excel to calculate wood density for both groups:

$$\mathbf{(h_1 * l * h_2) / 10^9 = A}$$

$$\mathbf{(1 / A) * m_1 = B} \qquad \mathbf{(2)}$$

$$\mathbf{B / 1000 = \rho\ (kg/m^3)}$$

Where ρ is wood density in kg/m^3

h_1, l, h_2 = dimensions of the material in millimeters

A = volume in cubic meters

M_1 = mass of the material in grams

B = mass of 1 cubic meter in grams

To assess the possibility of using hybrid aspen wood in construction, bending test results were compared against the lowest grade found in EN 1912:2004: Structural timber Strength classes-Assignment of visual grades and species. In order to recieve the lowest strength class (C14), samples need to withstand a force of 4800 N. This is called modulus of elasticity test or in other words bending strength.

3.Results

3.1 Mechanical properties of thermally modified hybrid aspen

3.1.1 Compressive strength

Mechanical properties namely compressive and bending strength and wood density are extremely important. Especially when the wood is used in certain types of load bearing construction elements (Bjurhager et al., 2008).

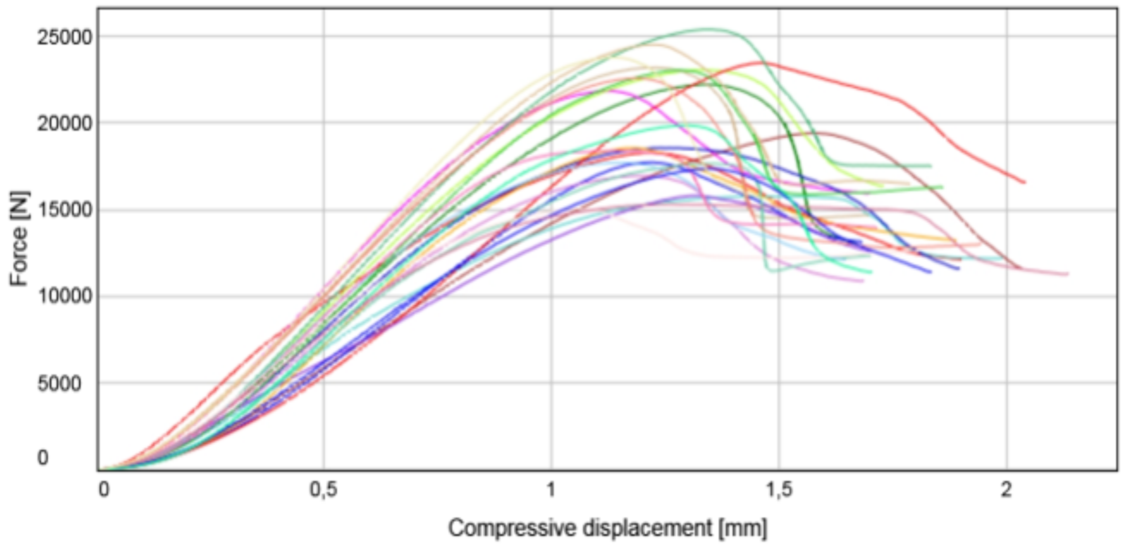

Figure 6. *Force applied to thermally modified hybrid aspen samples, measured in newton units (1 $kg{\cdot}m{\cdot}s^{-2}$) . Culmination of graph indicates beginning of deformations in the fibre structure due to excessive compression. Test was carried out according to standard ISO 13061-17 (Determination of ultimate stress in compression parallel to grain). Each line stands out for one sample, 25 lines in total.*

Compression strength had substantial differences between thermally modified samples and it ranged from 36,72 N mm^{-2} to 61,22 N mm^{-2}. Mean value of the hybrid aspen samples was 48,10 N mm^{-2} with a standard deviation of 7,61 N mm^{-2} (See Appendix C for images from the procedure). Measured mean value was notably higher than the mean values reported by Zeps et al. (2016) for untreated hybrid aspen clones and European aspen: 32,6 N mm^{-2} and 30,3 N mm^{-2}, respectively.

Results indicate that intense thermal modification at 190 degrees Celsius, increased the mean compressive strength of tested samples by 33,25 percent in comparison to untreated hybrid aspen samples. Furthermore, untreated European aspen showed signs of fibre deformation at a 37 percent lower force.

3.1.2 Bending strength

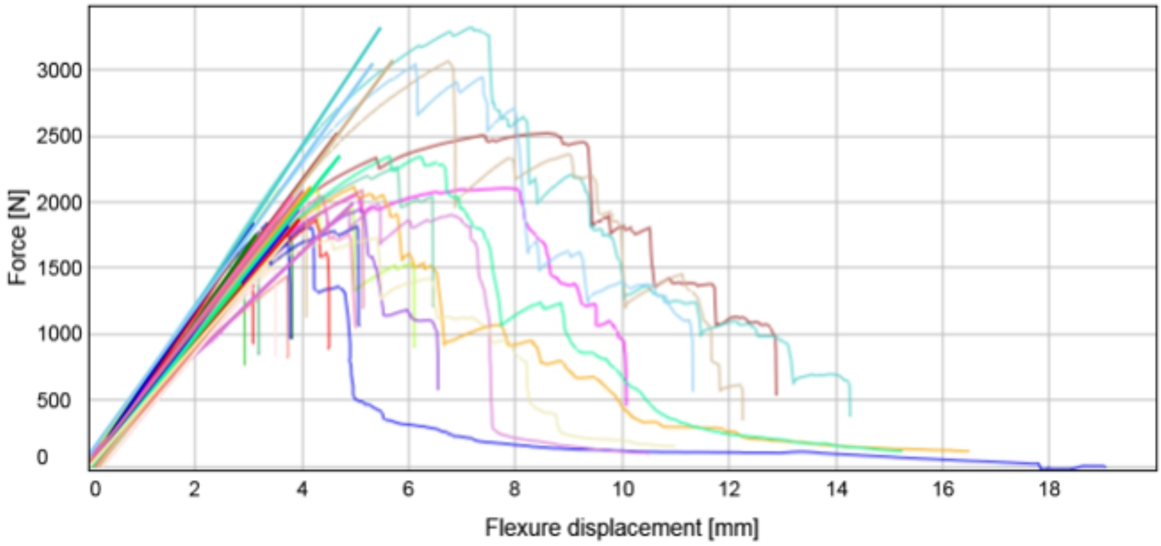

Figure 7. *Static load applied to simply supported thermally modified hybrid aspen samples, measured in newton units (1 kg·m·s^{-2}). Graph indicates maximum force applied until failure of the samples. Test was carried out according to standard ISO 13061-3 (Determination of ultimate strength in static bending). Each line stands out for one sample, 25 lines in total.*

Bending strength test showed notable variability between samples, it was from 94,31 N mm^{-2} to 39,86 N mm^{-2}. Mean value of thermally modified hybrid aspen samples was 58,33 N mm^{-2} with a standard deviation of 14,37 N mm^{-2} (See Appendix C for images from the procedure).

Measured mean value of bending strength or MOR (modulus of rupture), was remarkably lower than the mean values reported by both Zeps et al. (2016) and Heräjärvi H. (2009), for untreated hybrid aspen clones and untreated European aspen: 66,2 N mm^{-2} and 71,50 N mm^{-2}, respectively.

Intense thermal modification decreased the Bending strength of hybrid aspen samples by 11,88 percent compared to untreated samples. In comparison to untreated European aspen the difference was 18,41 percent.

Minimum requirement for obtaining structural timber strength class C14, is the ability to withstand a force of 4800 newtons. Best sample held 3077 newton units of force before failure. For this reason, thermally modified hybrid aspen wood can not be considered suitable for load bearing applications.

3.1.3 Wood density

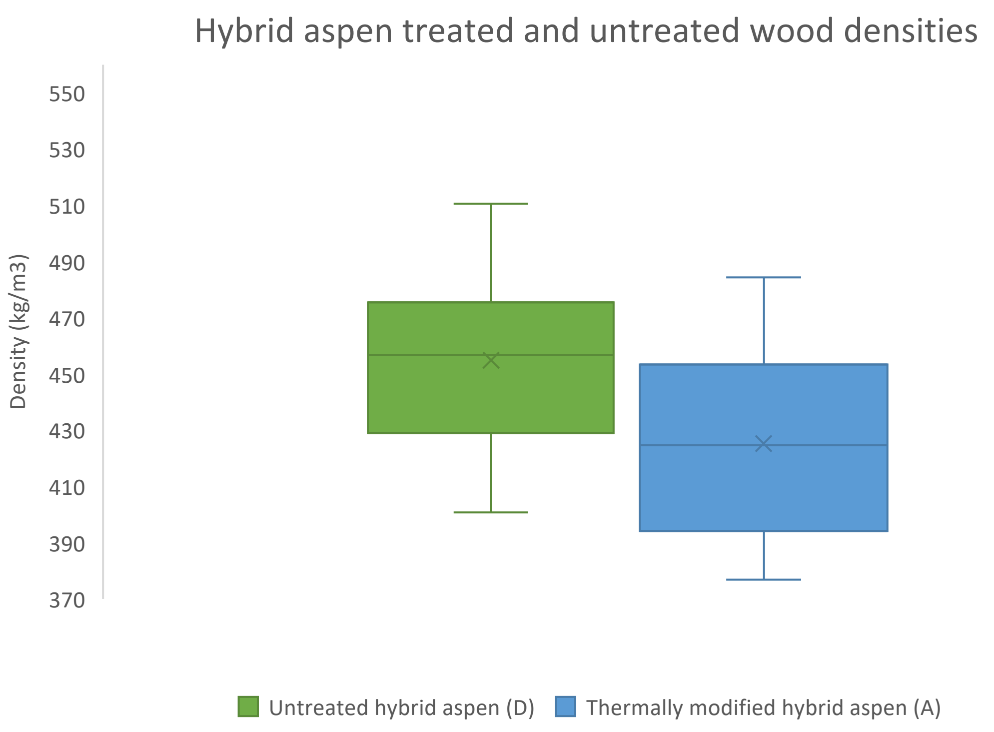

Figure 8. *Untreated hybrid aspen density (D) and thermally modified hybrid aspen density (A) in kg/m3. Test was carried out according to the standard ISO 13061-2 (determining the density of wood for physical and mechanical tests on small clear wood specimens). 27 samples were measured for both sample groups (D) and (A).*

Untreated hybrid aspen samples had a mean density of 456,8 kg/m^3 with a standard deviation of 29,2 kg/m^3. In control group (D) the density ranged from 400,8 kg/m^3 to 510,45 kg/m^3.

Thermally modified hybrid aspen samples showed mean denstiy of 425,2 kg/m^3 with a standard deviation of 31,6 kg/m^3. In group (A) the density varied from 376,9 kg/m^3 to 484,8 kg/m^3. Thermal modification decreased hybrid aspen wood mean density by 6,91 percent. Comparison between untreated wood densities found in the literature (Table 2) and measured wood densities diviated from each other.

Table 2. *Untreated hybrid aspen and European aspen densities listed in literature References: [1] Heräjärvi H, Junkkonen R (2006), [2] Tsoumis G (1991), [3] Säll H, Källsner B, Olsson A (2007), [4] Zeps et al., (2016); (ad) – air-dry density; (bd) – basic density; (ad/tm) air-dry density after thermal modification*

Species	Density (kg/m3) measured in this paper	Density (kg/m3)
European aspen	-	460 (ad) [2], 440 (ad) [3], 423 (ad) [3], 376 (bd) [1]
Hybrid aspen	425 (ad/tm), 457 (ad)	363 (bd) [1], 383 (ad) [4]

3.2 Observed wood characteristics and comparison between species

One-way ANOVA was carried out to compare the effect of tree species selection on observed wood defects index. This index consisted of previosly mentioned wood defects: spike knot, edge knot, broken knot, dead knot, bark knot, knot hole, end split, checks, fissures, shakes, spring, bow, twist, and cup .

ANOVA results showed that there was a statistically significant difference in wood characteristics between atleast two groups.

Tukey's HSD test indicated that the mean value of wood defects was significantly different between groups (A) and (B) as well as groups (A) and (C). Thermally modified hybrid aspen had significantly more defects than both modified and untreated European aspen.

There were no statistically signifiant differences between groups (B) and (C), see Table 3 for *P-values*. Between European aspen groups the differences in wood defects index was insignificant. Thermal modification process itself did not change measured index significantly.

The results of Tukey's test clearly show a significant difference between tree species. However the effect of thermal modification on wood defects index seems to be mild.

Table 3. *Results of Tukey's HSD test for comparing wood defects index between sample groups*

Groups	Tukey HSD	Tukey HSD	Tukey HSD
	Q statistic	p-value	inference
A vs B	15.4286	0.0010053	p<0.01
A vs C	14.4105	0.0010053	p<0.01
B vs C	1.0181	0.7325027	insignificant

Hybrid aspen showed a mean of 4,32 quality defects per board with a standard deviation of 1,90 defects, while the European aspen samples only showed a mean of 1,94 quality defects per board with a standard deviation of 1,21 defects. See figures 9, 10 and 11 for detailed overview of counted defects.

Hybrid aspen boards in group (A) counted for 17,8% more knots on the better face of the boards, than measured European aspen boards in group (B).

A total of 657 defects were counted on 240 boards that were used in the evaluation process. When geometrical defects are summarized: spring, bow, twist and cup, we can see that hybrid aspen boards are more crooked then European aspen ones. Geometrical defects in group A (40 defects), in group B (26 defects) and in group C (30 defects).

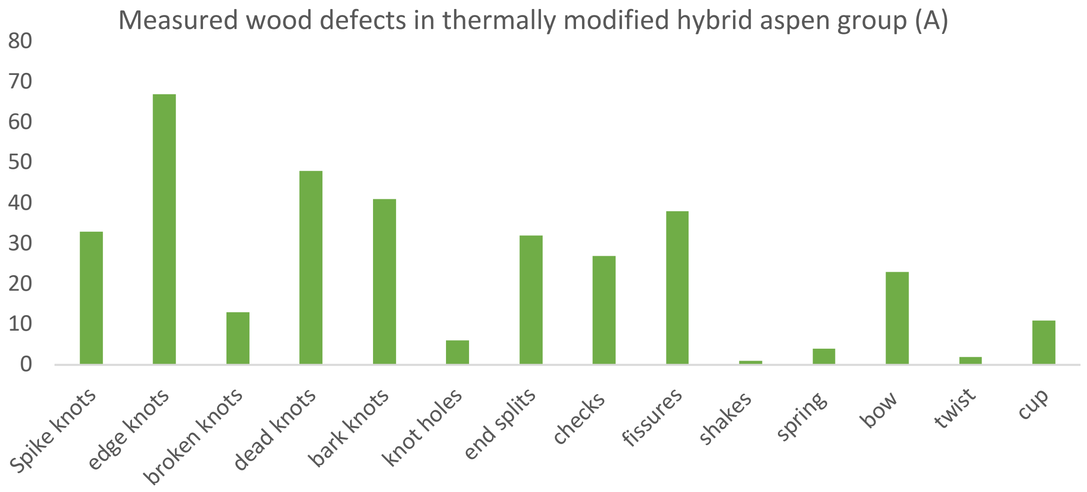

Figure 9. *Measured thermally modified hybrid aspen wood defects in detail. 80 sample boards in total.*

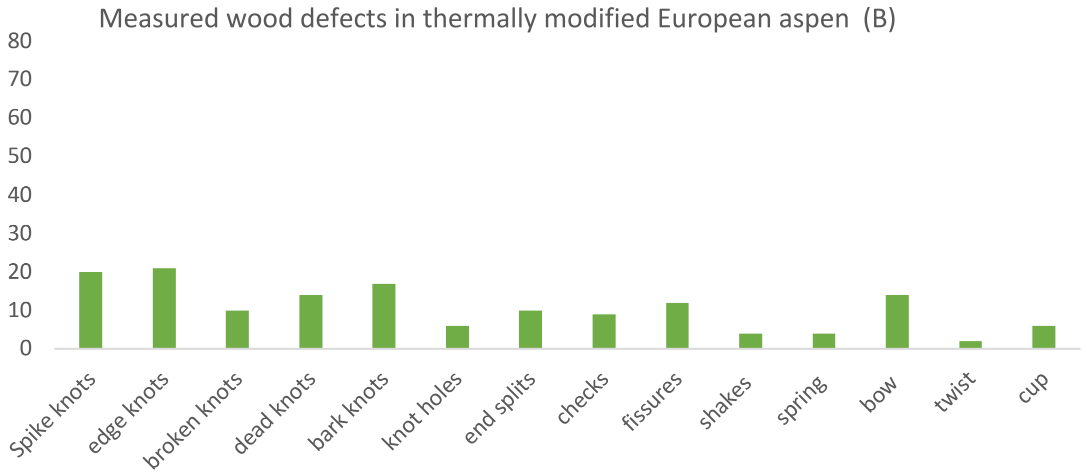

Figure 10. *Measured thermally modified European aspen wood defects in detail. 80 sample boards in total.*

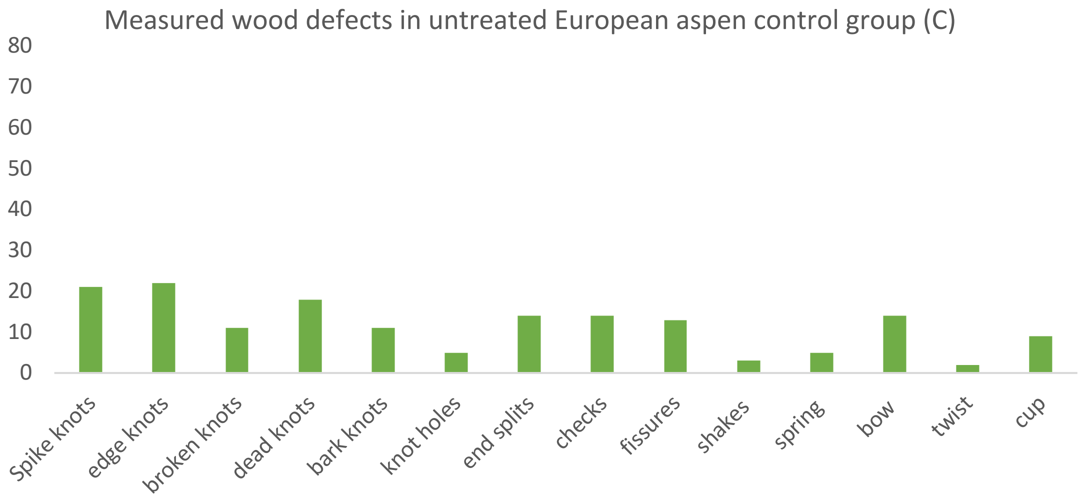

Figure 11. *Measured untreated European aspen wood defects in detail. 80 sample boards in total.*

Discussion

In this thesis I compared how thermal modification process affects the quality characteristics of two very similar tree species, hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) and European aspen (*Populus tremula* L.). Indirectly this study also gave an answer to the question which was asked in the very beginning. Is it possible to use wood from hybrid aspen for thermally modified products, rather than presuming that the wood is only good for bioenergy and pulpwood production. Results showed that thermal modification is not a good option for producing hybrid aspen wood with a purpose of being used as a load bearing construction element. Nevertheless, thermal treatment gave an aesthetical coloration to the material (See Appendix C) and it also improves other aspects such as biological durability and dimensional stability (Boonstra et al. (2011); Lahtela, 2021). There are some steps that can be taken in the phase of forest management to improve wood quality. Hybrid aspen sawn wood contains more knots compared to European aspen and therfore it would be beneficial to prune dead branches of young hybrid aspen stands after stand establishment. Future prices are an unknown variable when it comes to pruning, but past has shown that generally it is a good way of increasing value of the wood (Rytter & Jansson, 2009 ; Pretzsch & Rais, 2016).

Hybrid aspen samples studied in this research grew in a plantation, where the spacing between trees was 2-2,5 x 3-3,5 meters. Such spacing was used for keeping stand establishment costs low, but at the same time it gives trees more room to grow. Wide spacing is commonly used in plantation forestry, mainly because the aim is to grow large amounts of biomass. Since plantations are not very dense, trees have more space for the branches to grow bigger. Dry branches stay attached to the stem for a longer period of time. The difference found confirmation when were counted on the better faces of boards in sample groups (A) and (B). The rotation of hybrid aspen is very short and the branches do not have enough time to self-prune (See Appendix D for pictures of differences in branching between hybrid aspen monoculture and European aspen in a mixed forest). Inside hybrid aspen plantation there is little room for walking and the branches reach all the way to the ground. For that reason only a small part of the wood is knot free. Reasearch question for coming studies could be following: **„How does early pruning affect the quality of hybrid aspen sawn wood“.**

Pruning operations are not very commonly seen in short rotation forest management systems, but they might be essential when want to use wood for something other then just bioenergy or pulp.

Results found that hybrid aspen wood had more defects compared to the wood of European aspen. It should be taken into consideration, especially because mechanical properties were tested using only clean samples, without any defects. Knots, cracks and fissures lower the ability of wood to withstand stress. This means that the wood of hybrid aspen would most likely perform worse in load bearing applications, than we can see in the tests. For that reason thermally modified hybrid aspen should be mainly used for products that don't have to withstand static bending. Such products could include cladding and wood used in sauna interiors.

Intense thermal modification gave material great compressive strength, but at the same times the wood turned more brittle. Previous papers have confirmed this, when wood is being treated with heat, it loses density and flexural strength but gains compressive strength (Herrera-Builes, 2021).

Density of hybrid aspen wood is lower compared to almost any other tree species in Europe (Heräjärvi & Junkkonen 2006). However, hybrid aspen boards were much more crooked, than the ones cut from European aspen. This totally refutes the argument that the species with lower density are much easier to process in thermal modification processes. It seems that there are more factors in play, one of the major problems with hybrid aspen was, that the boards shrinked from the knots during thermal modification.

Mean density measurements showed unexpectedly big variation among specimen. But on the other hand we have to keep in mind that the sample trees were cut from a plot which had 15 different hybrid aspen clones growing. Wide variation in wood density can partly come from the genetic differences of trees.

Despite the challenges of thermal modification, hybrid aspen has a great potential of becoming an important source of raw material in the future.

Acknowledgements

I wish to express appreciation to my supervisors, Associate professor Henrik Böhlenius, Reimo Lutter and Professor Hardi Tullus who all guided and mentored me on this journey.

The physical and technical contribution of “Thermory AS” and hybrid aspen material contribution from “Södra Metsad OÜ“ is very much appreciated. Without their knowledge and help this project would have been less comprehensive.

My sincere thanks goes to Regino Kask and all of those who helped with the processing of samples in the wood laboratory of Estonian University of Life Sciences.

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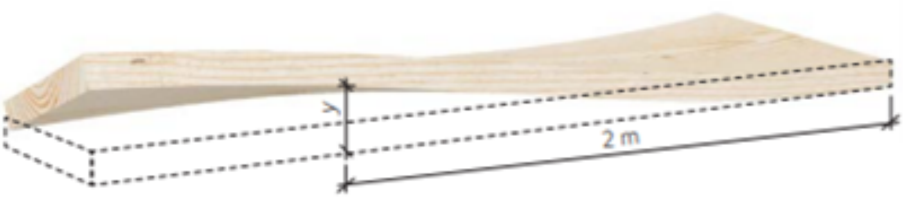
Appendix A. Measuring of wood defects

Twist



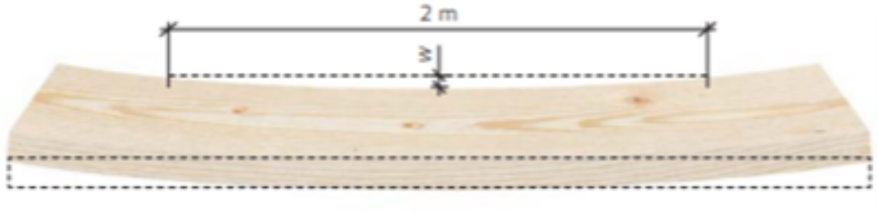
Definition	Lengthwise spiral distortion of a piece of timber.
Requirement	Maximum deviation, dimension *y*, in percent of the width of the piece of timber.
Measuring rule	Largest deviation, dimension *y*, over the worst 2 m length in relation to the outside face of the piece of timber.

Cup

Definition	Curvature of a piece of timber across the width of the face.
Requirement	Maximum deviation, dimension *z*, in percent of the width of the piece of timber.
Measuring rule	Largest deviation, dimension *z*, over the width of the piece of timber.

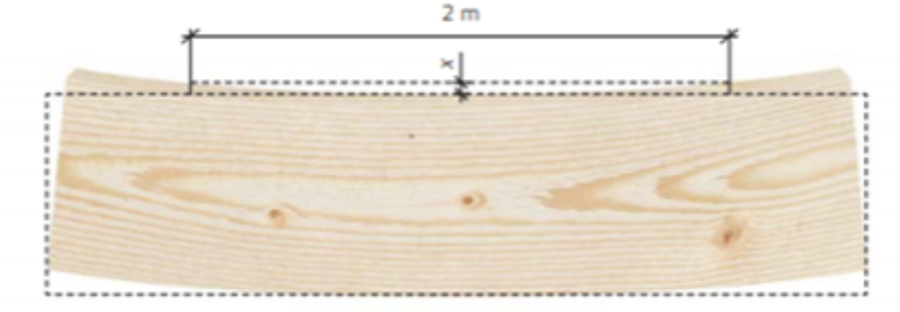
Measuring of twist and cup of a board, according to EN 1611-1 (Fröbel, 2016)

Bow



Definition	Lengthwise curvature of a piece of timber at right angles to the face.
Requirement	Maximum deviation, dimension *w*, in mm.
Measuring rule	Largest deviation, dimension *w*, over the worst 2 m length.

Spring



Definition	Lengthwise curvature of a piece of timber at right angles to the edge.
Requirement	Maximum deviation, dimension *x*, in mm.
Measuring rule	Largest deviation, dimension *x*, over the worst 2 m length.

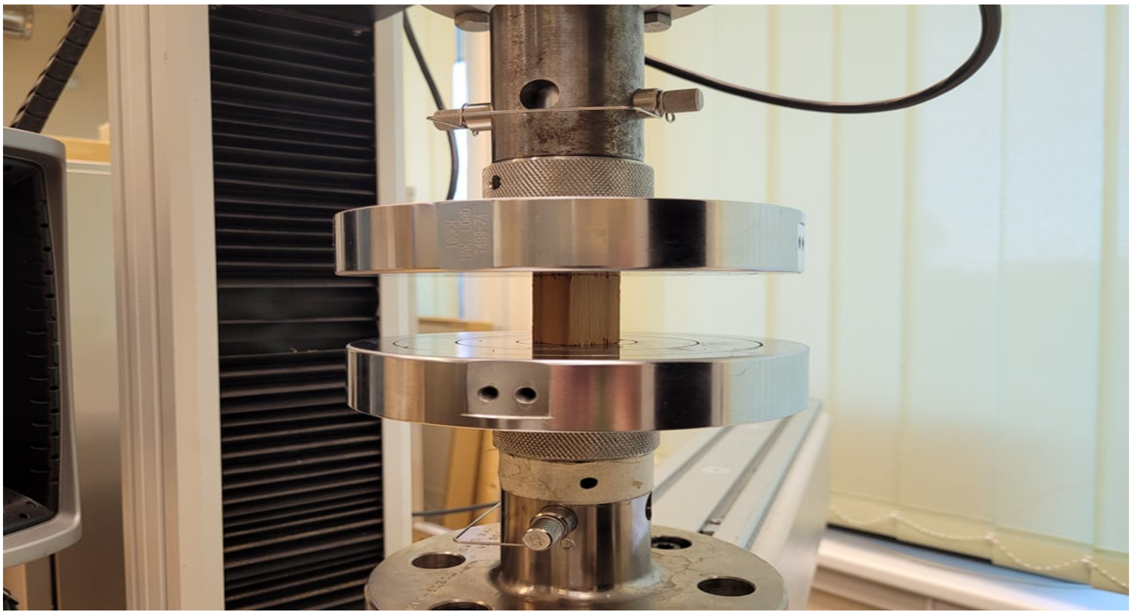
Measuring of bow and spring of a board according to EN 1611-1 (Swedish wood, 2016)

Appendix B. Photos from sample preparation

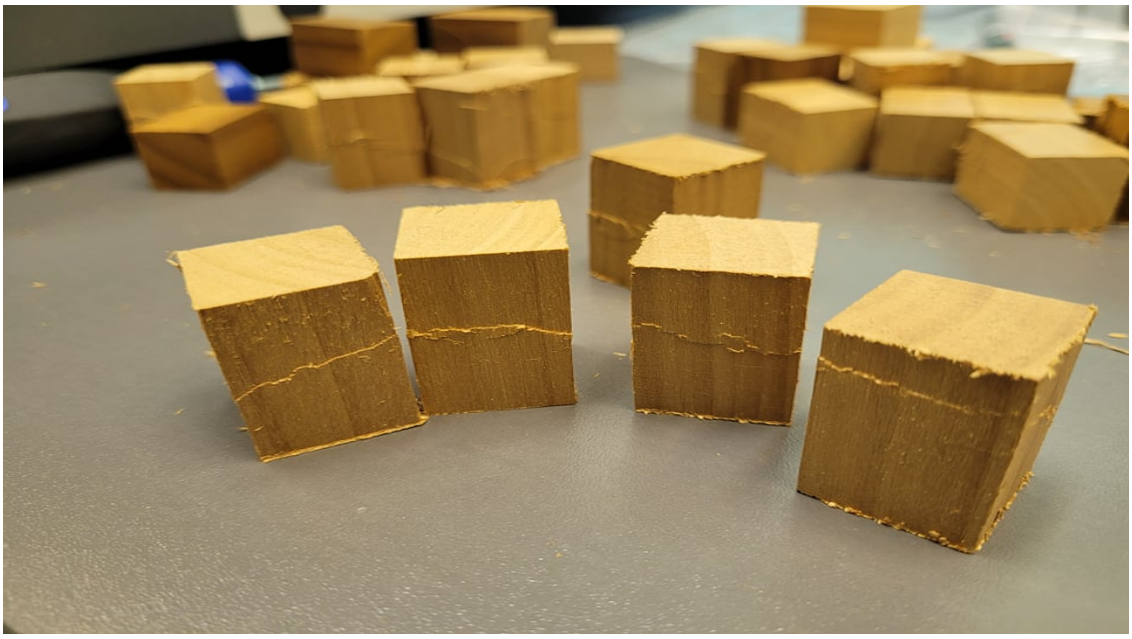
Hybrid aspen boards after sawing and edging, loaded onto a trailer, ready to be sent to kiln-drying

Hybrid aspen boards stacked after kiln-drying, right before thermal modification process

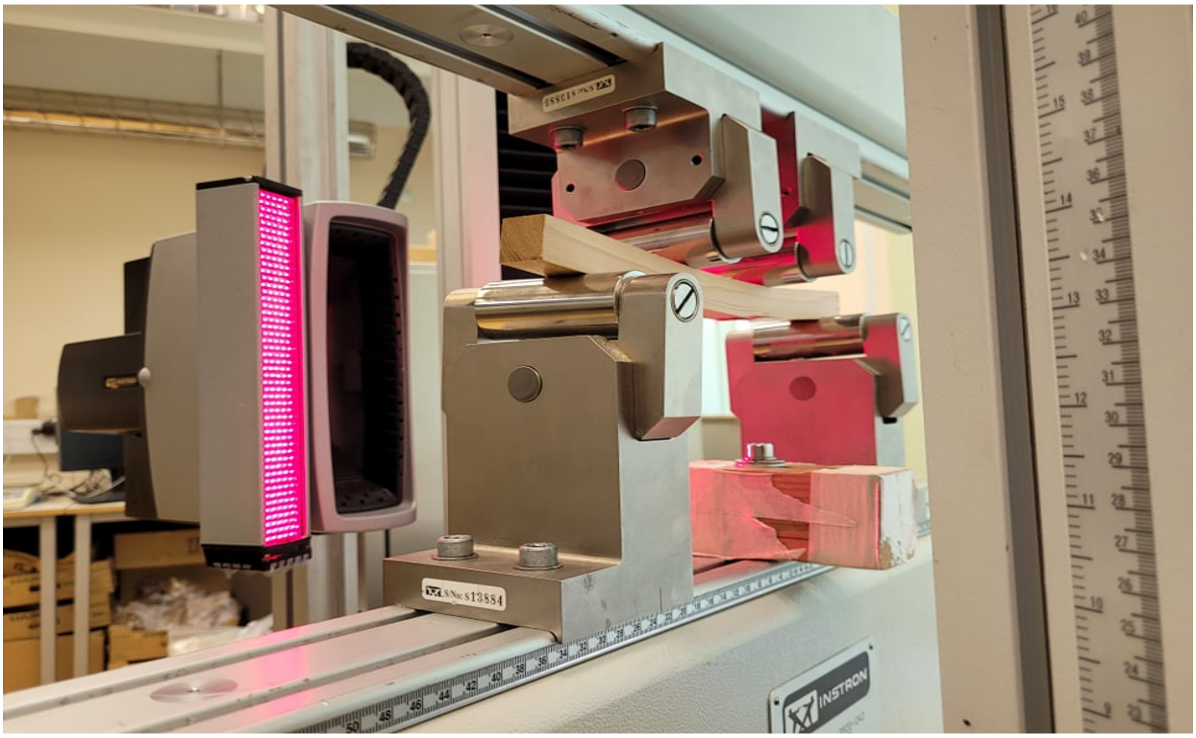
Appendix C. Photos from measuring mechanical properties



A photo made during the compressive strength testing



Samples after compressive strength testing



Bending strength testing of hybrid aspen samples using INSTRON 3369

All samples were measured before testing and newton value was calculated according to the surface area of every single piece in mm^{-2}

Cross section of a thermally modified hybrid aspen board

Overall appearance of thermally modified hybrid aspen wood, this piece was selected for showing sound knots in the wood

Appendix D. Photos of hybrid aspen and European aspen stands

Picture from the day of felling sample trees from hybrid aspen plantation in Nõgiaru; No pruning has been done and the branches start from almost ground level

Picture of European aspen growing in a mixed stand; Naturally regenerated European aspen stands are very dense and self-pruning happens in an early stage. Hybrid aspen stands are more sparse and branches grow thicker before they dry. Larger branches stay on the trees for longer time and are not braking off easily