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MASTER'S THESIS

Heat Treated Wood

- The Concept House Development

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Abstract
This thesis has been carried out at the division of Wood Physics at Luleå University of Technology, Skellefteå (LTU).

In communicating and introducing new technology and material experience show that demonstrating with real physical objects is very much effective. This is why this project has developed and realized a concept house made of heat treated wood in every visible detail.

The project has been founded by an investment program within LTU towards entrepreneurialism and by an international cooperation in research and development within the EU founded Northern Periphery Program. As a direct result of the communicating and introducing of the heat treatment technology that this project has been part of has lead to an industrial build up of two separately production plants for heat treated wood.

This thesis demonstrates the chosen solutions and experiences and knowledge gained from this development.

Content:

1. Introduction

This project is called Heat *treated wood- The Concept House Development*. The work is within the 20p course Master Thesis, IST806 at Luleå University of Technology, Skellefteå (LTU).

1.1. Background

Today the Swedish wood industry is realizing that different types of further processing have to be introduced to get a better use and value of our products from the forests.
Heat treatment is further processing of the wood that can enhance the usage of wood and through that increase the value of our natural resources within Sweden.

Why would the Swedish wood manufacturing industry pay any attention to heat treatment of wood one can wonder, and there are a number or reasons for that. One major one is to improve the utilization of one of Sweden's most valuable renewable natural resources.

That is the reason why research is done in wood modification, in which category of research heat treatment falls into. The purpose is to keep wood competitive to other not ecological sustainable material such as metal and plastics through enhancing the properties of wood. The enhanced properties reached with heat treatment can be of advantage in several applications

As a background to this Thesis, the author has run two projects connected to heat treated wood.

The first project investigated the attitude to and the knowledge about heat treated wood in the wood manufacturing industry in Sweden and Finland, done by Eliasson and Forsman[1]. When comparing the wood products manufacturing industries in Sweden and Finland one can conclude a difference in attitude to deploy new knowledge into new products in the industry. Though the result gave indications that there is a potential for heat treated wood in both Sweden and Finland, but in Sweden there is very little knowledge in the industry about the new material that heat treated wood is.

In the second project the author was producing information about heat treatment to transfer knowledge from the University and researchers to the industry, and presented a strategy discussion in topics of product development, commercialization, strengths and weaknesses of heat treated wood[2]. The information material created will be used by Luleå University of Technology and the Swedish University of Agricultural Sciences in the contacts with the industry.

Today the main production of wooden lumber is from softwoods like pine and spruce, other hardwood of ash, birch, beech and oak are produced only to a small extent. An extension of the range of wood material to select with a Swedish origin, considering colour, durability and other technical properties, would increase the number of possible wooden products.
Heat treatment of wood can be used to alter these properties of those Swedish wood materials.

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[1] Eliasson F, Forsman S, 2005, *Heat Treated Wood – An Investigation of attitudes in Swedish and Finnish wood industries.*
[2] Forsman S, 2006, *Heat treated wood – Information transfer and strategy discussion*

1.2. Problem

Due to little adoption of heat treated wood in the Swedish wood industry as a niche for further processing of wood products produced. There is also little practical knowledge of working with this material and about what products to produce and what the benefits will be in using heat treated wood. The industry sees little or no demand on this material but the market has no knowledge about this material and what products the want made of heat treated wood.

The problem statement used within this project is how to show and develop possible use of heat treated wood in wood products that can reflect the wood industry in the region of Norr- and Västerbotten.

1.3. Objective

The objective of this master thesis project is to plan, develop and perform the building of a **Concept House in Heat Treated Wood.**
The work will be in cooperation with companies in regional wood related industry and the division of Wood Physics at Luleå University of Technology, Skellefteå.

The project purpose is to produce an object exposing heat treated wood material used in applications, as well as to bring interest, experience and raise questions of the material when creating a physical object with some level of complexity.

Through the complexity of the object and the cooperation with regional industry experiences and questions concerning the value adding process of the material will be gained in several levels in a wood manufacturing value chain.
Within the project work, some research and experiments are to be conducted to gain necessarily knowledge to apply in the products in the concept house project.

To solve the problem I have formulated the following tasks:

- Establish a network of enterprises wanting to participate with their skills and time
  Goal: Find manufacturers to the planned products and features of the project

- Find suitable heat treatment process to use for the products of the house
  Goal: Process heat treated material needed in the project

- Find suitable end-use of the house
  Goal: Define purpose for the house for planning of needed features

- Plan and coordinate the production of the house
  Goal: Present solutions needed for the planned products and features

- Perform research and experiments to gain information to decide about planned solutions
  Goal: Give information wanted for decisions in the project

For the learning from the project

- Document experiences from the development of the concept house

2. Heat treated wood material

Since the purpose of this project is to communicate possibilities of the technology of heat treating wood a chapter with information of the properties gained with the technology is appropriate.

Within the project there has been developed a demonstration box with samples of heat treated wood made of seven wood species used in wood mechanical industry in Sweden. The boxes have been used for communication in the work of building up the network around the project.

Those seven species has been heat treated at different heat treatment temperatures and is shown without surface treatment as well as with oil and with lacquer surface treatment. The species showed in the boxes are represented in Figure 1 and are Pine, Spruce, Ash, Aspen, Beech, Birch, and Oak.

The softwood species have been heat treated at 190°C and 212°C which the standard temperature levels for softwood used in the industrial production of heat treated wood in Finland. For the hardwood the industry uses the temperatures of 185°C and 200°C for the same standard classes of Thermo-S and Thermo-D used by the ThermoWood Association[3]. For the demonstration boxes a third treatment temperature of 170°C also has been used on the hardwood material to show a gentle treatment level that easily could be adopted in the wooden joinery industry.

Together with the demonstration boxes an information material has been produced and showed as an appendix to this report.

Figure 1: Heat Treated Wood Samples

[3] ThermoWood Association, 2003, ThermoWood Handbook
http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

2.1. *Properties of heat treated wood*

Working with a complex material as wood makes even the easy questions difficult due to numerous variances even within a particular specie. Then the amount of species available the difficulties are further increased.

Therefore the general aspects of the changed properties for heat treated wood will vary with specie and circumstances of growth the particular tree and even where in the tree the wood comes from.

Heat treatment of wood causes a number of chemical and physical changes of the material that generally are correlated to the temperature and time of treatment. Originally the purpose of conducting heat treatment research on wood was to increase the biological durability and dimensional stability of wood, which still is much in focus in the international wood modification research[4]. Heat treatment can principally be performed on any wood specie but the focus has been to add value of the less durable ones.

2.1.1. Colour of heat treated wood

From the objectives of increasing durability and thereby value to less durable wood species the change of colour can be seen as a side effect. Though the purpose wasn't deliberate, the change of colour and the possibility of controlling it can also be an important asset in adding value to wood.

As wood is heated, acetic acid is formed from acetylated hemicelluloses by hydrolysis. The released acid serves as a catalyst in the hydrolysis of hemicelluloses to soluble sugars[5]. The heat caramelize the sugar to a brown colour that affects the colour of wood. As the degradation of hemicelluloses accelerates with temperature the colour will become darker with increased treatment temperature.

The colour of the heat treated wood is realized as homogenous for the human eye but measurement performed by Dennis Johansson[6] show that there are some colour heterogeneity. Due to the irregular colour of wood the human eye interpret the colour of the heat treated wood as homogenous.

When treating the colour of the heat treated wood as a valuable asset one would like to preserve that value. Like all wood the colour of heat treated wood is in time affected by light. Usually, to predict this change, accelerated ageing tests are performed with UV-light.

Ayadi et al[7] show that heat treated wood is better to withstand UV-radiation during experimental conditions. Despite that there are practical experiences showing sometimes rather fast colour changes of heat treated wood.

Experiences also show considerable differences of the colour of the material when it is coated with oil or lacquer compared with uncoated as well as between the two types of coating.

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[4] Militz H and Hill C, 2005, Wood Modification: Processes, Properties and Commercialisation

[5] ThermoWood Association, 2003, ThermoWood Handbook p.21
http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

[6] Johansson Dennis, 2005, Strength and colour response of Solid Wood to Heat Treatment p. 13-17

[7] Ayadi N. Lejune F. Charrier F. Charrier B. Merlin A. 2003, Colour stability of heat-treated wood during artificial weathering

Therefore more knowledge through research is needed to find optimal protection of heat treated wood in order to maintain the achieved colour from treatment. Also to utilize heat treated wood in product where the look of the material is the argument for the use of the heat treated material, knowledge about surface treatment of that material becomes essential.

2.1.2. Durability of heat treated wood

As mentioned earlier one main focus of the international research on wood modification is to increase the durability of less durable wood species. Even if there exist wood species with high natural durability, exploiting such species in a higher extent would threat virgin grown forests to be deforested, which in turn would give serious environmental consequences to man.

The natural durability varies vastly among different wood species. The demand for durability on wood varies with the intended use. The EN 335-1 and EN 335-2[8] standards defines five hazard classes concerning biological durability of wood and wooden products. It is against these definitions of NTR, which is the Swedish classification system for impregnated wood, is done. The NTR class AB is the impregnation that gives enough protection of the wood for use in hazard class 3, which is above ground without protection, which causes frequently wetting of the wood to moisture contents above 20%.
Other certificates like CTB, BS, RAL, DIN and KOMO work in similar ways.

The natural durability of numerous wood species is presented in the EN 350-2 standard where the wood species are classified into five classes from very durable to not durable, perishable. To determine appropriate use of a wood specie one have to use the EN 460 standard as a key to find the durability class needed to a certain hazard class.

Heat treatment of wood enhances the durability of the treated wood. How much improvement that is achieved, depends on the particular wood species reaction to heat treatment and on the temperature and time of the treatment.

To give an overview of the durability class and use of wood I have constructed Table 1, that is, regarding the increase of durability of the heat treatment, build on qualified assumptions of some known wood species and the results presented by researchers. The rest is build of the use of EN 460 as a key to the information in EN 350-2, EN 335-1, EN 252 and EN 113. Notice that there in many species are differences in durability between the sapwood and the heartwood, where the heartwood generally is more durable.

I also use the Thermo-S (185-190°) and Thermo-D (200-212°C) classes from ThermoWood association[9] to indicate the level of heat treatment. Worth noticing of these heat treatment classes is that there is different treatment temperatures for softwood (higher) and hardwoods (lower).

Even if scientist results indicating a certain durability of particular wood specie there is need for extensive field studies to prove the, through heat treatment achieved, durability.

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[8] SIS Swedish Standards Institute, 1998, Trästandardboken, Wooden Standards in Europe
[9] ThermoWood Association, 2003, ThermoWood Handbook
http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

For comparison with impregnation of wood I use the classification of NTR (≈Northern Wood Preservative Council). The NTR classes of impregnated wood are:

- B for use in hazard class 3, used on pre-manufactured bits and pieces
- AB for use in hazard class 3, the class that is most used and available
- A for use in hazard class 4, less available and more toxic
- M for use in hazard class 5, privates can not buy this kind of treated wood

Suitable use for different classes and species of heat treated wood are visualized in Table 1:

Heat treated wood (qualified assumptions)	Example of Wood species EN 350-2	Durability-class EN 252 EN 113	Hazard-class EN 335-1	Situation in service	MC of untreated wood
Thermo-S of Aspen, Birch, Beech etc.	Alder, Ash, Aspen, Birch, Beech, Maple	**5** Not durable	**1**	Above ground (dry)	Permanently below 18 %
Thermo-D of Aspen, Birch	Elm, Pine, Spruce, Larch	**4, (5)** Slightly durable	**2**	Above ground, covered, risk of wetting	Occasionally above 20 %
Thermo-S of Pine, Spruce[9]	Pine, Larch, Walnut	**3** Moderately durable	**3**	Above ground, not covered	Frequently above 20 %
Applicable ? Thermo-D of Pine, Spruce[9] Ash[10]	Oak, Western red cedar, Balau (yellow)	**2** Durable	**4**	In contact with ground or fresh water	Permanently above 20 %
Applicable? Thermo-D of Beech[10] indication of Scheiding et al. 2005	Teak, Iroko, Robinia	**1** Very durable	**5**	In salt water	Permanently above 20 %

Table 1 Durability and use of Heat Treated Wood

A comment to durability field tests performed by SP, Swedish National Testing and Research Institute[11], among others indicates problems, great loss of strength, with heat treated wood in ground contact. From the SP report one can read: "the high rate of failure was not caused by decay as confirmed by microscopically analysis". Thus this indicates that the reasons for the loss of strength in ground contact may not be due to biological breakdown. The reasons for this are not yet answered by the scientists.

An experiment done by students in Skellefteå show changed behaviour of capillary water sorption of heat treated wood that actually indicates increased capillary water sorption for heat treated wood. That together with the experience of increased brittleness of wet heat treated wood will be further investigated by PhD student Dennis Johansson, which might give some light on reasons for heat treated wood looses eventually all strength in ground contact.

2.1.3. Dimensional Stability

The ability of wood to soak up and release water, sorption, is a key factor of understanding swelling and shrinkage of wood, its dimensional stability characteristics.

[10] Scheiding W., Kruse K., Plaschkies K., Weiss B., 2005, Thermally Modified Wood for Play ground Toys: Investigation on 13 Industrially Manufactured Products.

[11] Jermer J., Bengtsson C., Brem F., Clang A., Ek-Olausson B., Edlund M-L., 2003 Heat Treated Wood – Durability and Technical Properties

Due to it hygroscopic properties wood as a material is not dimensional stable in environments where the humidity of the air varies. At a particular relative humidity in the air, if the wood is drier than the corresponding equilibrium moisture content (EMC) of that humidity it will swell, and shrink if the wood is more moisturized then corresponding EMC.

A change in EMC has a relation to changes in dimensional stability which is an effect of heat treatment on wood. Though the relation is not a direct one, hence there are differences of the improvement in dimensional stability with different species. As the case is for most of the changes in properties caused by heat treatment, treatment temperature and time affects the change. High treatment temperature and long time give high dimensional stability as well as low EMC of the material.

In Figure 2 and Figure 3 information about swelling of spruce, indicating an improvement in dimensional stability of 60% on average. Scheiding et al[12] show reductions of differential swelling ratios of 30% for heat treated softwoods (Pine and Spruce). Their investigation of hardwoods (European Beech and Ash) shows much more variances in reduction of the differential swelling, and the changes from untreated wood are not noticeable.

Others are investigating anti swelling efficiency of Beech (Fagus Orientalis) and Spruce (Picea Orientalis) find improvements of 53% and 40% respectively.

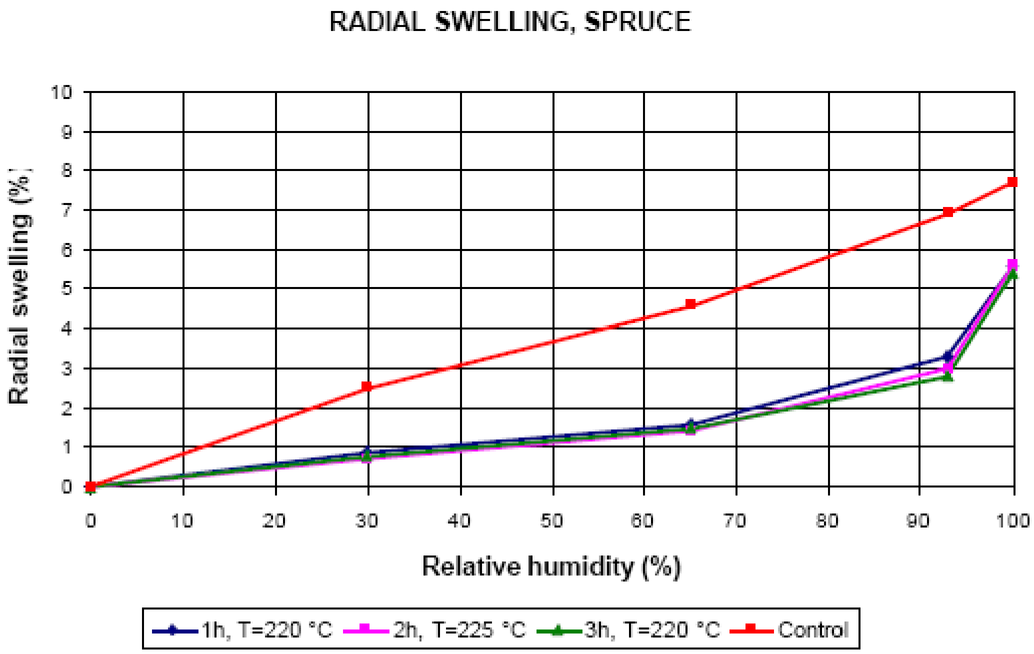

Figure 2 Radial Swelling of spruce as a function of relative humidity[13]

[12] Scheiding W., Kruse K., Plaschkies K., Weiss B., 2005, Thermally Modified Wood for Play ground Toys: Investigation on 13 Industrially Manufactured Products

[13] ThermoWood Association, 2003, ThermoWood Handbook p.30 http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

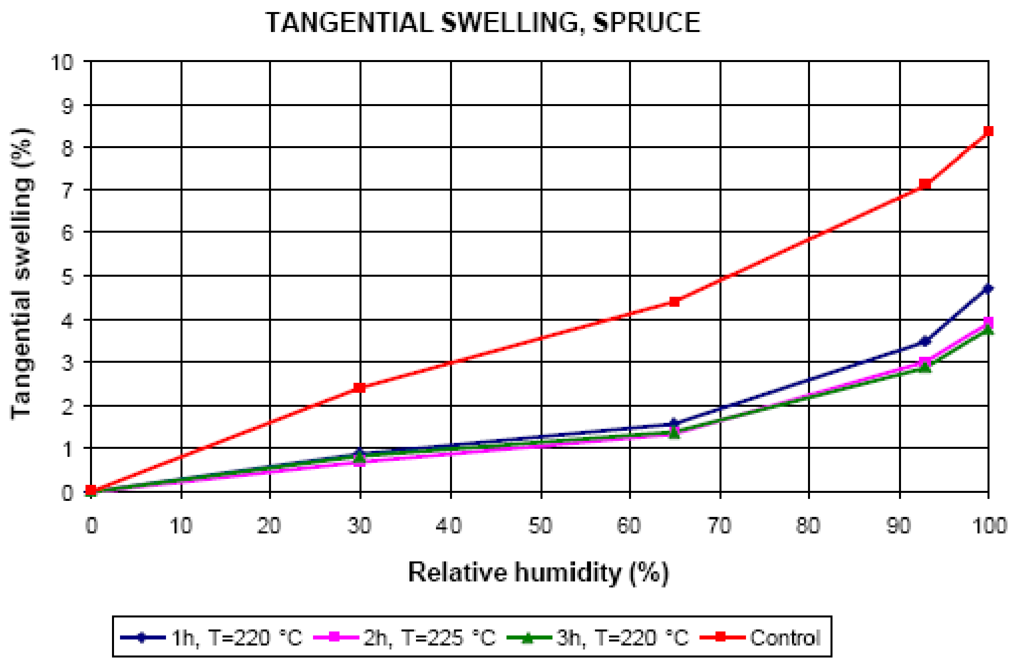

Figure 3 Tangential Swelling of Spruce as a function of relative humidity [13]

2.1.4. Strength properties

Under standing physical changes heat treated wood result on wood characteristics it is important to relate these to the chemical reactions developed during the heat treatment and their influences on the structure of wood.

Cellulose, hemicelluloses and lignin are main structure elements of wood and heat treatment involves degradation of these components in different levels. The hemicelluloses are the component that degrades to the highest extent and the decomposition of that constituent accelerates at temperatures between 200 - 260°C. The corresponding temperature for cellulose is about 240 - 350°C[14]. Lignin that holds the wood cells together is the least heat sensitive component of wood, and starts to degrade only when temperatures are exceeding 200°C.

Static bending strength

The bending strength of wood are strongly affected cell structure and irregularities in fibre grain[15]. Due to degradation of the wood constituents during heat treatment, heat treated wood have lost strength in the bounding between the fibres, making the wood easier to splint when exposed to stress perpendicular to grain.

Heat treatment also causes evaporation of resin that makes black knots to fall out when the resin that holds them in place vanish. This phenomenon together with fibre grain irregularities around knots also has impact on bending strength. Therefore is the quality of great importance when using heat treated wood where the bending strength is of importance.

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[14] ThermoWood Association, 2003, ThermoWood Handbook p.21
http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

[15] Hansson T, Gross H, Träbyggnadshandbok 9, Trätek

Once again the temperature and time of the treatment is crucial to the impact of the bending strength for the particular specie, and natural variances are common. Thus quantifying the reduction of bending strength for heat treated wood is a bit of a problem.

In the ThermoWood handbook[16] test on Pine show virtually no reduction in strength treated at 190°C and treated at 212°C the bending strength is reduced about 10% when using defect-free material over short span. They also show test on bending strength of Spruce according to EN 408, treated at 230°C with larger test pieces containing knots, resulting in a 40% decrease in strength.

At SP[17] they also have conducted a corresponding test (EN 408) with large test pieces with knots and a quality of the wood that is not defined. These where heat treated at 220°C and the results shows an average strength decrease by 50% for spruce and 47% for pine.

When Scheiding et al 2005[18] perform test on heat treated wood from 13 industrial manufactures they found strength reductions of 20% for pine, 18% for spruce, 13% for beech and 0% for ash. The treatment temperature and time wasn't declared.

These examples show the problem in determining the bending strength losses for a material with defects and natural variances.

Stiffness- Modulus of elasticity

Connecting to the same examples as above[16, 17,18] the test from SP and ThermoWood show similar results of around 5% reduction of modulus of elasticity, while Scheiding show an stiffness reduction of 20-30%, though the reference values in their test is from literature. These tests indicate that the stiffness loss is far less than the bending strength losses.

Impact, Shear and Splitting strength

These different categories of material strength are measurements showing the increased brittleness heat treatment result in to the wood characteristics.

ThermoWood handbook[19] show a decrease of 25% for impact strength for spruce treated at 220°C and a splitting strength reduction on Pine, Spruce and Birch with 30 – 40% on average. Sheiding[18] show a decrease in impact strength of 35% for spruce, 48% for pine, 66% for Beech and 45% for Ash.

These tests show that heat treated wood to a great extent is more brittle than untreated wood which gives need for special care when screwing, nailing, planning and milling heat treated wood.

Another example of special care due the increased brittleness is that heat treated wood is recommended to be planed, or that sawn board are brushed to remove early wood fibres, before painting, to accomplish better surface adhesion.

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[16] ThermoWood Association, 2003, ThermoWood Handbook p.25

[17] Jermer J., Bengtsson C., Brem F., Clang A., Ek-Olausson B., Edlund M-L., 2003 Heat Treated Wood – Durability and Technical Properties

[18] Scheiding W., Kruse K., Plaschkies K., Weiss B., 2005, Thermally Modified Wood for Play ground Toys: Investigation on 13 Industrially Manufactured Products

[19] ThermoWood Association, 2003, ThermoWood Handbook p.27
http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf

Hardness
From my contacts with the industry I have found that there sometimes is some kind illusion of significantly added hardness of the material is given through heat treatment. From what I have found in my investigations of the properties of heat treated wood, this doesn't seem to be the case.

One test on pine[20] shows a slight increase of the Brinell hardness of pine while others[21] show a decrease of 28% for pine. Though the second investigation show no loss of hardness for spruce, but for hardwood like beech and ash reductions of 19% and 30% are showed respectively.

Accordingly there are variances between different wood species and how they react on heat treatment regarding the hardness but it is not likely to find a significant increase of hardness on heat treated wood.

2.1.5. Other properties of heat treated wood

Emissions of Heat Treated Wood
Emission of volatile organic substances from untreated wood can some times cause trouble of usage of wood. When testing emissions from wood measurements are made on organic compound emitted from the material and summarize the quantity in a term called Total Volatile Organic Compound (TVOC)

I have found two reports measuring emissions from heat treated wood that performs measurements on pine[22] and spruce[23] respectively. They are quite similar but still they refer to different standards for the method in use which affect the possibilities of comparison between them. Anyhow they are both showing decreased values of TVOC.

- Pine treated at 180°C show a 44% reduction of TVOC
- Pine treated at 230°C show a 84% reduction of TVOC
- Spruce treated at 220°C show a more than 17% reduction of TVOC

Both test show significant lower emission values of all tested compounds accept furfural and acetic acid, of which there is an increase of emission from. The smoke-like smell that can be detected from recently heat treated wood most likely derives from the furfural emission.

Conductivity of heat treated wood
Degradation of the wood structure components result in lower density and more air in the material resulting in a less effective heat transfer – thermal conductivity, which means better insulation properties.

[20] ThermoWood Association, 2003, ThermoWood Handbook p.28
[21] Scheiding W., Kruse K., Plaschkies K., Weiss B., 2005, Thermally Modified Wood for Play ground Toys: Investigation on 13 Industrially Manufactured Products
[22] ThermoWood Association, 2003, ThermoWood Handbook p.45 http://www.thermowood.fi/data.php/200312/795460200312311156_tw_handbook.pdf
[23] Jermer J., Bengtsson C., Brem F., Clang A., Ek-Olausson B., Edlund M-L., 2003 Heat Treated Wood – Durability and Technical Properties p.18-19

Thus tests[24] showing decreased thermal conductivity which means improved insulation of 10-25% depending on treatment temperature and time. This is more decrease of thermal conductivity than the loss of density generally is for these treatment temperatures.

Resin in heat treated wood

In the temperatures where heat treatment of wood is done dissolve resin in wood and makes it evaporate. Thus heat treated wood need no special treatment to avoid secrete of resin when using it.

2.2. Environmental aspects

Since basically no chemicals are required and only water and heat is used, the heat treatment processes are generally environmentally friendly.

Slight differences occur between the different processes but the main idea to transfer heat and avoid oxygen in the process, therefore the only transfer to the wood is heat, despite the differences among the commercial heat treatment processes.

As the process releases extractives from the wood, these must be processed - for example, by burning to avoid an odour nuisance. By the ThermoWood process, reports show no significant amount of waste water is generated. The solid components of the generated waste water are separated out in a special settling basin, and the rest is processed at waste water works.

The PLATO process reports that their material has been reviewed by TME[25] (Institute for Applied Environmental Economics, The Hague, The Netherlands), who have assessed the environmental-economic performance of PlatoWood (heat treated wood) in comparison with other materials. The study covered all steps of the Life Cycle (production, transport, use and disposal) and was based on two approaches:

- Life Cycle Assessment (environmental impacts)
- Life Cycle Costing (environmental costs and production costs).

The investigation of the material is conducted as main material in two different types of products.

- Poles which are relative a simple product
- Window frames which are more complex

The study covered a number of substitute material available for these kinds of products

Poles

- PlatoWood pole (heat treated wood)
- Concrete pole
- PVC & recycled plastics pole
- CCA treated (dip/spray) spruce wood pole
- CCA treated (vacuum/pressure) spruce wood pole
- Creosote treated pine wood pole

[24] ThermoWood Association, 2003, ThermoWood Handbook p.32

[25] Plato International BV, The complete Plato document p.10
http://www.platowood.nl/DOCU0505/PlatoEnglish0505.pdf

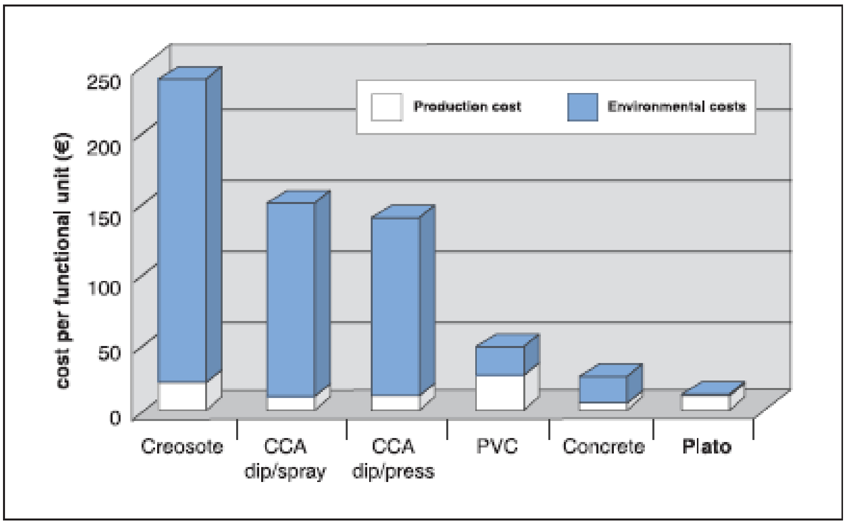

Figure 6: Environmental and production costs of poles made of six different materials.

Figure 4 Environmental impacts on poles of different materials [25]

Window frames

- PlatoWood window frame (heat treated wood)
- Painted and treated pine (softwood)
- PVC window frame
- Steel window frame
- Tropical hardwood window frame (Meranti)
- Aluminium window frame

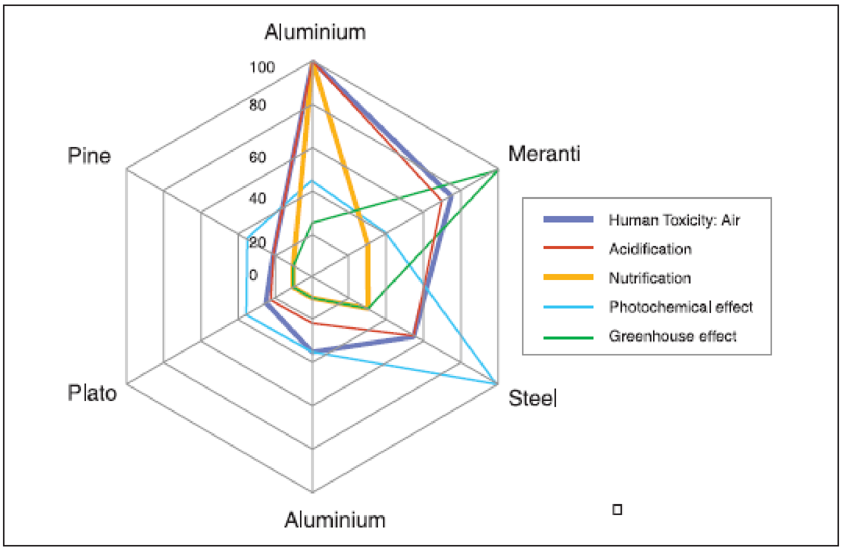

Figure 7: Relative environmental effects of window frames made of six different raw materials.

Figure 5 Environmental effects on window material[26]

After the service life, heat treated wood need no special care and can be treated as any household waste or be used as fuel for in heating plants, and by judging the results from Life Cycle Cost investigations heat treated wood are in good position regarding future government environmental regulations.

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[26] Plato International BV, The complete Plato document p.10 http://www.platowood.nl/DOCU0505/PlatoEnglish0505.pdf

3. Establishing of Network

The establishment of a network connected to Concept House Project has been an iterative process starting before the actual project and has been continuing ever sense. The establishing of a network has two main purposes. One is to find possible cooperation and resources for the realization of the project, and the second is to gain interest for the project and its purpose that could be used to initiate relations for future cooperation.

The use of a network is a strategy decision and by working together with other companies and organizations in a network will during time develop in an insight what the network members are capable of, and that will gain in a better usage of resources, knowledge and members will be more flexible to variations on the market. The increased information within the network members also benefits the knowledge about potential business opportunities.

The development of the network concerning the concept house of heat treated wood where dealt with according to Figure 6. The members in the network had different levels of interest and available resources resulting in different levels of connection and commitment to the project.

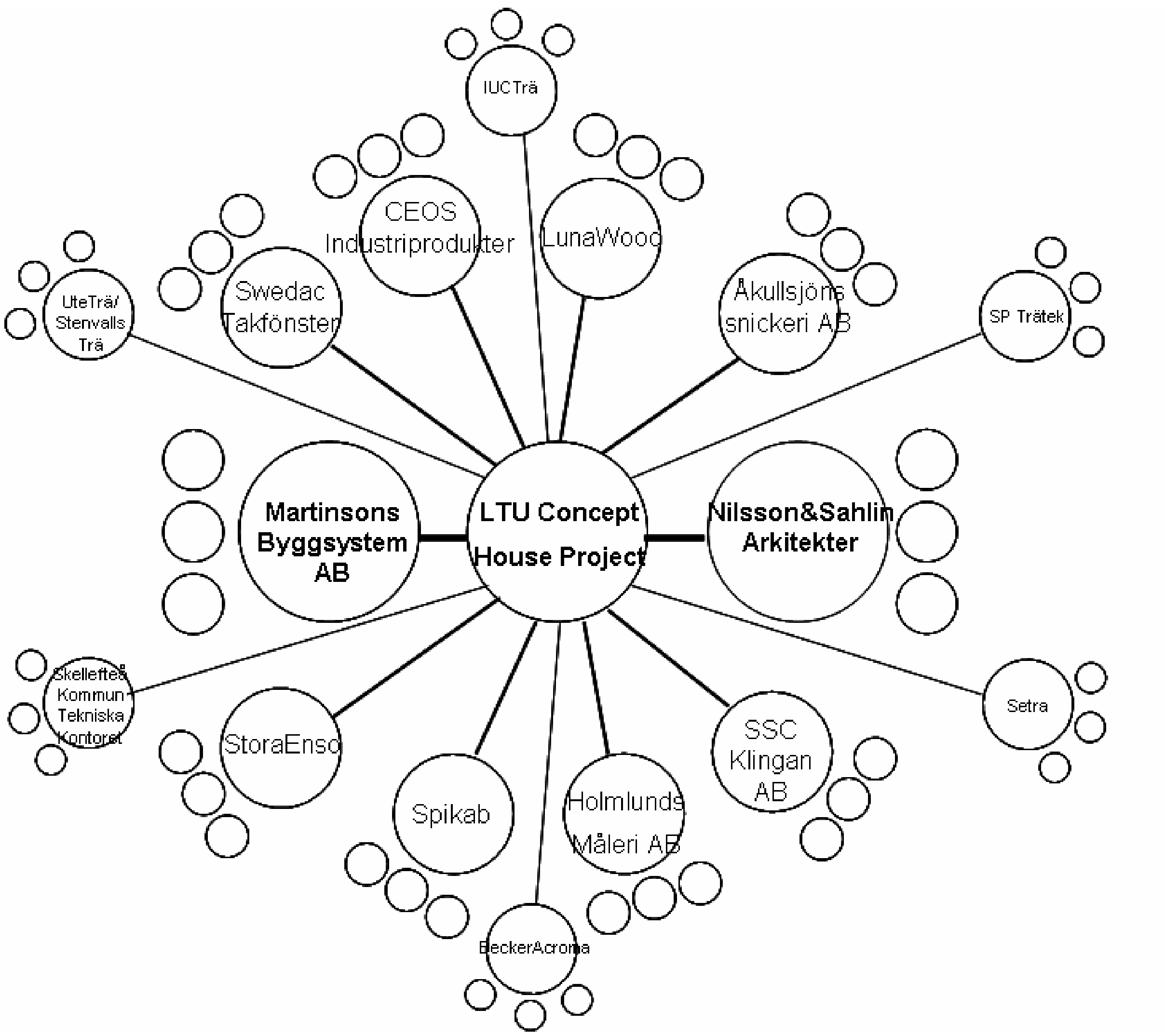


Figure 6: Project network and relation connection

The relations in core of the network where characterised by interchange of technical, know-how and economical resources as well as distributed know-how from other companies to whom the network member has business relations. This interaction result in an up scaling effect on the number of contacts and know-how that increased the efficiency of the project when certain knowledge and resources where made available to solve problems in the project.

The next level of commitment represent more of a buyer/supplier relation with interest to gain experiences of the heat treated wood material. For the project this is relation is needed to fulfil the project goals. Still there is a valuable interchange of know-how and experiences for the project as well as for the members.

The peripheral network members has the weakest connection to the project but it is a start of a relation that can develop to a closer connection due to increased knowledge of each others business, which improve the ability to see cooperation and business opportunities.

The establishment of network relations can have a direct impact on the project budget since increased interchange of resources contributes to less need for time and money to achieve certain actions in the project. All network members can benefit from being in the network and be beneficial to the project.

This interchange of resources can be exemplified with an experience from the project where one of the more peripheral network members with interest of the environmental benefits of the heat treated wood could very much contribute to the project.

This member saw the possibility to use this material in a project of his organization and the work in the concept house project where able to help this member with material to the project. The raw material needed where received from a second peripheral network member to whom services had been performed and processed in a heat treatment kiln by the project. In return the first peripheral member could contribute directly to the project with work needed through a member in his business network by performing mechanical processing of heat treated wood for the concept house.

The use of the heat treated wood material in the project of the peripheral network member created a second object with altered use of the material than in the concept house.
Thus the interchange of resources within the network supported the purpose of the concept house project, to create a reference object for marketing of the technology and gain experiences from using the material in different application. The end result where two objects made of heat treated wood from which long term experiences can be gained (Figure 7).

Figure 7: Bonus reference object in heat treated wood with opaque painting

4. Planning and Coordination

The planning of the project started as a result of early networking activities that lead to the information of possible financing of a project. The sponsor of the project had reserved money for the purpose of supporting projects transferring knowledge from the academic world to the regional industry with the aim of developing industrial use of the academic knowledge.

Then the project of developing a concept house where formulated in an application presenting actions to achieve knowledge, experience, and resource interchange with a network of companies connected in the project. The application where accepted and the work could start.

4.1. Project Set Up

For the project set up a definition of the project where produced describing the task, organization, and possible risk to the project where stated.
The organization where set up to support the project manager and performer of the project in decisions concerning the project.

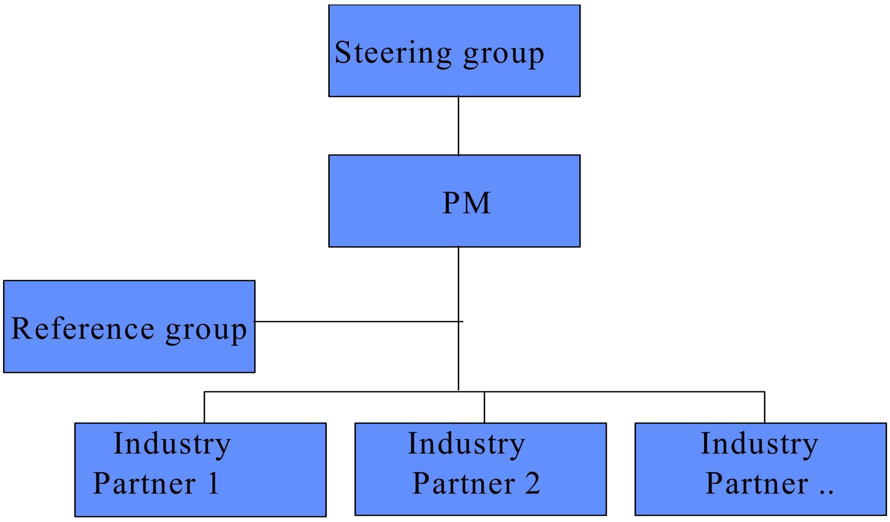


Figure 8: Project Organization

Steering group: Tom Morén, Professor in wood physics at LTU

PM: Samuel Forsman

Reference group: Tom Morén, Professor
Ove Nilsson, Architect

Industry partners: Martinsons Byggsystem AB (Örjan Kallin)
SP Trätek Skellefteå (Anders Gustavsson)
Nilsson&Sahlin Arkitekter (Ove Nilsson, Kristina Sahlin)
Åkullsjöns snickeri AB (Lage Eklund)
Wood Line (Åke Olofson)
And more.. (Figure 6)

The project was manned and run by the author who performed necessarily development in cooperation with the industry partners to fulfil production and assembling of the concept house and its constituting elements.

4.1.1. RISKS

The defined risks for the project mainly concerned the priority of the project from the industry partners and the will to participate.

The model of connecting companies to the network wanting to participate and being able to offer more of its resources than the economical compensation offered from the project would be where likely to affect the priority of project related work, that could cause time delays.

The second risk defined also related to the model for the participating companies where the risk of low attraction for the project causing increased needs to buy services, which affects the budget. Though the financing of the project where considered dimensioned to allow certain levels of purchase of material and services.

4.2. Defining use of the concept house

To have a base for the development of the concept house there was a need to further define how to use the concept house since it affects the features of the house.

It was decided within the reference group that the concept house should work as a showroom to show the project itself but also have the possible function of working as a room for exhibitions. Further it was decided that the concept house should be mobile.

The consequences of the decisions where that the size of the house where limited by transport rules and that the house should consist of only one room with a set up of furniture appropriate for the exhibition use.

The mobility where set to a level of being possible to transport by truck and avoid any transporting feature such as wheels integrated with the house.

4.3. Design decisions for the Concept house

The design of the concept house where done in close relation to the architects involved in the project. The architects where responsible for the esthetical value of the design of the concept house, and that the design details supported the idea for the total product of the concept house.

The author have worked in close relation with the architects to supply them with information and possibilities of the heat treated wood material and direct them to work according to the vision for the project. The author has also been investigating and solved the design of all of the specific details in cooperation of the architects.

The guidance in the design from the author to the architects involved the vision of the possible importance of the modification technology to the Swedish wood species processed by the mechanical wood working industry today. Therefore the mission to the architects became to find use for a number of these species with different level of heat treatment, and to use heat treated wood to an extent being as high as possible.

It was decided that all visible wood should be of heat treated wood, both exterior and interior. From that it was easy to decide that the cladding should be from heat treated wood but the author also desired to make use of the material as outer roof material and a solution for that where developed in cooperation with the architects, as well as a special system for the cladding to meet the demands of mobility for the concept house.

The idea for the structure of the house was to make use of a massive wood building system that could be used to create a rigid frame that was possible to separate into two parts to meet the mobility demand. The load bearing structure would also form the visible interior walls and roof of the house that lead to a need of integrating heat treated wood to that system. The idea of integration of heat treated wood to the structure elements as well as be the visible interior were supposed to give an industrialized touch to the design of the house.

The interior design of the house involved use Thermo-S heat treated Pine and Oak and to integrate those materials to the production of the massive wood boards required special attention to the altered properties of those materials.

The windows to the house where decided to make use of the heat treated wood material and to make that obvious it was decided that the wood should be visible wood. The use of visible wood and the size of the windows required special attention to the quality of the raw material before the heat treatment and to the final surface treatment of the window.

The design of the house also stipulated the use of a roof window and since there where no manufacturer in the region of Norr- and Västerbotten the screening for a company to manufacturing of a roof window in heat treated wood needed an expansion.

The entrance to the house where supposed to be through a front door with side windows and the architects choice of material from an esthetical perspective where Beech with Thermo-D heat treatment. Since non heat treated Beech is a wood material that swells and shrinks more than average wood this was a challenging choice of material.

Outside the entrance there where a wood decking with a pergola on top that also should be made of heat treated wood that involved a load bearing problem

Thus to meet the design requirements there where needs understanding of many of the processes of the manufacturing companies and the need for supplying them with correct quantity and quality of heat treated wood material, as well as specific development for this project.

Finally the series furniture for the interior of the house where designed by the architects using heat treated wood with several heat treatment levels and species to create contrast effects in the furniture material.

As no ready solutions where available for the design ideas the design work has been an iterative process closely connected to the development and experiments conducted in the project.

5. Concept house development

The descriptions in chapter 4.2 and 4.3 show that there where a number of solutions needed to fulfil the design of the apparently simple concept house.

To give an overview of the need of development involved with realizing the decisions concerning the design are summarized:

- The size of the house or modules of it are limited to the transport rules.
  The chosen solution where to have a rigid structure where the roof and gables could be separated and reassembled from the top of the house walls.

- The frame of the house should also be the visible interior wall and use heat treated wood for that purpose, creating need to integrate that material to the production of the massive wood sheets used for the frame.

- All visible wood should be heat treated, causing need to process a number of materials, develop appropriate products, and develop knowledge of the heat treatment process.

- The windows should be made of heat treated wood and the colour shall be translucent.
  The use of the house and using visible wood require high quality of the wood material and a transparent surface treatment suitable for outdoor use.

- An entrance door and side windows in heat treated Beech in a specific design and to meet standardized technical requirements on a door.

- Develop a Pergola with heat treated wood to meet design and load bearing requirements with heat treated wood.

- Develop a series of furniture specially designed by the architects with use various heat treated wood materials.
  (Not further discussed since the company Wood Line solved the realization of the furniture's, accept for the materials that where processed by the project)

The development of the concept house and the solutions to these design matters will be the topic of this chapter, where the development of the heat treatment process will be discussed in further detail and have a chapter of its own.

The development in this chapter will also reveal some of the problems of using a new material in existing production lines of established industries.

5.1. House framework development

The criteria's of the frame structure for the concept house are of both esthetical and technical nature. A reflection of meeting both esthetical and technical requirements is that it is a typical situation in all product development where the product shall meet the requirements of using it as well as attract the user to buy it.

The chosen model of constructing a house that is mobile with a limited disassembling needed and the architecture with a single room without any joint seem required a solution where the roof and gables could be separable from the top of the house walls.

This separation should be possible to do without dissembling the entire roof and cladding from the house, and the separation seem shouldn’t be apparent. The use of a sandwich construction with massive wood sheets and isolation made this possible, together with the use of a detachable cladding system.

The massive wood building system is developed together with Martinsons Byggsystem AB who is responsible for dimensioning of the strength for the structure and is therefore left out in this report. The integration of heat treated wood to the frame structure will be the topic here.

The integration of heat treated wood to the production of the massive wood sheets caused both logistical and technical problems.

The logistics where related to the limited capacity of the LTU heat treatment kiln that lead to the decision to buy the material with more volume need and perform Thermo-S heat treatment on the oak for the floor and back wall material. Thus the Thermo-S Pine material for the other walls and the roof where bought from Finland.

For the material to fit in the production of the massive wood sheets at Martinsons the heat treated wood needed to be planed to the specific dimension 19x94mm and to have a special end shape of the short ends of the boards. The specific end profile where only available at the Martinsons facility in Kroksjön.

Figure 9: Board Joint Profile for Massive Wood Sheet

Therefore the Thermo-S Pine from Finland where bought as sawn material from a supplier that deliver such a material within the timeframe of project. The supplier delivered a 22x100mm Thermo-S Pine from top log material to have a material with mainly sound knots due to the problems with black knots that fall out after a heat treatment. The Thermo-S Pine where planed to 19x94mm in Kroksjön.

After the planing several problems with the material where revealed, the material showed problems with:

- Sticker marks
- Number of knots
- Pith

Figure 10: Sticker Staining on Planed Heat Treated Wood

The problem with the sticker marks on the heat treated pine where that the stickers affected the colour of the boards at the contact area, these areas showed a lighter colour than the board in general. The cause of that is probably related to the thermal resistance of the wooden sticker used in the process.

The number of knots is related to the use of centre boards from the top of the log that results in boards with knots at a distance of every annual growth in length of the tree.
A second problem related to the use of thin centre boards of top log where that pith where still present on the boards and where occasionally present on both sides of the same board.
That was material qualities that the project desired to improve.

This lead to that every major heat treated wood producer in Finland where contacted with the desire to buy heat treated wood that used a raw material with A1 quality (Nordic Wood 1994). The answer received from all of the producers where that it wasn’t possible to deliver such a material within the timeframe of the project. In end the project got back to the first supplier that could deliver a 32x100mm material, which solved the problem with sticker marks by planning off considerably amount of wood to 19x94mm.

That incident made up for a test in the laboratory heat treatment kiln at LTU. Normally at the laboratory kiln metal stickers are used and the problem with sticker marks hasn’t been apparently. The conducted experiment tested the effect of sticker marks with stickers material of Stainless Steel, wood, Thermo-S wood, Thermo-D wood, and heat treatment processes where done at 190°C and 212°C. The result was evaluated in a 15 week project work of the LTU student Özgyr Gyner.

Further technical problems with using heat treated wood in the production are the altered properties of the wood affecting the wetting ability when gluing. On the Thermo-S (190°C) treated pine the change in wetting ability isn’t critical for the gluing process at the factory and by prolonging the time for the glue to wet the material within the specification for the glue type before put in to the high frequency glue press.

The glue used in the production of the massive wood sheets is of melamine type and is used in glued wood construction materials and the requirements of the glue are set in standards with very high demands. The lab manager of the glue supplier Casco, David Almkvist verifies the anxiety of gluing oak in general and heat treated oak in particular with the melamine glue type without affecting the strength of the glue joint.

To overcome the problem with the gluing in the massive wood production line it was decided to create a glued sandwich board in three layers with a thick heat treated oak board in the middle and pine board on the outside. This sandwich board where then thought to be split in two and then planned to the right dimension resulting in a board with an appropriate thick layer of heat treated oak on top.

Figure 11: Oak Pine Sandwich Board Material

To fit the glue line facilities at Martinsons in Kroksjön the creation of the pine-oak-pine sandwich board the oak layer should be of length of six meters and the heat treatment kiln at LTU only could produce material of 3 meters there where a need produce the six meter lengths by finger jointing the heat treated oak material.

Testing of finger jointing heat treated wood in general and oak in particular was an interesting test due to the increased brittleness of heat treated wood. Figure 12 shows a board of heat treated Oak after the milling the finger joint fingers and on the right side some cant damages occurs, but the extent is limited. In the lower part of the figure some of the samples fingers are broken not due to the milling itself but due to handling circumstances.


Figure 12: Finger Joint Milling of Oak

The result showed that finger jointing would be possible but there would be need for a less narrow finger profile due to the increased stiffness of Oak compared to the Pine used in the normal production. Also the hardness of the Oak material caused problems with the milling conveyer set up that couldn't hold the wood in place during the milling causing damage on both the wood and the machine.

Due to the problems with the finger jointing another partner was needed to perform the gluing of the Oak-Pine sandwich boards. That partner became the window producer Snidex that perform similar type of gluing to their production. The glue type in their production is of PVAC type and the glue supplier International recommends the amount of glue to be 100g/m² and with a short free air time.

After the gluing the result are tested with an easy splitting method showed in Figure 13 which indicates a successful gluing result.

Figure 13: Glue Joint Splitting

After the gluing the material is sent back to Kroksjön for planning and milling of the specific end profile required for the production line of the massive wood sheets and the result is shown in Figure 14. The milling of the specific end profile was tested in advance and the result proved it to be a possible method when the problems with cant damages where minor.

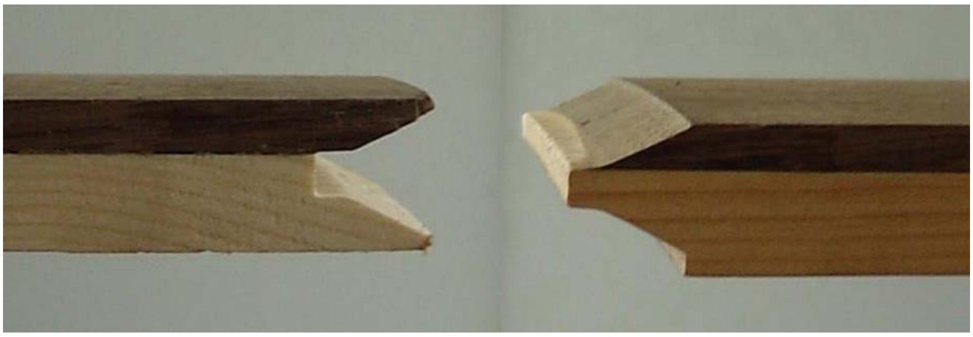


Figure 14: Finished Oak Pine Sandwich Board

The use of a sandwich board made the gluing possible in the production line and the weaker glue joint where moved closer to surface and minimizing the risk of decreasing the structure strength. Figure 15 show the method of moving the wooden sheets in the production line that also work as a test of oak glue joint.

Figure 15: Oak Pine Sandwich Sheet in 12m length

When the gluing of the massive wood sheets where conducted the sheets where cut and milled to specific shapes to fit the frame structure construction before assembling (Figure 18). When ordering the production of the house frame the integration of all details concerning the entrance, windows, cladding system and electricity needed to be ready for being able to cut and mill the openings of the house and the canals for the electricity (Figure 16). This integration needed close interaction with Martinsons that created a 3-D model of the frame from the 2-D specifications of the author. Before the frame is put in production this the 3-D model of Martinsons is approved by the author (Figure 17: 3D-model of the house frame).

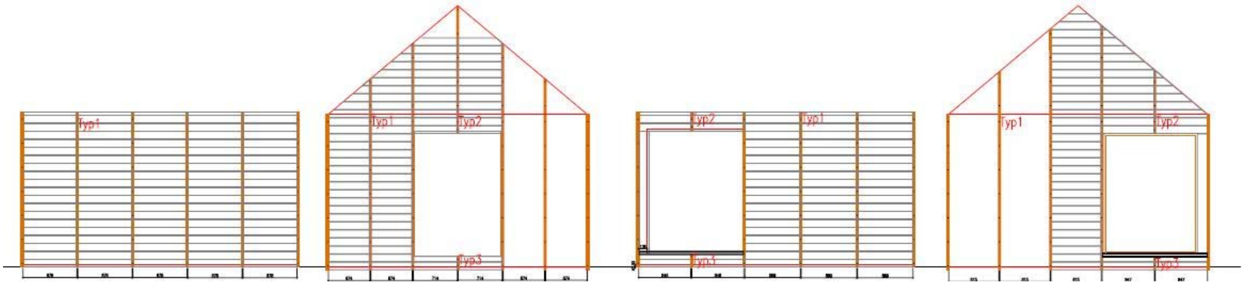


Figure 16: Frame Integration Complexity Example

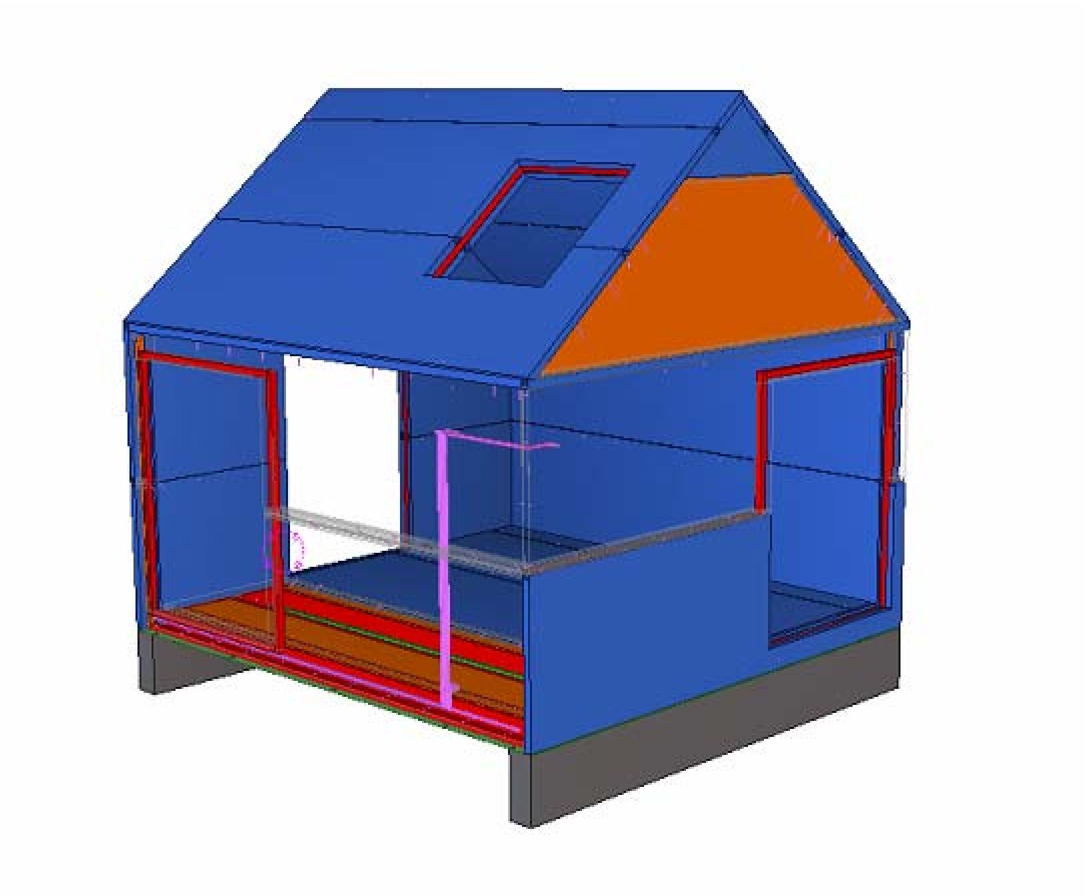


Figure 17: 3D-model of the house frame

Figure 18: Massive Wood Sheets before Assembling

Figure 19: Deliverance of House Frame

Finally all the problems of integrating the new material of heat treated wood to the production of the massive wood and isolation sandwich frame where overcome and the framework for the house could delivered to the place for the building of the concept house. (Figure 19 and Figure 20)

Figure 20: Wood Frame Interior

5.2. Cladding and Roof development

The development of the cladding system and the wooden roof was a challenging task due to the interaction with a number of materials, systems and companies and both timing and specifications needed to work together. The material should of course be heat treated wood and the chosen material was Spruce, heat treated at 212°C (Thermo- D). The choice of material was due to low capillary absorption abilities of heat treated spruce the make it an appropriate outdoor material.

5.2.1. The Cladding

The architects had an idea of an architectural expression of the house with a cladding in modules in a column arrangement. That would give the possibility to work with different colours (levels of heat treatment) of the cladding material to give a special appearance, illustrating the possibility of the process to control the colour change of the material.

There where also a need for a cladding system allowing partial disassembling to meet with the mobility requirement and the chosen solution for the house frame that where separable at the roof baseline and the assembling screws where placed on the outside of the frame walls. As the cladding where decided to use heat treated spruce treated at 212°C the material is more brittle than normal wood and require pre drilling if mounted traditionally with nails.

The chosen way to go on these matters became to develop a steel cladding assembly system where the wooden cladding hang up on a ladder system and then clamped by a rail steel profile that is screwed into the frame (Figure 21 Figure 22). That system would also allow a conceptual idea of a more industrialized cladding repair where the cladding could be removed and planed to get a ground for a new painting system if the old paint needs to be restored.

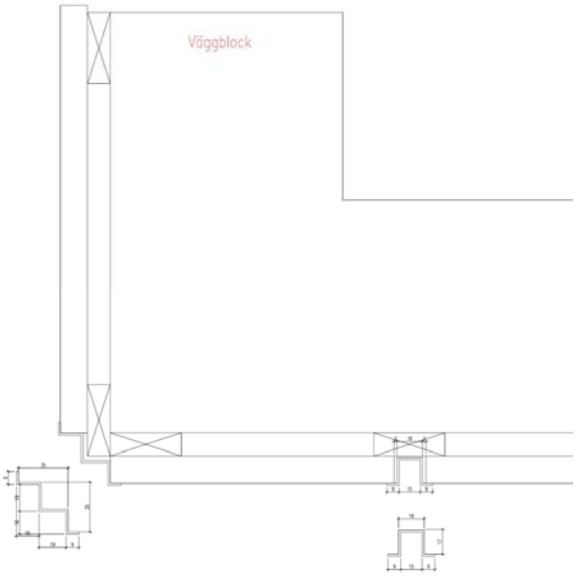


Figure 21: Cladding Assembly Clamps

Figure 22: Cladding Assembly Ladder & Clamp

The assembly system was produced in 1,5mm thick stainless steel and then powder coated to fit in colour of the house. To have enough clamping power to withstand the wind load on a one floor buildings in typical urban density of buildings the number of screw holes and their distribution where designed according to equation (5.1) and (5.2).

The characteristic wind load is calculated by:

$$w_k = \mu q_k = 0{,}46 * 1 = 0{,}46 kN / m^2$$

5.1[27]

w_k = *characteristic wind load [kN/m²]*
q_k = *characteristic velocity pressure [kN/m²] = 0,46*
μ = *shape factor from appendix*[28] *= 1*

The elongating force of screw perpendicular anchored to the wood is calculated by:

$$R_{tk} = 11(2{,}5 + d)(l_g - d) = 11(2{,}5 + 4{,}8)(30 - 4{,}8) = 2023 N$$

5.2[29]

R_{tk} = *Force to elongate [N]*
d = *Screw diameter [mm] = 4,8*
l_g = *length of screw thread anchored in the wood [mm] = 30*

Due to the powder coating the profiles couldn't be cut during assembly and that caused a need for a very specific length for each of the profiles when ordering for the production of the system. This where also complicated by the joint between the house two separable parts and the solutions for the door and window openings that required precise dimensioning (Figure 23). Thus became the dimensioning of the cladding system dependent on the dimensioning of the house frame and the planned solutions for the door and windows.

Figure 23: Cladding Assembly System Overview

The profile of the cladding boards where designed to fit on the ladder and clamping system of the assembly and the planned horizontal orientation of the boards required a design suitable

[27] Boverkets Handbok om snö- och vindlast BSV 97
[28] Boverket and Boverkets Handbok om snö- och vindlast BSV 97
[29] Regelsamling för konstruktion - Boverkets konstruktionsregler BKR

for water run off from the cladding. The developed design gave the board a 30° sloping top and on the bottom of the board there where a drip nose for easy water take off from the board to the next. The distance between the drip nose and the next board where designed to be 7mm to avoid water drops staying between the boards and through capillary forces be sucked in behind the cladding.

This type of design with a drip nose on horizontally orientated boards is seldom used and is not part of the standard product range for wooden cladding profiles of the Swedish industry[30], and was developed with knowledge input from the architects of the project (Figure 24).

Due to the altered properties of heat treated wood the increase brittleness makes a sawn surface loose in its structure and therefore it’s favourable for the performance of the paint system to have a planed surface for the cladding as well as for the roof panelling boards.

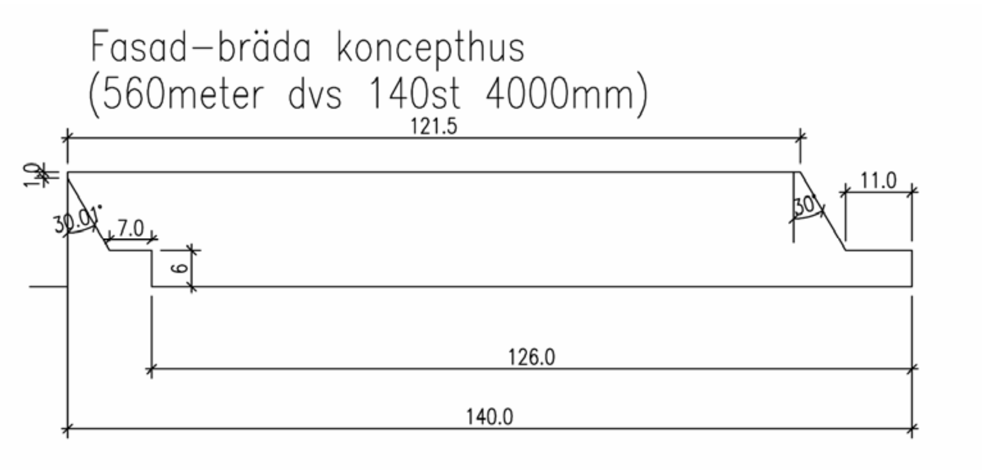


Figure 24: Cladding Board Profile

[30] http://www.traguiden.se

Figure 25: Assembled Cladding

5.2.2. The roof

The author wanted the architects to find a solution for using heat treated wood as an outer roof material because the exposure of a roof material would be a tough test of the material.

The traditional method of using wood as an outer roofing material where to use wooden chips placed side by side vertically in horizontal rows of centre from each others, or by using vertically oriented boards as a lock panel system along the whole roof plane that where the methods presented by the architects.

The use of wooden chips roof system where considered to be to time consuming in the assembling and where therefore excluded, and the lock panel didn't fit the desired architectural expression of the house. These problems raised the idea of constructing a system with tilted horizontally oriented boards that solved the problem with the architectural expression. The roof material where decided to be made of the same sawn material as the cladding material to lower the cost and ease the access of the heat treated wood.

To avoid water penetration of the roof a system for assembling the boards where needed where the nailing of the boards could be concealed and still hold the board securely on the top as well as on the bottom side of the roof board to withstand the wind load.

The chosen solution for those problems where to develop a system with roof boards with a specific profile and wedges with a matching profile that can lock the bottom of the horizontally oriented board to the roof. The wedges should be mounted on the roof board equal to the number and distance as the batten that the roof boards are mounted on (Figure 26).

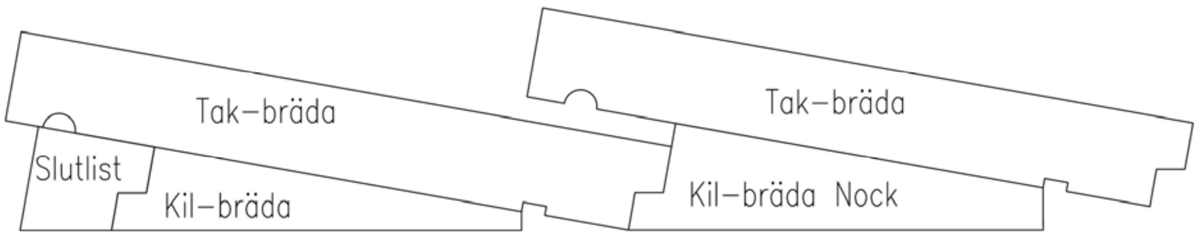


Figure 26: Board System for the Outer Roof

Beneath the roof boards at the ridge the wedges where designed to be thicker to create an opening for circulating air beneath the outer roof.

As water drains over the roof boards the close connection to each other at the overlapping area capillary forces will make water absorb between the boards. To overcome this capillary phenomenon, a 5mm half circle rill is added to the profile. The square shaped rill of the down side of the board is for aiming when mounting the wedge to the roof board. The roof system is exemplified in Figure 27.

Figure 27: Roof System at Assembling

The dimensioning of the fastening of the roof boards are similar to the one for the cladding but involves both nailing and screwing. The upper part of the horizontally oriented board is nailed with 75mm nails and the lower part is hold by the wedge that is screwed to the roof board with two screws. Since the wedge is clamped to the roof by the roof board below it is the nailing that sets the dimensioning.

The characteristic wind load is calculated by:

$$w_k = \mu q_k = 0{,}46 * 1 = 0{,}46 kN/m^2$$

5.3[31]

w_k = *characteristic wind load [kN/m²]*
q_k = *0,46 [kN/m²] = characteristic velocity pressure from table*[32]
μ = *1=shape factor from appendix*[33]

The elongating force of nail perpendicular anchored to the wood is calculated by:

$$R_{tk} = d * l * f_{tk} = 4 * 50 * 0{,}9 = 180N$$

5.4[34]

R_{tk} = *Force to elongate [N]*
d = *Nail diameter [mm] = 4*
l = *length of nail anchored in the wood [mm] = 50*

[31] Boverkets Handbok om snö- och vindlast BSV 97
[32] Boverket and Boverkets Handbok om snö- och vindlast BSV 97
[33] Boverket and Boverkets Handbok om snö- och vindlast BSV 97
[34] Regelsamling för konstruktion - Boverkets konstruktionsregler BKR

f_{tk} = *strength parameter from table [MPa] = 0,9*

Thus there is need for three nails every square meter and that is more than fulfilled in the use of nails for securing the roof.

5.3. Window development

Windows is a product type where the use of wood as a frame material sees an increased competition from substituting materials. Therefore there are numerous technological developing activities to increase the advantages of using wood and avoiding the drawbacks.

Using heat treated wood in window production is one of these activities and the experiences from the concept house project are of interest for the development of the heat treated material as well as the development of wood material for windows.

Figure 28: Window integration to concept house

A window is a far more complex product than apparent and by looking into the European norm EN 14351-1[35] one gets an idea of the complexity the window producer is confronted with. As well as there is a European standard for the window as a product there are requirements for the wood material to use within the product that are compiled in the European standard EN 14 220[36].

For this project it was too complicated and expensive to find a supplier of small volumes of wood material to meet such requirements as in EN 14 220. Therefore wood material for the windows of the concept house were hand selected from different local suppliers with as high quality as possible.

The size of the windows in the concept house and the will to have an object of demonstrating value creates high requirements on the selection of material for the windows. The dimension

[35] European Standard EN 14351-1, Windows and Doors –Product standard, performance characteristics Part 1

[36] European Standard EN 14220, Timber and wood-based materials in external windows, external door leaves and external doorframes – Requirements and specifications

of the wood used in a window frame generates the need for a heat treatment process that can produce heat treated wood in thicker dimensions without internal checking.

The first try used a wood material of 75x170mm for meeting the architectural desire of a special frame profile adapted to the frame of the concept house. A high quality material was selected for the heat treatment and the first check of the result indicated a successful processing. However at the window producer the material turned out to have problems with internal checking and with knots falling out from the material.

The problem with knots falling out has to do with the heat treatment temperature that causes the resin to melt and evaporate and it's the resin that holds black knots in place in a wooden board.

Thus the problem with knots falling out is a matter of material selection. The problem is to find wood material of 50mm or thicker with widths exceeding 150mm with three sides mainly free of knots and without black knots. For window material in window applications with visible wood of pine there are very high requirements and such material many times are selected already in the forest and commands a price of such Pine wood material that many times are related to hardwood for joinery production.

What is further making the selection complex is the shrinkage during the heat treatment that causes a need for greater margins in dimension for a particular product, such as window frame material. This greater margin is a loss of material as well as it causes a need to consider what material is planed away. For example if planing a board in a three sided knot free quality of a thicker dimension one do not know exactly where the knots in the wood starts to appear as shown in Figure 29 where each planing removes 1mm of material.

The solution to both the problems with internal checking as well as to the knot free quality became to use a three sided knot free material of thinner boards that were heat treated at 212 °C and then glue laminated.

Figure 29: Planing on three sided knot free material

By multiple planing a board by 1mm each time an additional problem showed up that exemplifies the weaker connection between the annual growth rings of the wood material that is caused by the heat treatment.
Figure 30 show thin layers of annual late wood of the heat treated wood starts to fringes form the surface after planing one to three and after the fourth planing a major piece from the material is lost.

Thus the increased brittleness of the heat treated wood material and the selection of wood to avoid black knots, are problems that need consideration when using heat treated wood in windows.

Figure 30: Multiple planing of one board sample

An additional variant of the problem of the decreased binding between the annual growth rings in the heat treated material is exemplified in Figure 31 where the joining of window profiles weren't considered the change in material properties. The joining showed no signs of glue and the only securing of the joint were a screw with a less strategic position.

If continuing with the producer of the roof window (from south of Sweden) they recognized the lower moisture content of the heat treated and predicted problems of swelling. The material used in their production has a target moisture content of 12% and their measurements of the heat treated wood showed a moisture content of 6%. Fortunately this correspond exactly to the 50% reduced equilibrium moisture content of Pine heat treated at 212°C.

Figure 31: Roof Window Breakage

5.3.1. Electrostatic painting of window frame materials

Within the project there was an opportunity to cooperate with Becker-Acroma in evaluating the method of electrostatic painting on heat treated wood. Electrostatic painting is an industrialized method for painting wooden frame material used in the window producing industry and the concern was weather the changed properties of electrical conductivity of heat treated wood affects the function of the electrostatic paint method

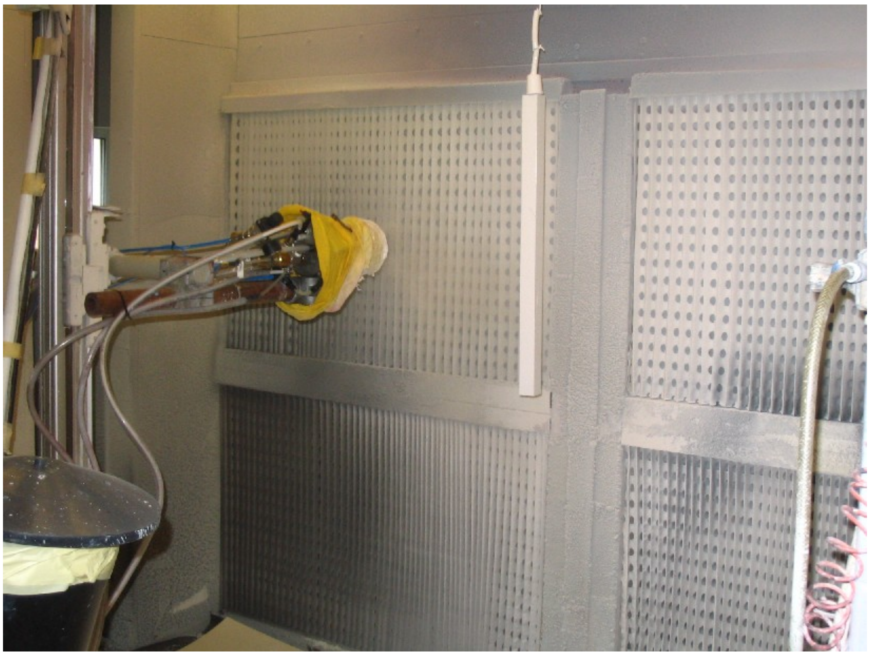


Figure 32: Electrostatic Painting

An electrostatic paint spray system is a highly efficient method for applying paint to specific work pieces. The technology uses negatively charged atomized paint particles and a grounded work piece creates an electrostatic field were charged particles are attracted to the grounded work piece.

This attraction causes paint particles that pass a work piece to be attracted to and deposited on the back of the piece. That phenomenon is known as "wrap" and results in a nearly surrounding paint covering of the work piece.

The experiment was conducted at the laboratories at the head office of the paint producer Becker-Acroma outside of Stockholm and heat treated Pine and Spruce where compared to no heat treated Pine in order of paint film thickness.

Wood sample material		
Specie	**Heat treatment**	**Dimension (mm)**
Pine	-	45x45
Pine	190°	26x92
Pine	212°	45x45
Spruce	212°	45x45

Figure 33: Electrostatic Paint Evaluation Material

The settings of the equipment for the electrostatic painting where kept constant during the experiment and are showed in Figure 34.

Electrostatic coating equipment settings			
Paint feed (bar)	**Conveyor speed (m/s)**	**Distance to object (cm)**	**Icebell (rpm)**
2	2,60	16	30 000

Figure 34: Settings of the Paint Equipment

The test procedures where designed with four series with three samples of each material, see Figure 33, together with equal amount of reference material of Pine. Each sample where measured at the upper part, in the middle, and on the lower part of the sample. Each sample where measured on four sides (Figure 35). Three of the series used primer paint and on the fourth series a top layer where applied on some of the samples from the first three series.

Figure 35: Measurements on Coat Thickness

The results illustrated in Figure 36 show that using heat treated wood in an electrostatic paint system would give a coat thickness equal to non heat treated wood. The results for heat treated spruce shows a less coat thickness but the likely explanation is that the surface smoothness after planing of the spruce weren't equal to the same on the other samples. On series 3 the heat treated spruce samples where sanded to achieve a smother surface. Though by doing so the structure became much different than to the planed samples and therefore the paint likely is absorbed to the material differently and therefore affecting the paint film thickness negatively.

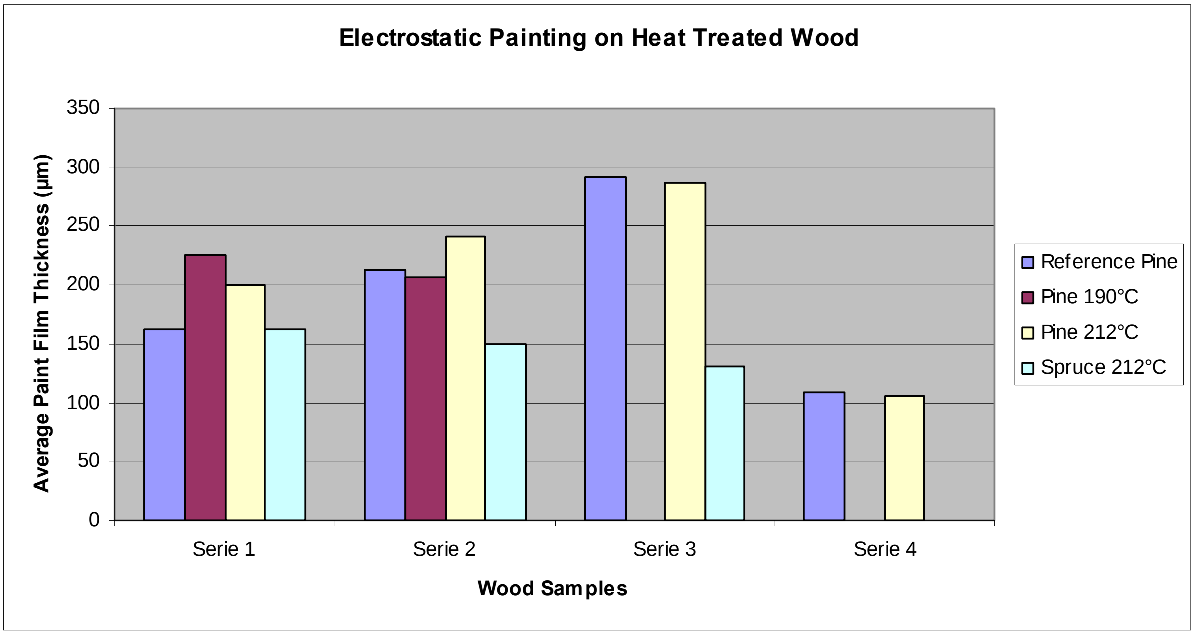


Figure 36: Paint Film Thickness from Electrostatic Painting

When considering the production capacity of electrostatic paint system line or other production painting line using oven drying of the work pieces a beneficial of using heat treated wood can be found due to the possibility to use an increased drying temperature without any secretes of resin on the work piece.

During the trials of electrostatic painting the samples were oven dried at a temperature of 35°C and with an air flow of 1,8m/s for 90 minutes duration. When testing an increased temperature of 60°C the duration where decreased to 45minutes and there where no signs of resin secrete yellowing the heat treated painted samples.

Figure 37: Oven Drying of Painted Samples

The reason for this improvement is due to the temperatures used for the heat treatment of wood that causes resin in wood to evaporate from the wood. Which is a valuable property of heat treated wood also for the lifetime of the window product since colour stains from secreting resin from the window frame material is avoided.

The experiment also raises the question weather high temperature drying above 100°C can be used for decreasing the problems with yellow stain from secreting resin from the window frame material and increase the esthetical lifetime of a window as a product.

5.4. Entrance door development

For the entrance door development to the concept house there where a need to find a solution for meeting the design requirements from the architects and the production requirements from the producer and to supply both with required knowledge for the manufacturing of an entrance door in a heat treated material.

To fulfil the vision of the project of illustrating the use of heat treated material from many of the home-grown species of Sweden with a wood mechanical industry, and to match the colouring design of the house, the chosen material became Beech, heat treated at 200°C.

The problem with using a material like beech in door blade construction is the swelling and shrinkage characteristics of that material that are higher than most other Swedish wood species (Figure 38).

Shrinkage direction	Beech	Birch	Pine	Spruce	Oak
Parallel to grain from green to dry (%)	0,3	0,6	0,4	0,3	0,4
Radial from green to dry (%)	5,9	5,3	4	4,2	5
Tangential from green to dry (%)	11,8	7,8	7,7	8,8	10

Figure 38: Shrinkage Characteristics of Wood Species[37]

What was further problematic was the lack of data on the swelling characteristics of corresponding heat treated wood, which lead to the set up of a test for the swelling and shrinkage characteristics of available heat treated materials in the project.

Building a door blade of an entrance door is far more demanding than it would appear. An entrance door is exposed to both outdoor- and indoor climate, where the temperature and the humidity are the main factors affecting the dimensional change of the door blade materials and are illustrated in Figure 39.

[37] Boutelje, Rydell, 1989, Träfakta – 44 träslag i ord och bild

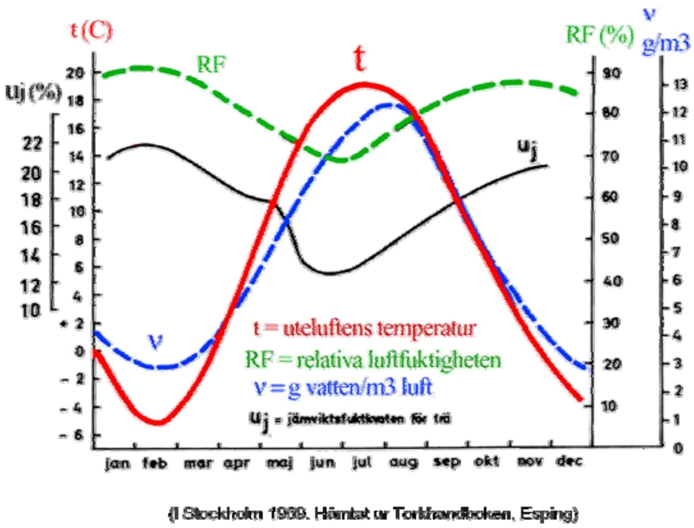


Figure 39: Seasonal Outdoor Climate in Stockholm

As the absolute humidity of the air during the winter is low usually result in an indoor climate with low relative humidity since the cold outdoor air is warmed up. This creates a dryer indoor climate than on the outside during the winter months that affects the dimension of the door blade.

The organization Svensk Fönster & Dörr kontroll, SFDK[38] have composed approval regulations for the manufacturing of doors and windows. According to the SFDK categorization of door blades regarding dimensional stability they have stipulated three quality classes for doors. SFDK uses the requirements for dimensional stability from the European standard EN 12219[39] when stipulating their classes.

Class A	EN 12219 class 2 (Twist ≤ 4mm Bow ≤ 4mm Cup ≤ 2mm)
Class B	EN 12219 class 2 (Twist ≤ 4mm Bow ≤ 4mm Cup ≤ 2mm)
Class C	EN 12219 class 1 (Twist ≤ 8mm Bow ≤ 8mm Cup ≤ 4mm)

The door producer involved within the project manufactures doors that are customer adapted and have no standard model in their production. Still they have a typical construction set up and the use of oak as outer layer material is predominantly. They typically use an aluminium foil as a moisture barrier on both sides of the door blade.

The European standard EN 1121:2000[40] describes the climate that door are to be tested against to measure twist, bow, and cup of the door blade when to be classified to EN 12219.

The standard EN 1121 reveals that the maximum relative humidity (RH) the door blade is exposed to in the testing procedure is 85% at 3°C on side 2 of the door blade (outside) and on side 1 the climate is 23°C with a 30% relative humidity. The minimum relative humidity of the outside is 50% at a temperature of 18°C. The minimum outdoor temperature for the tests is -15°C and at that temperature the relative humidity is unspecified.

[38] www.sfdk.se
[39] EN 12219 Doors – Climatic influences – Requirements and classification
[40] EN 1121 Doors – Behaviour between two different climates – Test method

To resemble the temperatures affecting a door blade in use exposed to sun radiation a summer day the test procedure of EN 1121 requires an indoor temperature of min 20°C and max 30°C and that the outdoor climate of a radiation source of IR-lightning should be the indoor temperature plus 55°C.

Thus from the test procedure in EN 1121 the minimum and maximum relative humidity's affecting the material of the door is 30% and 85%. Correspondingly the min and max temperature is -15°C and 85°C. These climate extremes can then be used for calculating the climate affect on the materials of the door leaf.

The design of the door (Figure 40) with horizontal oriented lamellas with spacing allowing the material of each lamella to shrink and swell will have negligible effect on the bow of the door blade and is therefore not taken into account in the calculations. Though is the length of the horizontal lamellas affecting the cup of the door blade if the material would vary in length dimension due to humidity variations.

Figure 40: Door Blade Construction

The maximum change in humidity in EN 1121 testing procedures is from 85% RH to 30% RH resulting in a ΔRH of 55% for the outside. By looking in tables[41] the corresponding change in equilibrium moisture content of the wood will be 9,9% EMC when affected of a climate change of 55%RH. Thus the change in length of a Beech (if non heat treated) material without surface treatment of lacquer would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{9,9}{30} * 0,003 * 824 = 0,82mm$$

5.5

ΔEMC = *change in equilibrium moisture content of climate*
$MC_{fibresat}$ = *moisture content at saturation point (correlated to shrinkage in* Figure 38*)*
Shrinkage = *shrinkage values in* Figure 38
Length = *Length of the horizontal wooden lamella in* Figure 40

Examining the interior design of the door blade that uses a flat surface of a wooden sheet of heat treated Beech material with a vertical grain direction. This will result in a tangential shrinkage/swelling of the door blades horizontal direction affecting the cup characteristics of the door blade. The indoor climate of the test EN 1121 is rather stable and the maximum change in humidity is 10%RH which is equal to a change in EMC of 2,7%.
Thus with a non heat treated wood material the tangential dimensional change would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{2,7}{30} * 0,118 * 824 = 8,75mm$$

5.6

The vertical dimensional change of a non heat treated wood the wood on the indoor side would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{2,7}{30} * 0,003 * 1923 = 0,52mm$$

5.7

If comparing the dimensional change of the wood due to humidity change with the thermally induced dimensional change of the aluminium the door manufacturer typically uses as climate barrier. The European standard EN 1121 reveals the ΔT of 85-(-15°)C, thus ΔT = 100°C. Thus will the dimensional change of the aluminium in the door under the influence of the testing in EN 1121 be:

$$WidthDoorblade * \alpha * \Delta T = 824 * 23 * 10^{-6} * 100 = 1,9mm$$

5.8

$$HeightDoorblade * \alpha * \Delta T = 1923 * 23 * 10^{-6} * 100 = 4,42mm$$

5.9

Door blade = *height and width of door blade*

[41] Esping 1992, Trätorkning 1a

α = *thermal expansion coefficient of Aluminium*[42]
Shrinkage = *shrinkage values in* Figure 38
ΔT = *temperature difference from max and min values in EN 1121*

These calculations indicates that the swelling/shrinkage of the inside of the door blade can be problematic for meeting the requirements in EN 12219 regarding cup if using non heat treated Beech material.

It is therefore a need to know more about how the material dimensional stability changes with heat treatment at different temperatures and with different species, especially with the chosen design of the door blade. Since there is limited information available from other investigation in this matter on these materials a test of the affect of heat treatment on the climatic dimensional changes of wood.

After the results from the test the affect on the cup and bow that the climate induced dimensional changes of the material causes on the door blade.

5.4.1. Test of dimensional stability on various heat treated hardwoods

The test has been conducted on five Swedish hardwood species Ash, Aspen, Beech, Birch and Oak and the samples are heat treated at 170°C, 185°C, 200°C and a reference that is not heat treated. Each specie and temperature has 3 sample and the samples are 100x100x20mm in size

After heat treatment the samples are made and weighted and measured before put in to climatic chambers. One sample from each heat treatment level is put in to each climatic chamber. After 26 days the samples are weighted and measured and again put into the climatic chambers, but now in new climate, from RH 25% to RH65% to RH85%. The procedure is showed in Figure 41.

[42] Handbok och formelsamling I Hållfasthetslära, Institutionen för hållfasthetslära KTH

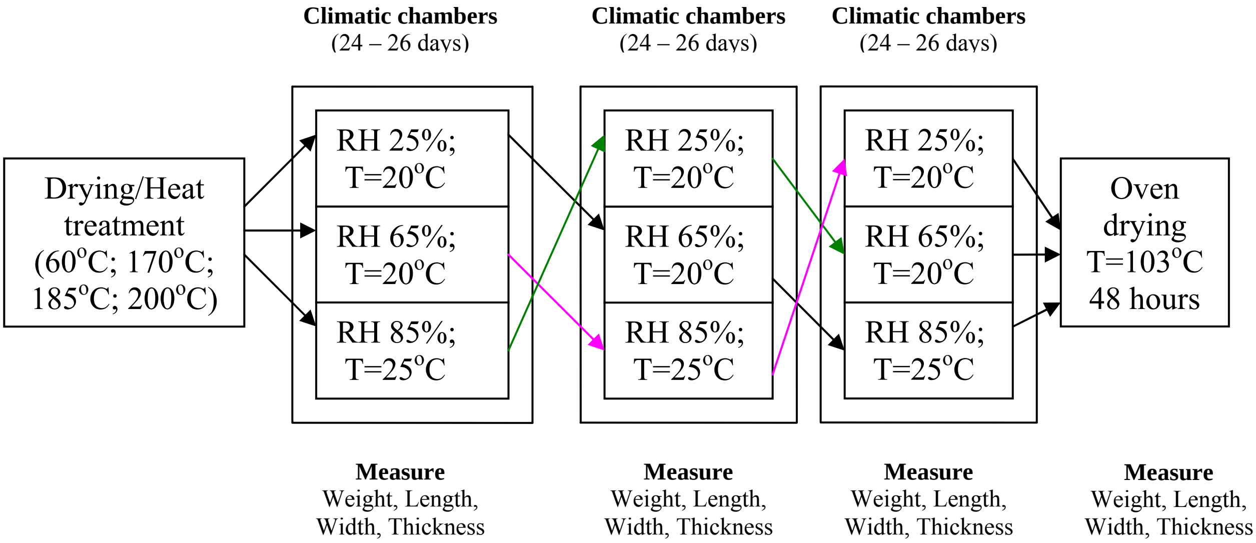
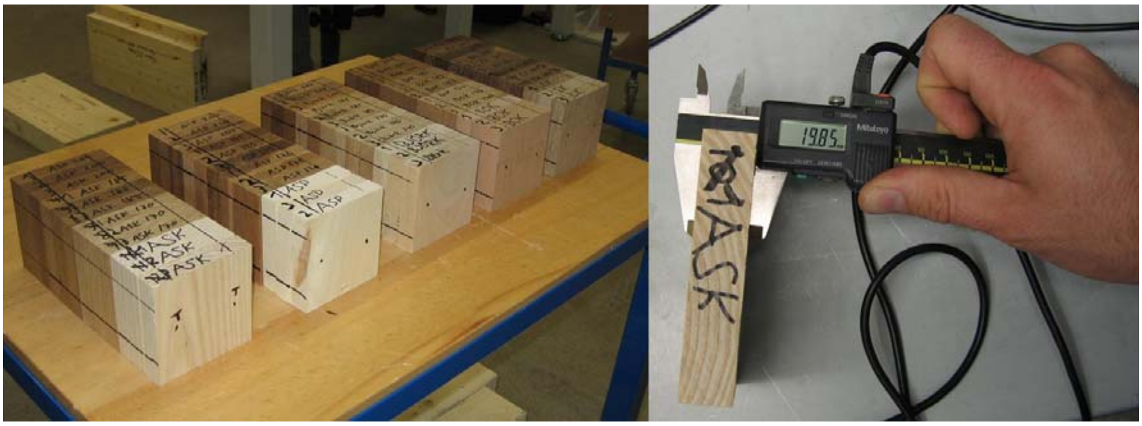


Figure 41: Climate Test Procedure

The test samples are weighted with a digital scale.
The test samples are measured with a digital calliper, measuring length, width, and thickness at 2 places each.



There have been 3 climatic chambers in use in this test.

- Chamber 1 – RH 25% and T 20°C
- Chamber 2 – RH 65% and T 20°C
- Chamber 3 – RH 85% and T 25°C

After the test runs in the climatic chambers the samples has been oven dried in 103°C for 48 hours. Note that the oven dry method is for 24 hours, hence one can consider if any noticeable amount of extractives have absent the samples affecting the dry weight measurements.

The results show that with increasing heat treatment temperature a decrease in swelling/shrinkage characteristics are reached. (Figure 42, Figure 43, Figure 44, and Figure 45)

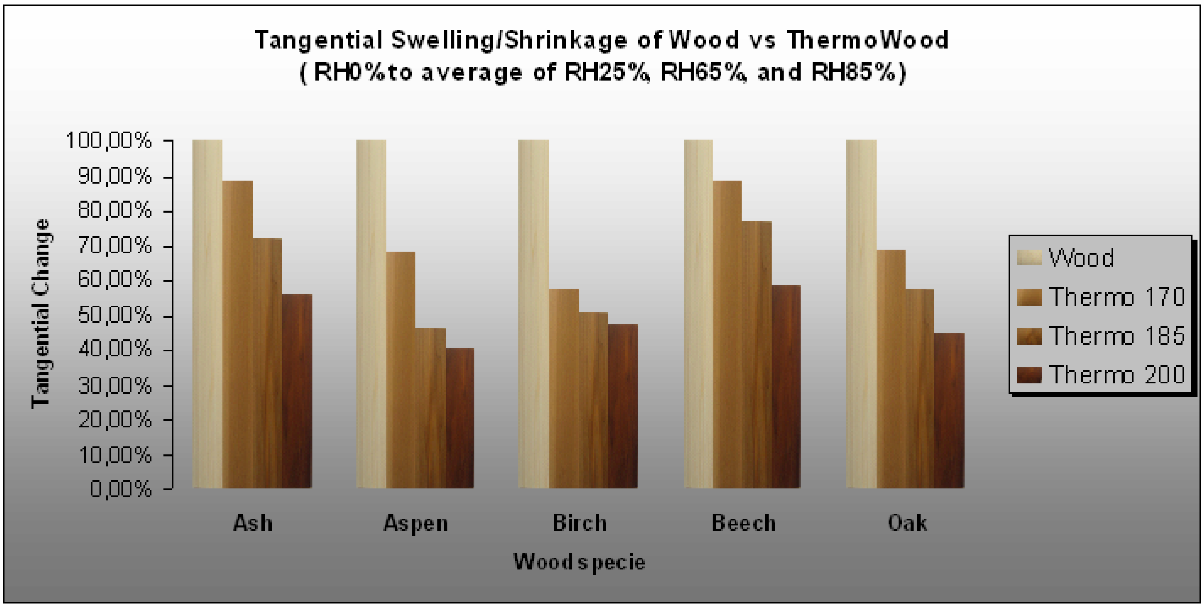


Figure 42: Tangential Swelling/Shrinkage of Heat treated Wood vs Wood

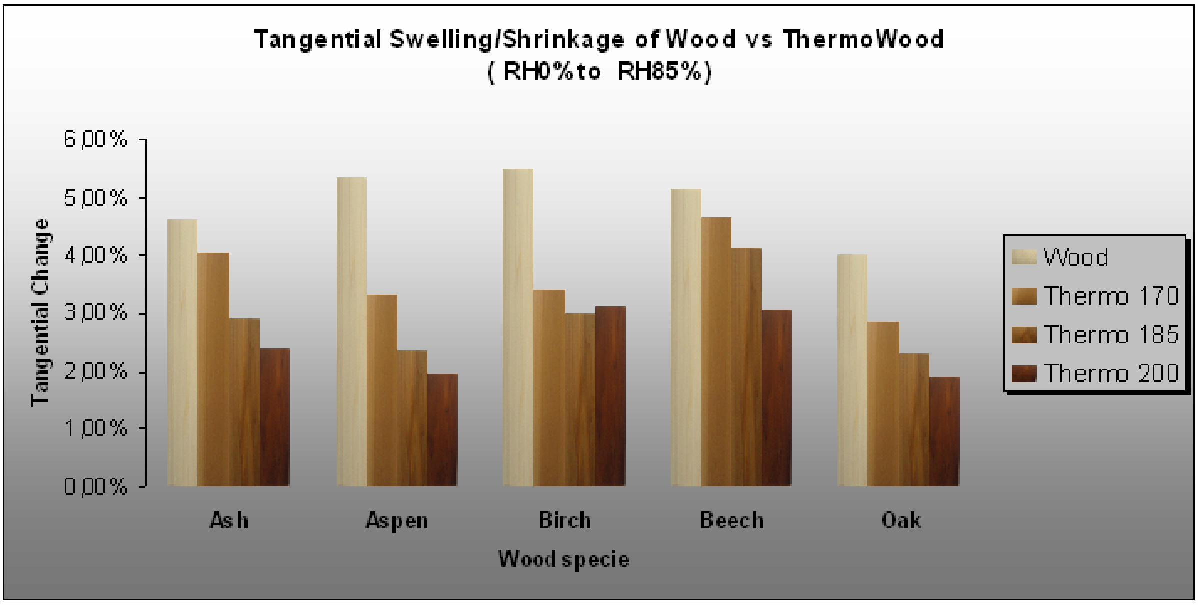


Figure 43: Actual Tangential Swelling/Shrinkage of Heat treated Wood vs. Wood

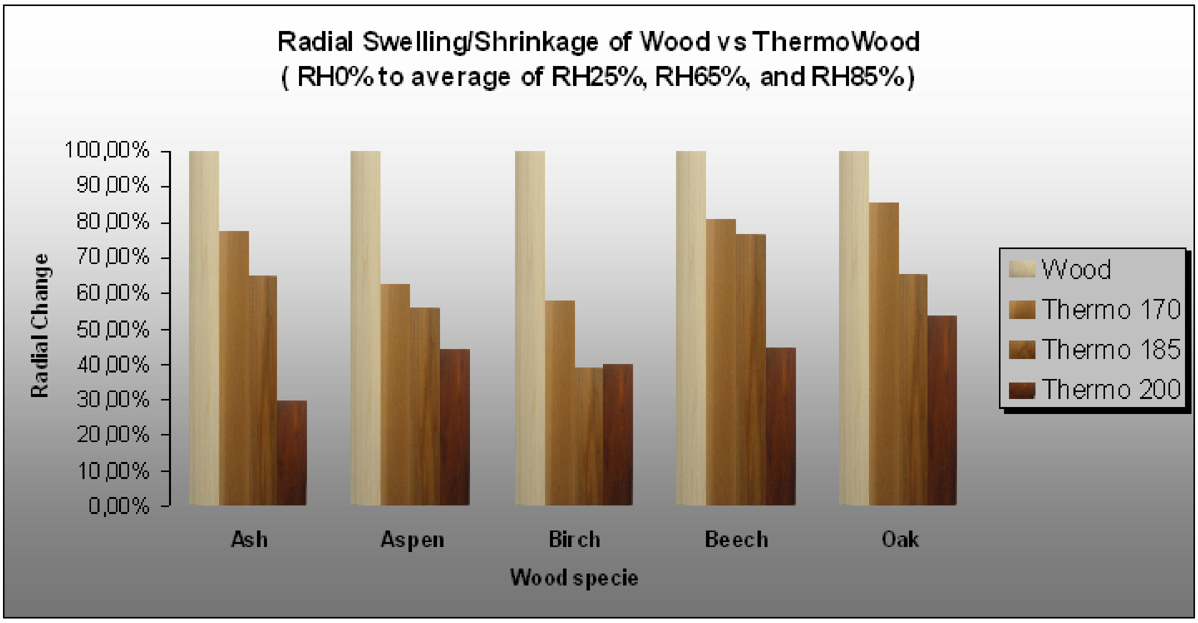


Figure 44: Radial Swelling/Shrinkage of Heat treated Wood vs. Wood

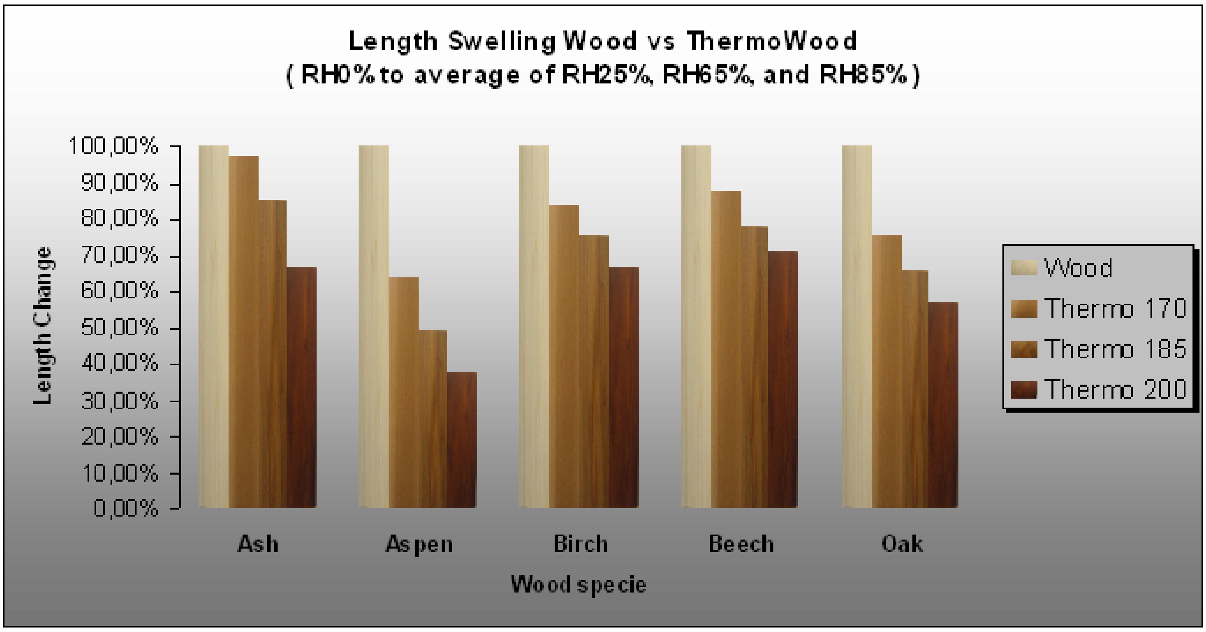


Figure 45: Length Swelling/Shrinkage of Heat treated Wood vs. Wood

5.4.2. Further door blade calculations

With the knowledge about the increased dimensional stability reached by the heat treatment of the wood from the test, further door blade calculations can be done with the new data.

Shrinkage direction	Beech	Beech 170	Beech 185	Beech 200
Parallel to grain from green to dry (%)	0,3	0,26	0,23	0,21
Radial from green to dry (%)	5,9	4,77	4,51	2,64
Tangential from green to dry (%)	11,8	10,49	9,09	6,92

Figure 46: Shrinkage Characteristics of Beech Wood Species

Thus with the new data the calculations of equations 5.5, equation 5.6, and 5.7 can be recalculated according to EN 1121 testing procedures.

The swelling of the horizontally orientated Beech 200 lamella on the door outside would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{9{,}9}{30} * 0{,}0021 * 824 = 0{,}57mm$$

5.10

The tangential swelling of the vertically orientated Beech 200 wooden sheet on the door inside would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{2{,}7}{30} * 0{,}0692 * 824 = 5{,}13mm$$

5.11

The longitudinal swelling of the vertically orientated Beech 200 wooden sheet on the door inside would be:

$$\frac{\Delta EMC}{MCf_{ibresat}} * Shrinkage * Length = \frac{2{,}7}{30} * 0{,}0021 * 1923 = 0{,}36mm$$

5.12

ΔEMC	*= change in equilibrium moisture content of climate*
$MC_{fibresat}$	*= moisture content at saturation point (correlated to shrinkage in* Figure 38*)*
Shrinkage	*= shrinkage values in* Figure 38
Length	*= The door blade dimensions in* Figure 40

Though these values show improvements by using Beech heat treated at 200°C the choice of design still generates a tangential swelling horizontally on the inside of the door blade that can cause the to cup.

By assuming that the use of aluminium in the door blade is verified and proved working considering the thermal expansion of the material the thermally induced tension on the aluminium layer, that can be served as a comparison to the humidity expansion of the heat treated beech wood.

The thermal expansion of the 0,4mm thick aluminium layer in the door in the test climates of EN 1121 causes a tension in the door that can be calculated as:

$$\sigma = E * \alpha * \Delta T = 70 * 10^3 * 23 * 10^{-6} * 100 = 161MPa$$

5.13

σ	*= thermally induced tension on Aluminium*
E_t	*= E modulus of Aluminium*
α	*= thermal expansion of Aluminium*[43]
ΔT	*=temperature span in the test procedure of EN 1121*

If doing the assumption that the E modulus of heat treated Beech is similar to non heat treated Beech, the tension caused by the 8mm thick heat treated Beech in the door blade would be:

[43] Handbok och formelsamling i Hållfasthetslära

$$\sigma = E_{\tan Beech} * \alpha * \Delta u \frac{\Delta EMC}{MCf_{ibresat}} = 0{,}065 * 11900 * 0{,}0692 * \frac{2{,}7}{30} = 4{,}82 MPa$$

5.14

σ	= *humidity induced tension on Beech*
E_t	= *E modulus of Beech in tangential direction*
α	= *shrinkage values in* Figure 46
ΔEMC	= *change in equilibrium moisture content of indoor climate in EN 1121*
$MC_{fibresat}$	= *moisture content at fibre saturation point (correlated to shrinkage from green)*

Since the aluminium layer and the heat treated Beech wood layer have the same area of the door the force affecting the door blade will be comparable by correcting for the thickness of the layers. When the Beech wood layer is 20 times the aluminium the force would correlate to the tension caused by the materials in the EN 1121 testing procedures. Thus the force correlation would be:

$$\sigma_{\tan Beech} * BeechThickness \leq \sigma_{ALUMINUM} * Alu\min iumThichness \Rightarrow 4{,}82 * 8 \leq 161 * 0{,}4$$

5.15

5.4.3. Conclusion

The calculations show that the heat treated Beech wood would be affected by the climates in the EN 1121 testing procedures if not being coated with a lacquer that further reduces the wood moisture absorption. The resulting force of the woods dimensional changes would still be less than the force from the thermal expansion of the aluminium layer in the door blade.

Therefore would the design wishes of the architects be possible to fulfil with the production possibilities of the door manufacturer and the project as a material supplier.

5.5. Pergola development

For the development of the pergola to the concept house there has been use of new to the world technology of heat treated wood that likely can be developed further for industrial applications of the material. The wood in the pergola have been heat treated at 212°C to get a highly durable material for outdoor use above ground.

The by appearance easy task of construction where no obvious load are to be applied to the structure wouldn’t be a problem even with the reduced strength properties of heat treated wood. By adding the possibility that someone uses the pergola roof crossbars as a platform during the house assembly or that someone reaches for the roof to hang within complexes the construction since there are no available strength data for the material.

The strength of heat treated wood is very much affected by irregularities of the wood structure, especially around knots. This very much disqualifies the use of heat treated wood for load bearing constructions since it is much more complicated to chose an appropriate construction wood from the production, especially since there is no standardized method available. Test performed on heat treated wood show a various decrease in bending strength in orders of up to 50% but the stiffness only changes with about 5%.[44] However those test where performed on a non special selection material, and therefore the result of the heat treatment can be considered worst case material.

By experiences of heat treating glued wood poles for increasing their durability with an environmentally friendly method the idea where raised for heat treating glulam. By contacts with Casco representatives knowledge about the temperature resistance of melamine glue where gained. The Casco representative told of an experience from glulam exposed to fire in a building were the glulam had been examined after the house was burnt down and Casco found that the glue line still where intact.

This encouraged experiments with heat treating glulam, though the need for a suitable process increased since the dimensions of a glulam generally is rather thick considering the problems with internal checking with the heat treatment process, a topic that will be further developed later in this report. The experiments where successful and supported the use of glued products.

Then could the design of the pergola continue and the choosing of dimension for the material be done. The desired design is shown in Figure 47.

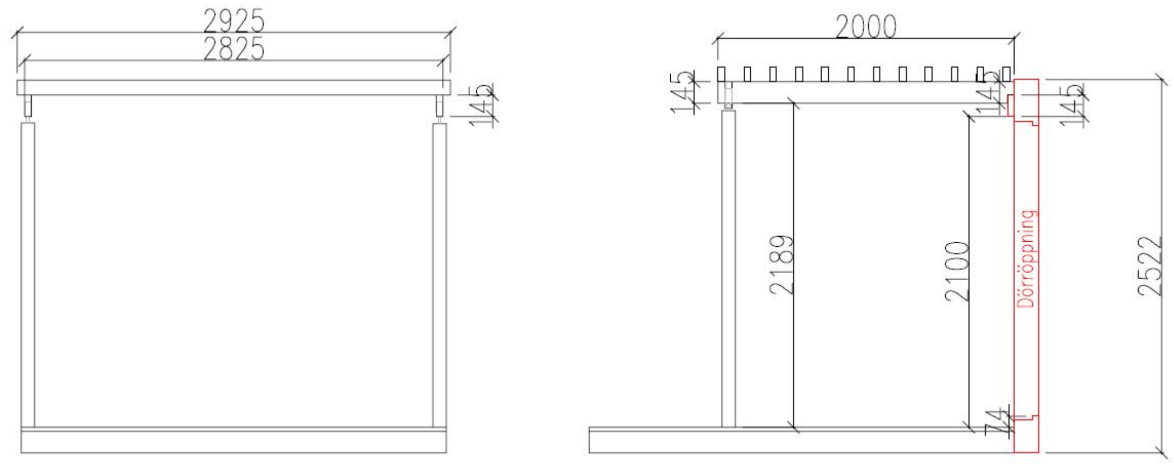


Figure 47: Front and Side view of Pergola

Since the pergola is open between the crossbars and only gives the illusion of a roof outside the front door the snow and wind load on the construction will not be significant and therefore no need to consider that for the dimensioning of the design. However for an eventual load of a human or other that reaches for the crossbars there is a need for considering the strength.

[44] Heat Treated Wood – Durability and Technical Properties, SP Report 2003:25

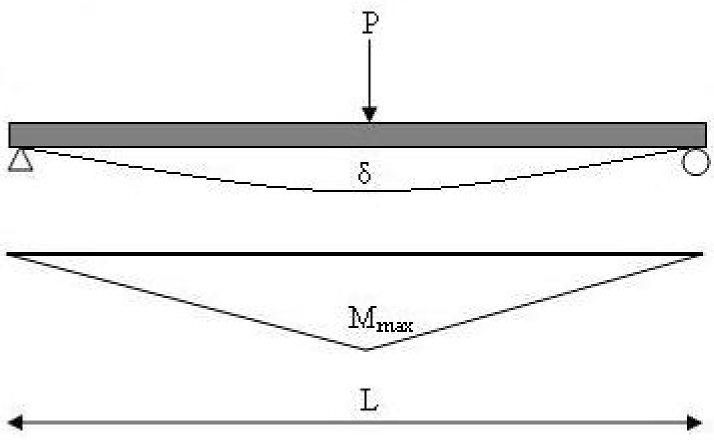


Figure 48: Strength and deflection of a beam under central point load

The load on the construction is calculated by model of a simply supported beam with central point load. The dimensioning is set for a load of 100kg that will cause a load of:

$$P = 100 * 10 * \lambda_m = 100 * 10 * 1{,}3 = 1300N$$

5.16[45]

γ_m *= load case factor*

The bending tension caused by the load is calculated by:

$$\sigma = \frac{M_{\max}}{W}$$

5.17

$$W = \frac{b * h^2}{6}$$

5.18

$$M_{\max} = \frac{PL}{4}$$

5.19

Thus by putting equation 5.17, 5.18 and 5.19 together we have:

$$\sigma = \frac{3PL^3}{2bh^2} = \frac{3 * 1300 * 2770}{2 * 55 * 80} = 15{,}35MPa$$

5.20

P *=central point load [N]*
L *= length of crossbar [mm]*
w *= width of crossbar [mm]*
h *= height of crossbar [mm]*

[45] Regelsamling för konstruktion - Boverkets konstruktionsregler BKR

This type of load would create a need for a material of C_{18} quality of non heat treated construction wood. By using the E modulus for a C_{18} construction wood the deflection of the crossbar can be calculated by:

$$\delta = \frac{PL^3}{48EI}$$

5.21

$$I = \frac{b*h^3}{12}$$

5.22

$$\delta = \frac{PL^3}{4E*b*h^3} = \frac{1300*2770^3}{4*9000*55*80^3} = 27{,}26mm$$

5.23

δ =*deflection of beam/crossbar [mm]*
P = *central point load [N]*
L = *length of crossbar [mm]*
w = *width of crossbar [mm]*
h = *height of crossbar [mm]*

Thus for a design shown in Figure 47 with the dimensions of 55x80mm for the crossbars there is a need to find heat treated wood that matches the bending strength of C_{18} construction wood. Through Martinsons a glued wood product called duolam where available for the project and heat treatment where performed on that material at LTU. After the heat treatment the material where planed to the specified dimensions.

The duolam were a product used by their wooden bridge production and of high quality. By laminating two layers to one board the effects of the natural defects in the material is reduced.

After processing the material a simple central point load test where performed and the result confirmed the calculations for the crossbars.

As a foundation for the crossbars a 145x50mm glulam has been used that also have been heat treated in the heat treatment kiln at LTU, and the glulam is hoisted by a glued pole product that is called Quadrolit (Figure 49).

Figure 49: Heat Treated Quadrolit poles

The meeting of the glulam beam and the Quadrolit pole required a solution for the junction due to different dimensions that would leave the cross cut top of the pole exposed to water. There where no available standard product for this kind of open design for the poles and the solution became to produce a distance that protects the cross cut of the pole and holds the beam on top. The pole is hollow and a threaded iron bar is used within that anchors the beam to the pole and the pole to the floor. The distance is powder coated to match the cladding clamp system.

Figure 50: Quadrolite pole Glulam Junction

Finally the surface coating for the pergola system where chosen to maintain the colour of the heat treated material that will turn grey of the weathering without protection. The desire of exposing the material as visible wood required a translucent paint system. Therefore a glazing colour system where chosen and pigmented with colour pigments similar to the heat treated wood to create a natural heat treated look with a weathering discolouration protection.

6. Heat treatment process control

Wood drying and heat treatment of wood with the ThermoWood process principle share basic principles of transporting water from the material but the high temperatures and decomposition of the wood material constituents give further complexity to the process.

When running the project of the Concept House in Heat Treated Wood there was a need to convert theoretical knowledge into practical to be able to produce Heat Treated Wood material to the specific parts in the project.

Since project followed a strategy to show a spectrum of materials with a Swedish origin, heat treatment of both hardwoods and softwoods where to be conducted. Basically there has been done heat treatment on seven species, two softwoods and five hardwoods.
The wood species where:

- Scots Pine
- Spruce
- Ash
- Aspen
- Beech
- Birch
- Oak

Heat treatment can be done at different treatment temperatures that together with time affect the property changes of the wood material. The ThermoWood Association[46] has a product classification that declares two standard treatment classes, Thermo-S and Thermo-D. The treatment temperatures for the two classes differ between hardwoods and softwoods.

	Thermo-S	**Thermo-D**
Hardwoods	185°C	200°C
Softwoods	190°C	212°C

Figure 51: ThermoWood Classes

Beside these temperatures other temperatures, such as 170°C and 210°C on hardwood, have been processed to achieve desired property changes of the material.

Summing up the materials there is a need to find an appropriate process to about 14 – 21 different materials. When considering the need to process such a number of materials in different dimensions and to obtain some quality of the processed material. The main problem was concerning cracking, both surface and interior cracking.

6.1. The Kiln

The heat treatment kiln at Luleå University of Technology is an experimental kiln delivered by Valutec AB and is designed to work according to the ThermoWood process principles. Figure 52 shows a graphical description of the kiln, which is similar to a traditional wood drying kiln but designed for higher temperatures and to withstand the higher acidity in the

[46] www.thermowood.fi

process air that is developed during the process. Due to the design with the airflow along the wood boards there is need for sticker with air passage.

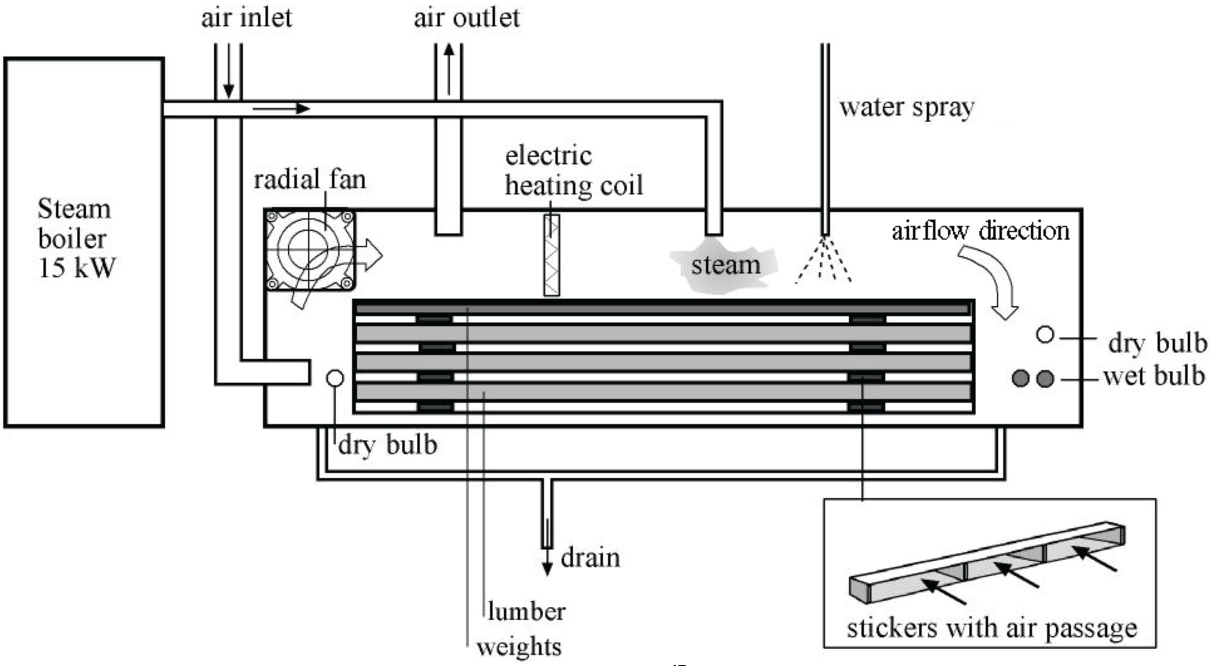


Figure 52: Experimental Heat Treatment Kiln Description[47]

The air is warmed with an electric heating coil and/or with pressurized water steam at 4bar, and is circulated through the wood to transfer the heat/energy to the boards. With the dry and wet bulb temperatures the kiln control system can manage the process climate.

6.1.1. Kiln Scheduling

When designing the schedules for the runs in the heat treatment kiln the plan was to benefit of the accumulated experiences of research done at Luleå University of Technology.
In the licentiate thesis of Dennis Johansson the process is explained as follows[48]:

[47] Dennis Johansson – Strength and Colour Response of Solid Wood to Heat Treatment
[48] Dennis Johansson – Strength and Colour Response of Solid Wood to Heat Treatment

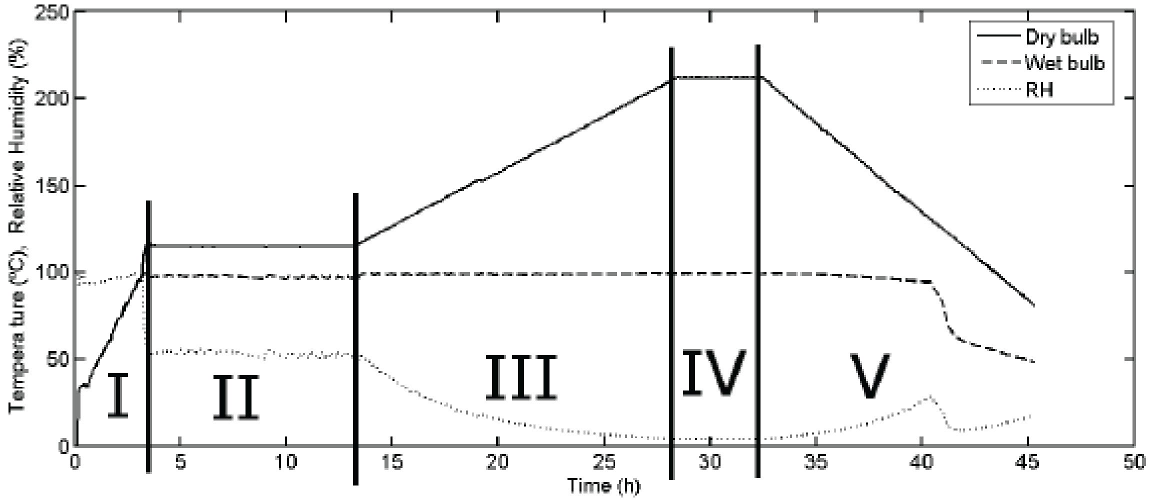


Figure 53: Example Heat Treatment Schedule

- **I)** **"Heating regime:** Heating with saturated steam generated at 130°C that is injected
  into the kiln, which is at atmospheric pressure.
- **II)** **1st drying regime:** Drying step that can be either high or low temperature drying (above or below 100°C).
- **III)** **2nd drying regime:** The regime during which the final drying takes place. During this regime the chemical reactions accelerate with rising temperature.
- **IV)** **Treatment regime:** The temperature is kept constant, typically for 2-4 hours. Time
  and temperature during regime IV normally define the heat treatment class.
- **V)** **Cooling regime:** Cooling the wood with steam at 130°C followed by water spraying until the kiln is opened. In industrial practice it is common to include a remoistening regime for remoistening. In these experiments, that has not been necessary, since this part of the process does not influence the development of internal checking"

The control system provided with the kiln, the Valpas Rosterautomatik, in which the process schedule view lets the user to schedule the process in terms of time, dry temperature, wet temperature, fan speed, and position of air outlet valve.

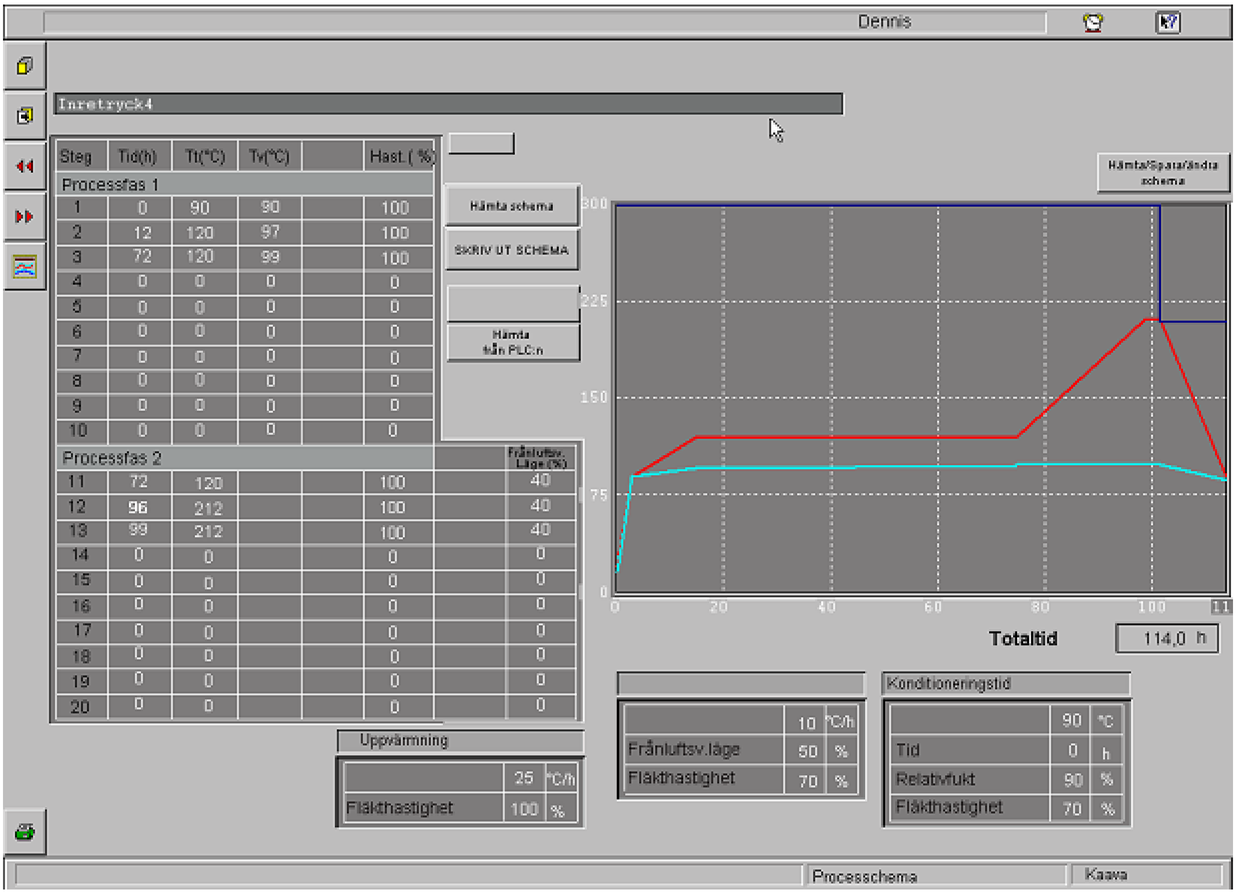


Figure 54: Process schedule view of Valpas system

Both pre-dried and wet wood can be used in the heat treatment kiln but in the Concept House Project the wood has always been pre-dried to some extent below fibre saturation point.

The specific setting of each of the five process steps described by Johansson (2005), together with the wood material properties affects the result on the heat treated boards.

6.1.2. Process regimes problems

When facing the task to process heat treated material for the concept house project further understanding of the process regimes and the limitations of the control system where gained. Following comments reveal some of the projects experiences about the process regimes:

Heating regime The heating up with steam generates a damp climate that keeps or remoistens the surface of the processed wood. This is a heritage from traditional wood drying and the purpose is to maintain a wet surface to avoid case hardening and surface checking. When performing heat treatment on wood, and especially hardwoods, with low moisture content (about 10%), the heating up can create a remoistened surface of the processed boards which can result in surface checking if the following drying regime isn't carefully designed.

1st drying regime The main drying step is to lower the moisture content significantly before the raise to curing temperature in the 2nd drying regime. This can involve either high or low temperature drying or both. Depending on the moisture content of the wood in the start, the properties of the material the drying force need to be controlled to avoid checking, mainly on the surface.

2nd drying regime In the 2nd drying regime the temperature is raised to treatment temperature and the final drying takes place. If the treatment temperature is higher than 165°C the drying will result in 0% moisture content[49] of the material if the process time is long enough. Depending on the speed of the temperature raise and the wood material that is processed this regime likely induces internal checking due to high vapour pressure in the wood.

Treatment regime When the treatment temperature is reached the temperature is kept constant for 2-4 hours. At the treatment temperatures level the different wood components, hemicelluloses, cellulose and lignin decomposes. The longer the time at treatment temperature the more decomposition of the wood material, therefore is the time for the treatment regime a balance between gaining desired properties such as durability and colour, and to minimize unwanted properties like brittleness and strength reduction.

Cooling regime During cooling the temperature is lowered with water steam and later spray. It is important not to create a wet surface on the wood during cooling and to control the climate after the cooling to avoid any uncontrolled drying of the wood surface.

Conditioning regime Without conditioning of the heat treated wood the moisture content will close to or at 0%. The heat treated material will therefore try to reach equilibrium with its surrounding, which will give a swelling of the wood which can give problems when further processing the material to a product. Therefore a conditioning phase can be added to the process to increase the moisture content of the heat treated wood.

Due to the heat treatment the equilibrium moisture content of the material is reduced, which influence the target MC. The conditioning can also create a material with a moisture gradient inversed to that on normally dried wood. Conditioning can give a surface material with higher moisture content than the in middle of the board.

6.2. Wood drying Theory

To deal with the problems with heat treatment of wood stated above some fundamental understanding of wood drying is needed. Drying of wood means a transport of water from the wood, a transport that depends on the properties of the wood that is drying and the properties of the energy and vapour transport medium, which in most cases is air at different temperatures, humidity, and velocity.

[49] W T Simpson, H N Rosen 1980 Equilibrium Moisture Content of Wood at High Temperatures

To specify the amount of water in the wood the term moisture content is commonly used, and is defined as weight of the water in the wood divided by the oven dry weight of the wood. Normally this is the moisture content presented in percentage:

$$u = \frac{(m_u - m_0)}{m_0} \; [\%]$$

6.1

m_u = mass of the wet wood $[kg]$

m_0 = mass of the oven dry wood $[kg]$

$m_u - m_0 = m_{H2O}$ = mass of the displaceable water $[kg]$

The drying result is not only dependent on controlling the drying process according to the wood specie and dimension and appropriate climate but also on a number of specific properties of each individual board, such as , heart wood/sap wood, density variation, fibre angle, annual ring pattern, and so on.
In this text these specific wood properties are left out and only more general properties of wood as a material and how drying of that material works.

Wood is a material with inhomogeneous drying properties that easily causes drying damages on individuals in the drying batch. Examples of wood drying related damages are checking, uneven moisture content distribution, compressive and tension stress, warp, cant hook, flat bow, collapse, knot fallout, resin flow, and colour faults. Since heat treatment of wood involves drying of wood most of the possible wood damages also can occur due the heat treatment, and due to the high temperatures an additional set of possible process damages can occur.

6.2.1. Water transport in wood

Wood is a biological material that comes from the stems of trees and has a cellular structure and transports water through this structure in the living tree. The green wood (never dried) contains water in three forms, capillary and steam in the cell lumen, and bound water in the cell walls, Figure 55.

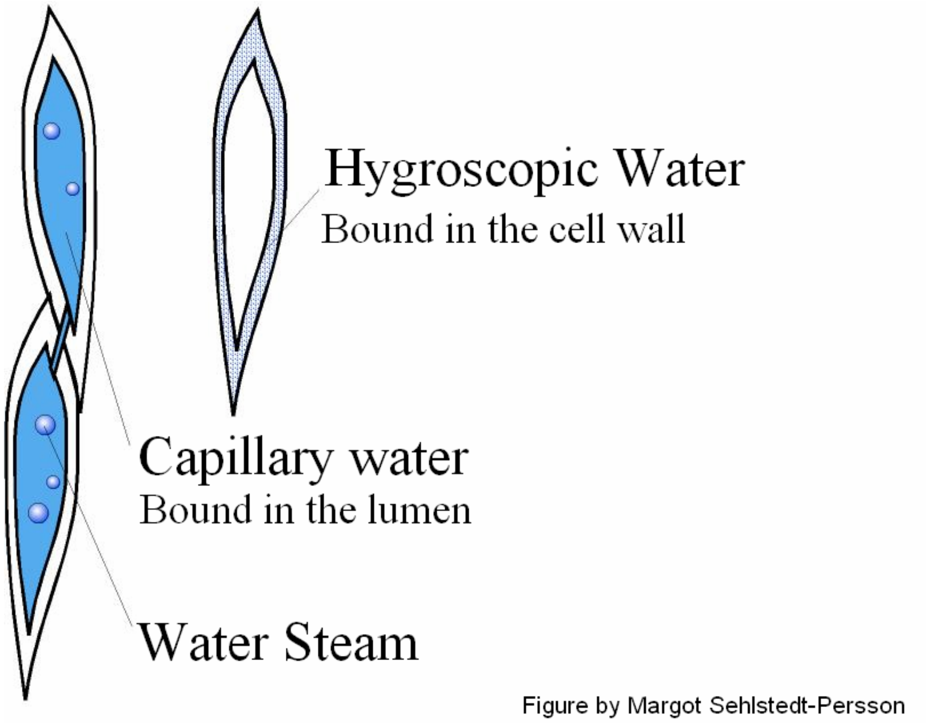


Figure 55: Water in tracheid wood cells

Water profoundly affects the wood. Due to the hygroscopic properties of the wood cell, wood can exude or absorb moisture depending on its surrounding atmosphere. Below fibre saturation point the drying transforms a rather plastic material to a relatively brittle material. Wood above certain moisture content is also biodegradable. Thus to make use of the structural properties of the wood material there is a need to dry out the water from the wood.

In air circulated kilns the wood dries from "the outside in", indicating the need for a pressure or concentration difference between the woods surface and the core, for drying to take place.

When drying wood the three forms of water found in wood need to be transported from the wood, which involves mainly two mechanisms, capillary and diffusion forces. Dependent on the state of the water in the wood different mechanisms are involved with the moisture transport.

Figure 56 show moisture transport through the wood structure at different states of the water (after Stamm AJ 1967a) [50].

[50] Stamm AJ (1967a) Movement of fluids in wood – Part 1 Flow of fluids in wood, Wood Science and Technology Vol.1 p.122-141

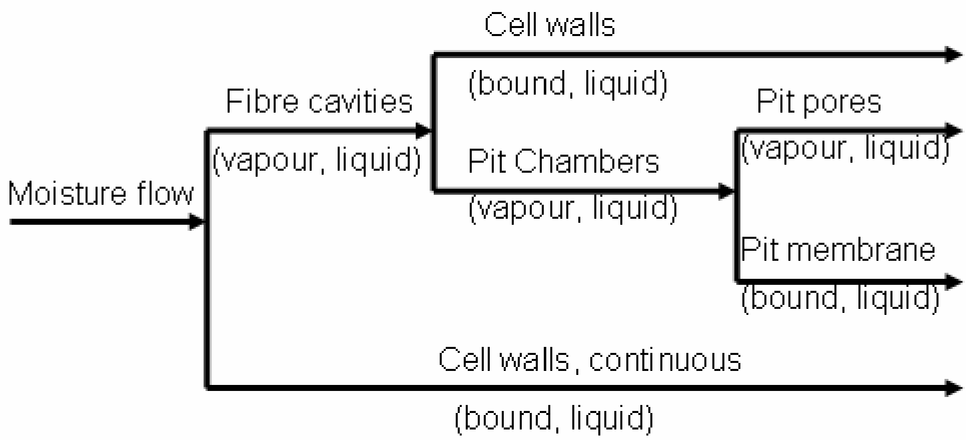


Figure 56: Various flow paths through softwoods

When the wood still contains free capillary water the drying is said to be in the capillary regime, where capillary water are transported due to pressure potential and capillary forces. During drying steam and air in the wood expands due to the temperature increase and creates an excess of pressure in the wood.
Darcy law expresses the speed of the flow of a fluid (gas or liquid) in a porous medium.

$$v = k * \frac{\Delta p}{d} \; [m/s]$$

6.2

$v =$	speed of fluid $[kg]$
$\Delta p =$	pressure differential over distance d $[Pa]$

The free water is transported between the cells through bordered pits that are present in every cell. If the capillary transport is to strong the cell can collapse and thus affect the quality of the wood. The capillary force in the cell depends on size of the pit radius and the surface tension. The ability to withstand the force depends on the cell structure, which varies through the wood but in general the thinner cell walls in the early wood in the annual ring pattern are more prone to collapse than the cells in the late wood with thicker cell walls.

When the cell lumen dries out capillary forces from the neighbouring cell where water is still present in the lumen, closes the membrane of the bordered pit, and the pit gets aspirated. Figure 57 shows how pit membrane is affected by the capillary force during drying. The aspiration of the bordered pit is irreversible and thus of great importance to avoid aspiration as long as there is capillary water present.

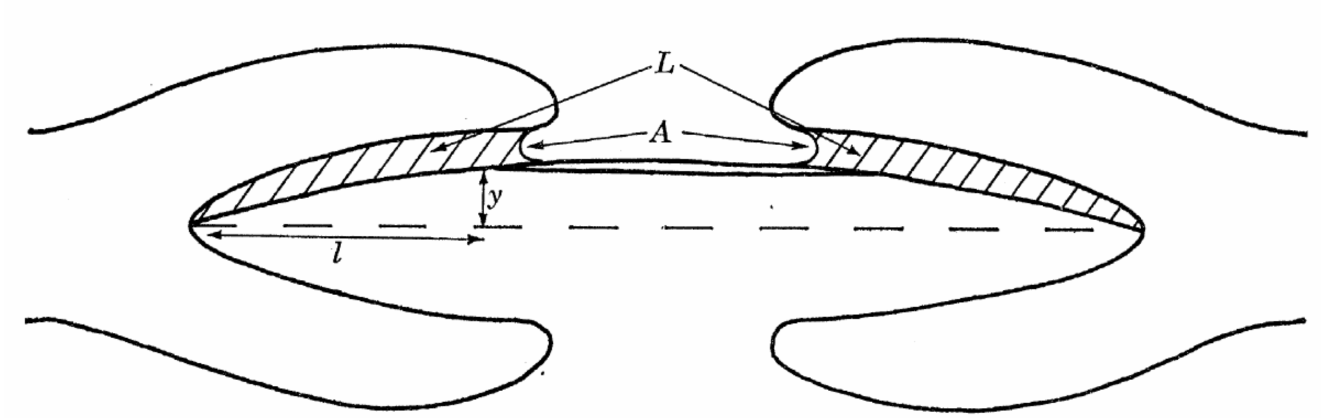


Figure 57: Bordered pit during drying[51]

As the drying continues and the wood drying enters a transition regime where there is a mixture of capillary and diffusion forces that transports the water from the wood cells. This can be illustrated by Figure 58 which shows a modelling (Salin 2007) of the free water drying process of a 100x180 square fibre network with inactive vertical borders.

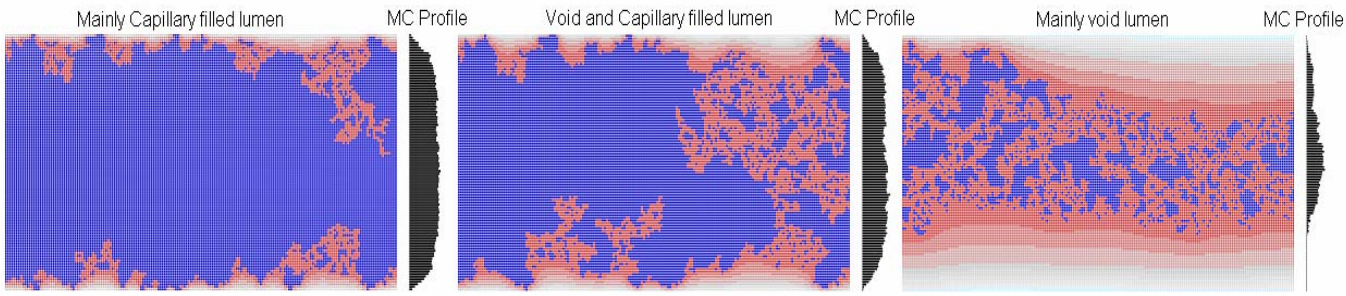


Figure 58: Drying from the upper and lower borders of a 100x180 square fibre network[52]

Finally when the capillary water is no longer present in the wood cells the dominant water transport is due to diffusion, which has a lower capacity of transporting water from the wood. The diffusion drying regime starts at the fibre saturation point (Figure 59) and continues until the target moisture point.

[51] J. A. Petty, **The Aspiration of Bordered Pits in Conifer Wood,** *Proceedings of the Royal Society of London. Series B, Biological Sciences* Vol. 181, No. 1065 (Jul. 4, 1972), pp. 395-406

[52] Salin JG, 2007, A Percolation Approach to the Free Water Drying Process

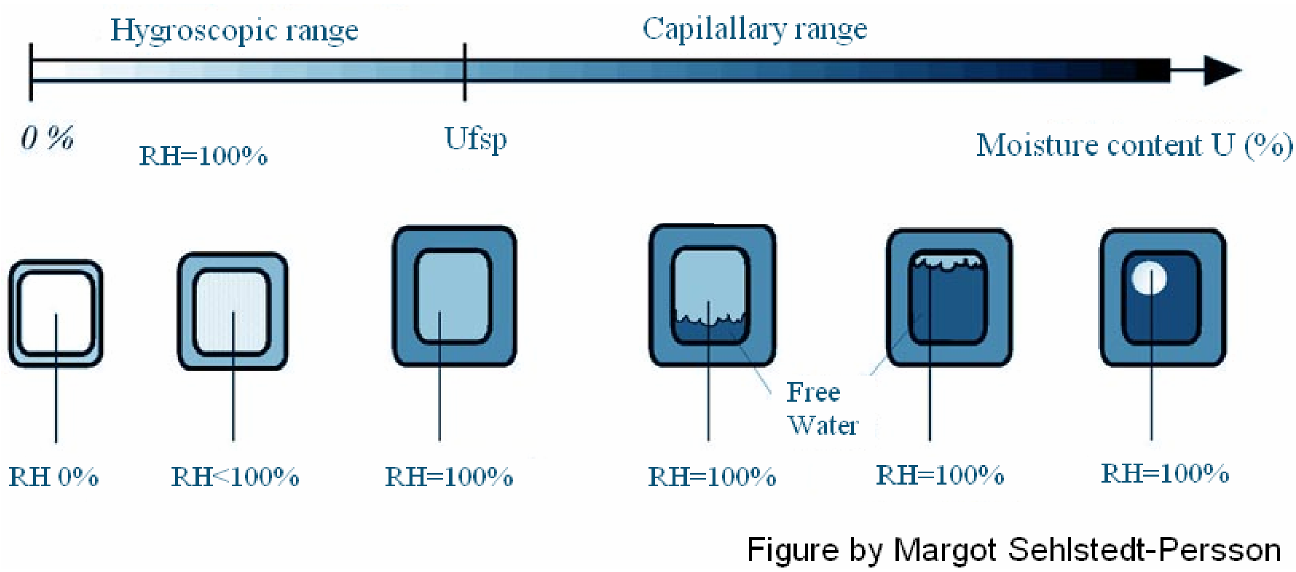


Figure 59: Wood cell Saturation levels

The moisture flow through diffusion is described by Ficks law:

$$g = -D * \rho_{0u} * A * \frac{\Delta u}{\Delta x} \text{ [kg/s]}$$

6.3

g = moisture flow [kg/s]
D = diffusion coefficient [m^2/s]
ρ = wood density: dry weight / wet volume [kg/m³]
A = area [m^2]
Δu = difference in moisture content
Δx = distance in flow direction

Diffusion takes place through pore spaces and through the cell wall and thus has some specific conditions between different species as well as individuals during drying.

Below the fibre saturation point it is the bound water in the cell walls that is transported from the wood and when the cell wall dries it starts to shrink. The shrinkage of the cell wall induces anisotropic dimensional changes of the wood and stress in the wood during the process that is important to have an understanding about to control the process. Thus will there be differences even between boards within the same batch depending differences on the annual ring pattern on the boards.

6.2.2. Wood drying tensions

The forces induced by the water transport during drying affect the wood cell, the capillary flow can give cell collapse, and the diffusion of the bound water in the cell walls gives shrinkage of the cell wall which induces tension in the board as it is drying.

When green wood is drying the outer dries faster than the core and starts shrinking, while the moisture content of the core is still high and maintains its volume. This statement causes tensions stress on the outer that can either crack or stretch in a plastic manner.

As the drying continuous the core also starts to shrink, and when that happens the outer wood that has stretch out to hold the swollen core, now has a bigger volume than the core. Thus will the outer of the wood strive to resist the shrinkage of the inner part of the wood, which causes an interaction between the compression on the outer of the wood and the tension of the core of the wood. This interaction causes drying induced stress in the wood which is illustrated in Figure 60.

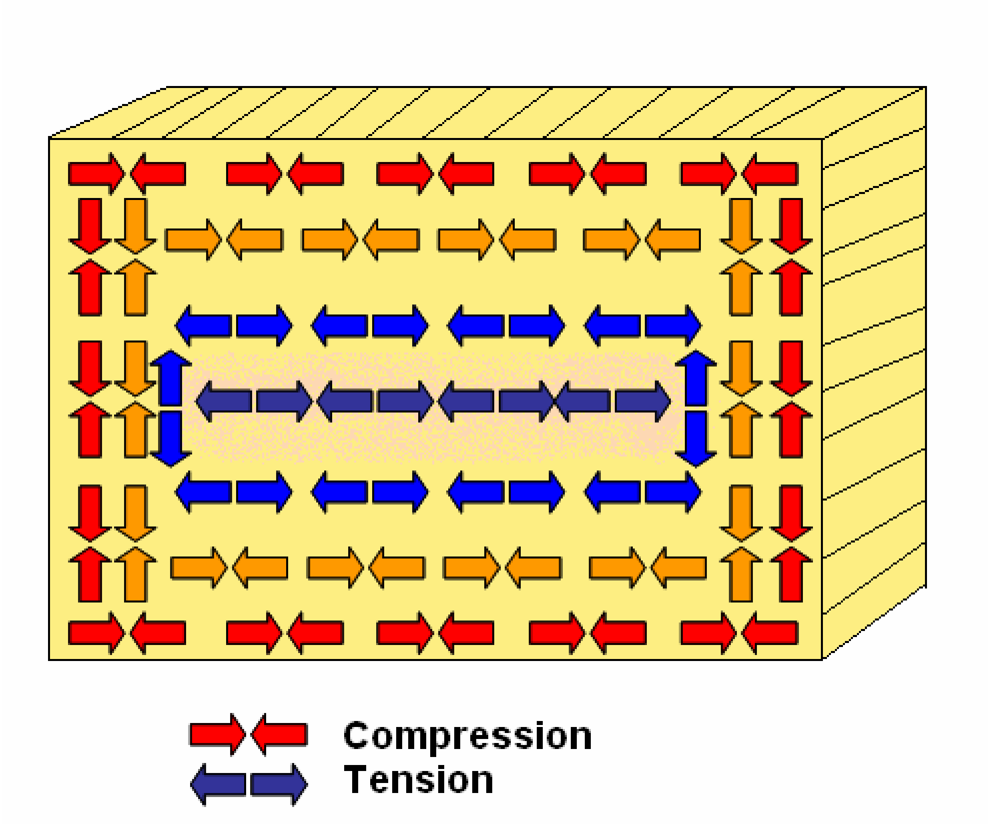


Figure 60: Drying induced stress in the wood

Different materials, the dimension, and the moisture level and distribution affect the level of stress and the ability to cope with the stress build up during drying.

If the level of stress gets to high internal checking can occur and this is an undesired feature. The ability to withstand the drying induced stress can also have been affected during the transport of capillary water that could have caused cell collapse or weakening of the cell walls of cells being close to collapse.

The level of the stress in the wood depends on the moisture content gradient between the outer wood and the core. That gradient depends on how the water in the wood is transported in the wood, and by the rate that is happening. The rate of the water flow is, as mentioned earlier, dependent on the differential between the moisture at surface and the moisture in the core. The moisture at surface depends on the climate at the drying.

6.2.3. Evaporation and Humidification

Water in wood bound in the cell walls and free in the lumen can be liquid and vapour state. Liquid water will evaporate even at temperatures below the boiling point until the concentration of vapour from the wood reach an equilibrium partial pressure with the surrounding air.

Thus will the amount of water in the surrounding air has crucial bearing on the rate at which a piece of wood will dry out. The wood material has a hygroscopic property that means that it can emit moist, or water molecules, if being in a surrounding with less concentration of water molecules, or the opposite if the surrounding is damper than the wood it will receive water molecules. Finally the wood reaches equilibrium (Figure 61) with the air and the evaporation or humidification stops.
Thus is the rate of the evaporation and humidification dependent on the moisture in the air.

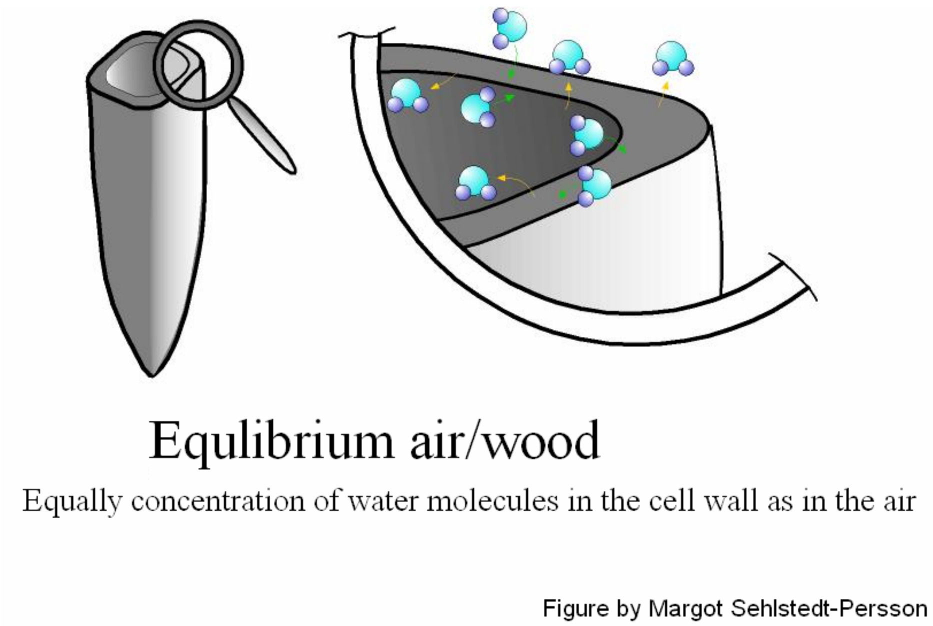


Figure 61: Wood equilibrium with air

In wood drying, air is used for both water transport from the wood, and to transfer heat (= energy) to the wood. Thus some understanding of the heat and energy transfer properties of air and the thermodynamics of moist air clarifies the interaction between wood and air that takes place in the drying process.

Moisture in air

The concentration of water molecules, or the ratio of water vapour to dry air, on a mass basis, is called the humidity, and can be expressed as the absolute humidity in a volume of dry air.

$$v = \frac{m_{H2O}}{V} \quad \textbf{[kg/m}^3\textbf{] or [g/m}^3\textbf{]}$$

6.4

m_{H2O} = mass of water vapour in the volume V [kg]

Air itself is a mixture of nitrogen, oxygen, argon and carbon dioxide, with the nitrogen and oxygen as dominant elements. The nitrogen content is substantially uniform over the earth but the amounts of oxygen as well as the mixture with water vapour vary through out the world.

When describing air properties in wood drying air is simplified described as one gas component and when examining the pressure–temperature behaviour this is expressed by the equation of state

$$Z = \frac{PV}{RT}$$
6.5

Z = compressibility factor
P = pressure (absolute)
V = specific molar volume
R = the universal gas constant, 8,314 J/mol K^{1}
T = absolute temperature

At atmospheric pressures and at kiln temperatures (20°-100°C) the compressibility factor Z is close to 1, and air behaves as an ideal gas[53]. The behaviour of water vapour can be represented by the same equation. For water vapour at atmospheric pressure the value of Z = 0,986 at 107°C (Hilsenrath et al. 1955) and thus water vapour may be regarded as behaving essentially as an ideal gas.

When treating the dry air and the water vapour as ideal gases one can calculate the humidity Y as related to the partial pressure p_w of the water vapour through the expression:

$$Y = \left[\frac{M_W}{M_G}\right]\frac{p_w}{P - p_w}$$
6.6

$[M_W/M_G]$ = molar mass ratio = 0,622. [54]
p_w = partial pressure of water vapour
P = absolute pressure

The maximum value of p_w is the saturation value p^0_w, commonly known as vapour pressure, which rising significantly with increasing temperature. This method ($Y = \left[\frac{M_W}{M_G}\right]\frac{p_w}{P - p_w}$ 6.6) on a dry air basis makes it easier than in equation ($v = \frac{m_{H2O}}{V}$ [kg/m³] or [g/m³]

6.4
) to follow changes in humidity throughout a kiln, since the mass of the circulating moisture – free air isn't altered by the drying process.

With the Clapeyron relationship[55] the vapour pressure in a fix volume can be calculated.

$$ps = \frac{\alpha e^{-\beta/T}}{T^{\gamma}}$$
6.7

p_s = pressure of water vapour at saturation, [Pa]
T = temperature, [°C]

[53] Keey, Langrish, Walker, 1999, Kiln Drying of Lumber, p 43
[54] Keey, Langrish, Walker, 1999, Kiln Drying of Lumber, p 44
[55] A.J. Hunter, M. Tamasy-Bano 2002, Psychrometric charts for use with normal and high temperature drying of wood, Wood Science and Technology, Springer Verlag

α, β, γ, are constants to be found in Table 2

Temperature range °C	0–100	100–200	200–300
α	6×10^{25}	2.564×10^{19}	2.133×10^{12}
β	6800	6024.5	4947
γ	5	2.874	0.597

Table 2: Coefficients to Clapeyron relationship

Temperature (°C)	Temperature (°K)	Vapour pressure at satutarion (kPa)	Atmospheric pressure (kPa)	Relation to atmospheric pressure (atm)
0	273,16	0,609	101,038	0,006
20	293,15	2,337	101,038	0,023
40	313,15	7,392	101,038	0,073
60	333,15	19,974	101,038	0,198
80	353,15	47,413	101,038	0,469
100	**373,15**	**101,038**	**101,038**	**1,0**
120	393,15	198,2	101,038	2,0
140	413,15	360,9	101,038	3,6
160	433,15	617,7	101,038	6,1
180	453,15	1 002	101,038	9,9
200	473,15	1 553	101,038	15,4
220	493,15	2 316	101,0	22,9

Table 3: Clapeyron calculation of vapour pressure

Thus the humidity of air saturated with moisture correspondingly rises rapidly from 0,0149 at 20°C (0,622*(2,337/(101,038-2,337) to infinitely at the boiling point. This exemplifies how the capacity of air to hold and transport moisture increases rapidly with increasing temperature, and is one economic reason among others for choosing the highest possible temperature when scheduling the wood drying process.

In a wood drying process the air need to transport moist from the wood and therefore there is need for only fractionally saturated air to be able to take up moist from the wood. To measure the partial saturation the term *Relative humidity* φ (phi) is used.

At thermodynamic equilibrium, the activity of the moisture in wood is closely equal to the relative vapour pressure p_w / p^0_w of the environment. Thus for convenience, is the **relative humidity** defined on a similar basis, namely:[56]

$$\varphi = \frac{\mathrm{pw}}{\mathrm{p}^0{}_{\mathrm{w}}}$$

6.8

p_w *= partial pressure of water vapour [Pa]*
p^0_w *= pressure of water vapour at saturation [Pa]*

This means that there is a relation between the relative humidity in air and the equilibrium moisture content of wood and by controlling the humidity in the process, control over the wood drying is achieved.

[56] Keey, Langrish, Walker, 1999, Kiln Drying of Lumber, p 44

A practical and commonly used method of measure the relative humidity in wood drying kilns is to use a dry bulb temperature and a wet bulb temperature. The principle of the dry/wet bulb temperatures is that if the circulating air isn't saturated, the relative humidity is less than 100% and causes evaporation from the wet cloth around the wet bulb, which causes cooling of the wet bulb thermometer when the energy for the evaporation is lost from the wet cloth.

The difference of the temperature between the dry/wet bulb temperatures is called the psychrometric difference, which is used in calculations or tables to get a value of the relative humidity, as in Figure 62 that also show the equilibrium moisture content of wood and is based on the measurements of Keylwert, Madison 1951.

In wood drying literature relative humidity/psychrometric charts and tables generally is limited to 100°C dry bulb temperature.

Dry Bulb Temperature

Psychrometric difference	61	62	63	64	65	66	67	68	69	70
1,0	95/21,0	95/20,9	95/20,7	95/20,6	95/20,4	95/20,2	96/20,8	96/20,7	96/20,6	96/20,4
1,5	93/19,2	93/19,1	93/19,0	93/18,9	93/18,8	93/18,6	93/18,4	93/18,3	93/18,1	93/18,0
2,0	91/17,8	91/17,6	91/17,5	91/17,4	91/17,3	91/17,2	91/17,1	91/17,0	91/16,9	91/16,8
2,5	88/16,2	88/16,1	88/16,0	89/16,4	89/16,3	89/16,2	89/16,1	89/16,0	89/15,9	89/15,8
3,0	89/15,4	86/15,2	86/15,1	87/15,4	87/15,3	87/15,2	87/15,1	87/15,0	87/14,9	87/14,8
3,5	84/14,7	84/14,6	84/14,5	84/14,6	85/14,6	85/14,5	85/14,4	85/14,3	85/14,2	85/14,1
4,0	82/14,0	82/13,8	82/13,7	82/13,6	82/13,6	83/13,7	83/13,7	83/13,6	83/13,5	83/13,4
4,5	80/13,4	80/13,3	80/13,2	80/13,0	80/13,0	81/13,1	81/13,1	81/13,0	81/12,9	81/12,8
5,0	78/12,7	78/12,6	78/12,5	78/12,5	79/12,6	79/12,6	79/12,5	79/12,4	79/12,3	79/12,2
5,5	76/12,1	76/12,0	76/11,9	76/11,8	77/12,0	77/12,0	77/11,9	77/11,8	77/11,7	77/11,6
6,0	74/11,7	74/11,6	74/11,5	75/11,6	75/11,5	75/11,5	75/11,4	76/11,5	76/11,4	76/11,3
6,5	72/11,2	72/11,1	73/11,2	73/11,2	73/11,0	73/11,0	73/10,9	73/10,9	74/11,0	74/10,9
7,0	70/10,8	70/10,7	71/10,8	71/10,7	71/10,6	71/10,6	71/10,4	72/10,6	72/10,5	72/10,4
7,5	68/10,4	68/10,3	69/10,4	69/10,3	69/10,2	69/10,2	70/10,2	70/10,2	70/10,1	71/10,1
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8,5	65/ 9,8	65/ 9,7	65/ 9,6	65/ 9,5	66/ 9,6	66/ 9,6	66/ 9,4	67/ 9,5	67/ 9,5	67/ 9,4
9,0	63/ 9,4	63/ 9,3	64/ 9,4	64/ 9,3	64/ 9,3	64/ 9,2	65/ 9,2	65/ 9,2	65/ 9,2	65/ 9,1
9,5	61/ 9,0	61/ 9,0	62/ 9,0	62/ 9,0	63/ 8,9	63/ 9,0	63/ 8,9	63/ 8,9	63/ 8,8	64/ 8,8
10,0	59/ 8,8	60/ 8,8	60/ 8,8	60/ 8,7	61/ 8,7	61/ 8,7	62/ 8,7	62/ 8,6	62/ 8,5	62/ 8,4
10,5	58/ 8,6	58/ 8,5	58/ 8,5	59/ 8,5	59/ 8,5	59/ 8,5	60/ 8,5	60/ 8,4	60/ 8,4	60/ 8,3
11,0	56/ 8,3	57/ 8,3	57/ 8,3	57/ 8,3	58/ 8,3	58/ 8,3	58/ 8,2	58/ 8,1	59/ 8,2	59/ 8,2
11,5	54/ 8,0	54/ 8,0	55/ 8,1	55/ 8,0	56/ 8,1	57/ 8,1	57/ 8,1	57/ 8,0	57/ 8,0	57/ 7,9
12,0	53/ 7,8	53/ 7,8	54/ 7,8	54/ 7,8	55/ 7,9	55/ 7,9	55/ 7,8	56/ 7,8	56/ 7,8	56/ 7,7
12,5	51/ 7,6	52/ 7,6	52/ 7,5	53/ 7,6	53/ 7,6	53/ 7,6	54/ 7,6	54/ 7,5	55/ 7,6	55/ 7,5
13,0	50/ 7,4	50/ 7,3	51/ 7,3	51/ 7,3	52/ 7,4	52/ 7,4	52/ 7,3	53/ 7,4	53/ 7,3	53/ 7,2
13,5	48/ 7,1	48/ 7,0	49/ 7,1	50/ 7,2	50/ 7,2	50/ 7,1	51/ 7,1	51/ 7,1	51/ 7,0	52/ 7,0
14,0	47/ 6,9	47/ 6,9	48/ 6,9	48/ 6,9	49/ 7,0	49/ 6,9	49/ 6,9	50/ 6,9	50/ 6,9	50/ 6,8
14,5	46/ 6,7	46/ 6,7	47/ 6,7	47/ 6,7	48/ 6,7	48/ 6,7	49/ 6,8	49/ 6,7	49/ 6,7	49/ 6,6
15,0	44/ 6,5	45/ 6,6	45/ 6,5	45/ 6,5	46/ 6,5	46/ 6,5	46/ 6,4	47/ 6,5	47/ 6,5	48/ 6,5
16,0	41/ 6,1	42/ 6,2	42/ 6,2	43/ 6,2	43/ 6,2	44/ 6,3	44/ 6,2	44/ 6,2	45/ 6,2	45/ 6,2
17,0	38/ 5,8	39/ 5,8	40/ 5,8	40/ 5,8	41/ 5,9	41/ 5,9	41/ 5,8	42/ 5,9	42/ 5,8	43/ 5,9
18,0	36/ 5,5	37/ 5,5	37/ 5,5	38/ 5,6	38/ 5,5	39/ 5,6	39/ 5,6	40/ 5,6	40/ 5,6	41/ 5,6
19,0	34/ 5,1	34/ 5,1	35/ 5,2	35/ 5,2	36/ 5,2	36/ 5,2	37/ 5,3	37/ 5,2	38/ 5,3	38/ 5,2
20,0	31/ 4,8	32/ 4,8	32/ 4,8	33/ 4,9	34/ 5,0	34/ 4,9	34/ 4,9	35/ 4,9	35/ 4,9	36/ 4,9
21,0	29/ 4,5	30/ 4,5	30/ 4,5	41/ 4,6	41/ 4,6	32/ 4,6	32/ 4,6	33/ 4,7	33/ 4,6	34/ 4,7
22,0	27/ 4,2	28/ 4,3	28/ 4,2	29/ 4,3	29/ 4,3	30/ 4,4	31/ 4,4	31/ 4,4	32/ 4,5	32/ 4,4
23,0	25/ 4,0	25/ 4,0	26/ 4,0	26/ 4,0	27/ 4,1	27/ 4,0	28/ 4,1	28/ 4,1	29/ 4,2	29/ 4,1
24,0	23/ 3,7	24/ 3,8	24/ 3,8	25/ 3,8	25/ 3,8	26/ 3,9	26/ 3,9	27/ 3,9	27/ 3,9	28/ 4,0
25,0	21/ 3,4	22/ 3,5	22/ 3,5	23/ 3,6	23/ 3,6	24/ 3,7	24/ 3,6	25/ 3,7	25/ 3,6	26/ 3,7

Relative Humidity
Equilibrium Moisture Content

Dry Bulb Temperature

Psychrometric difference	70	75	80	85	90	95	100
1	96/20,5	96/20,0	96/19,6	96/19,2	96/18,7	96/18,3	96/17,9
2	91/17,0	92/16,7	92/16,4	92/16,1	93/15,8	93/15,5	93/15,1
3	87/14,8	88/14,6	88/14,3	89/14,1	89/13,8	89/13,6	89/13,4
4	83/13,3	84/13,1	85/12,8	85/12,7	86/12,5	86/12,3	86/12,1
5	79/12,1	80/11,9	81/11,7	82/11,6	82/11,4	82/11,2	83/11,0
6	76/11,1	77/11,0	78/10,8	78/10,7	79/10,5	79/10,3	80/10,1
7	72/10,3	73/10,2	74/10,0	75/ 9,8	76/ 9,6	76/ 9,5	77/ 9,3
8	69/ 9,7	70/ 9,5	71/ 9,3	72/ 9,2	73/ 9,0	73/ 8,9	74/ 8,7
9	65/ 9,1	67/ 8,9	68/ 8,7	69/ 8,6	70/ 8,4	70/ 8,3	71/ 8,1
10	62/ 8,5	64/ 8,4	65/ 8,2	66/ 8,1	67/ 7,9	67/ 7,8	68/ 7,6
11	59/ 8,0	61/ 7,9	62/ 7,8	63/ 7,6	64/ 7,4	65/ 7,3	66/ 7,1
12	56/ 7,5	58/ 7,4	59/ 7,3	61/ 7,2	62/ 7,0	62/ 6,9	63/ 6,7
13	53/ 7,1	55/ 7,1	56/ 7,0	58/ 6,9	59/ 6,7	60/ 6,6	61/ 6,4
14	50/ 6,8	52/ 6,8	54/ 6,7	55/ 6,6	57/ 6,4	58/ 6,2	59/ 6,0
15	48/ 6,4	50/ 6,4	51/ 6,3	53/ 6,2	54/ 6,0	55/ 5,9	56/ 5,7
16	45/ 6,1	47/ 6,1	49/ 5,9	51/ 5,8	52/ 5,7	53/ 5,6	54/ 5,4
17	43/ 5,7	45/ 5,7	46/ 5,6	48/ 5,5	49/ 5,4	50/ 5,3	51/ 5,2
18	40/ 5,4	43/ 5,4	44/ 5,4	46/ 5,3	47/ 5,2	48/ 5,1	49/ 5,0
19	38/ 5,2	40/ 5,2	42/ 5,2	44/ 5,1	45/ 5,0	46/ 4,9	47/ 4,8
20	36/ 4,9	38/ 4,9	40/ 4,9	42/ 4,9	43/ 4,8	44/ 4,7	45/ 4,6
21	34/ 4,6	36/ 4,6	38/ 4,7	40/ 4,6	41/ 4,5	42/ 4,5	43/ 4,4
22	32/ 4,4	34/ 4,4	36/ 4,4	38/ 4,4	39/ 4,3	40/ 4,3	41/ 4,2
23	30/ 4,1	32/ 4,1	34/ 4,2	36/ 4,2	37/ 4,2	38/ 4,2	39/ 4,2
24	28/ 3,9	30/ 3,9	32/ 4,0	34/ 4,0	36/ 4,0	37/ 4,0	38/ 4,0
25	26/ 3,7	29/ 3,7	30/ 3,8	32/ 3,8	34/ 3,8	35/ 3,8	36/ 3,8

Figure 62: Psychrometric tables example[57]

Heat and energy transfer with air

When dying of wood with air, there will be an energy transfer interaction between the wood and the circulated air throughout the process to create potential that generates the moisture flow from the wood.

Thus is an understanding of how the energy in the air depends on the dry air and the vapour mixture and its temperature, and how that energy is transferred to the wood.

[57] Esping 1992, Trätorkning 1a

Heat is defined as thermal energy transferred across the boundaries of a system solely because of a temperature difference and its surroundings.
Heat can be transferred in three different ways:

- Conduction - by physical contact of two medias
- Convection - by external movement of a liquid or a gas
- Radiation. - by means of electromagnetic waves

Enthalpy of air/moisture mixture
Generally is convection the case in wood drying kilns, and the thermodynamic properties of the dry air/water vapour mixture is of importance when the mixture transfers the energy.

The law of conservation of energy states that energy can not be created or destroyed; it can only be changed from one form to another. Applied on thermodynamics, the change in the internal energy of a closed thermodynamic system is equal to the sum of the amount of heat energy supplied to the system and the work done on the system
The first law of thermodynamics states:[58]

$$\Delta U = Q + W + W'$$
6.9

ΔU = *change in internal energy (only changes of internal energy can be measured) [J]*
Q = *heat added to a system [J]*
W = *mechanical work don on a system [J]*
W' = *other energy added (potential energy e.g.) [J]*

As the air/vapour mixture can be treated as an ideal gas the internal energy U is the sum of the internal energies of the mixture constituents: [59]

$$U = U_{air} + U_{vapour} \text{ [J]}$$
6.10

U = *System internal energy*
U_{air} = *Dry air internal energy*
U_{vapour} = *Vapour internal energy*

Enthalpy or heat content of a medium and is defined as the heat change that occurs when 1 mol of substance reacts completely with oxygen to form products at 298°K at 1atm pressure.
In absence of an external field the enthalpy may be defined as:[60]

$$H = U + pV \text{ [J]}$$
6.11

H = *Enthalpy or heat content*
U_r = *Internal energy*
p = *vapour pressure*

[58] http://en.wikipedia.org/wiki/Internal_energy
[59] Haberman William L, John James E.A 1980, Engineering Thermodynamics, p110
[60] http://en.wikipedia.org/wiki/Enthalpy

V = *Volume*

Thus is Enthalpy the sum of the internal energy U and the work potential energy of the pressurized vapour in a volume.

The change of enthalpy with temperature at constant pressure is known as the heat capacity C_P.[61]

$$C_P = \left[\frac{\partial H}{\partial T}\right]_P \quad \textbf{[J /g K]}$$

6.12

C_P = *Heat capacity*
H = *Enthalpy [J]*
T = *Temperature [K]*

As well as the internal energy is an extensive property, the heat capacity C_P (at constant pressure) and the heat content (H) may be estimated from partial capacities and enthalpies of the various constituents.

$$C_P = C_{Pair} + C_{Pvapour}$$

6.13

$$H_{Tot} = H_{air} + H_{vapour}$$

6.14

Heat capacities of air and water vapour increase linearly with temperature, so that is possible to evaluate enthalpy differences of these gases from the heat capacity with changing temperature T_1-T_2:[62]

$$\Delta H = [C_P]_{av} * (T_2 - T_1)$$

6.15

ΔH = *Enthalpy change*
C_P = *Heat capacity o air/vapour mixture*
T_2-T_1 = *Temperature change [°K]*

When computing enthalpies on a dry air/moist air basis the system enthalpy of a unit mass of dry air plus its associated vapour, and is referred as humid enthalpy (*I*):

$$I_{mix} = H_{air} + H_{vapour} * Y$$

6.16

I_{mix} = *humid enthalpy of air/vapour mixture*
H_{air} = *enthalpy of dry air*

---

[61] Keey, Langrish, Walker, 1999, Kiln Drying of Lumber, p 45
[62] Keey, Langrish, Walker, 1999, Kiln Drying of Lumber, p 45

H_{vapour} = *enthalpy of vapour*
Y = *humidity*

The enthalpy (humid enthalpy) of vapour is a composite of the product of heat capacity of water vapour and temperature change ($CP_{vapour},{*}T_2-T_1$) and the latent heat of vaporization of water ΔH_{vo}.
Thus can the humid enthalpy be calculated as:

$$I_{mix} = C_{Pair} * T + \left[C_{Pvapour} * T + \Delta H_{vap}\right]Y$$

6.17

At the triple point temperature, 0°C, the heat content can be served as a reference to which changes can be compared to. Then can the total change in heat content in the air vapour mixture be calculated in blocks of three.

Heat content in the air $\Delta H_{air} = C_{Pair}*T = 1*T$ [kJ/kg*°C][63]

Latent heat of vaporization $\Delta H_{vap} = 2501{,}6-(T*2{,}446)$ [kJ/kg]

Heat content in the vapour $\Delta H_{vap} = C_{Pvap}*T = 1{,}866*T$ [kJ/kg*°C]

In the beginning of a wood drying process air saturated with water vapour is used to heat the wood, heat means energy transfer to the wood, and when the steam hits the cold wood material it condensates and changes state from vapour to liquid water. The change of state from vapour to liquid means a release of energy to the wood of a magnitude of the latent heat of vaporization, a value accessible from tables, 2501,6-(T*2,446) kJ/kg. [64]

Adiabatic saturation and wet bulb temperatures

[63] Tables in: Haberman William L, John James E.A 1980, Engineering Thermodynamics, Allyn and Bacon Inc,

[64] Tables in: Haberman William L, John James E.A 1980, Engineering Thermodynamics, Allyn and Bacon Inc,

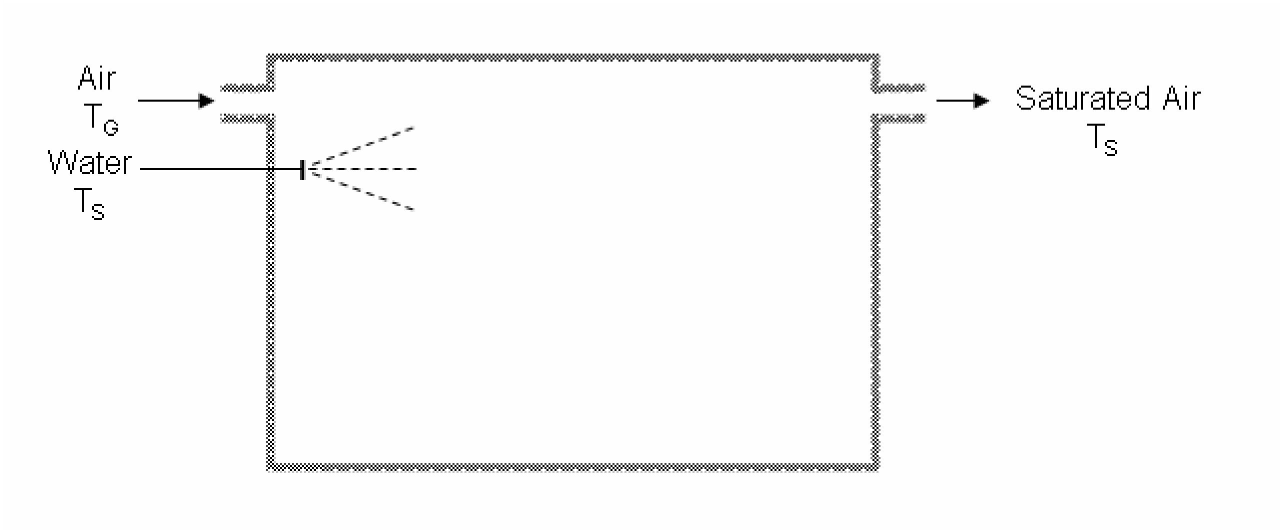


Figure 63: Adiabatic saturation chamber

A wood drying kiln can be regarded as an adiabatic chamber to a first approximation, a process that occurs without heat transfer to or from the system.

As shown in the situation in Figure 63: Adiabatic saturation chamber air at temperature T_G and humidity Y_G is being humidified with water spray at a lower temperature T_S. If enough amount of water the air will leave the chamber saturated at this temperature $T_{S,}$ and the corresponding humidity of the saturated air is then Y_S. An enthalpy balance over the system yields the expression:

$$\frac{Y_S - Y_G}{T_S - T_G} = -\frac{C_{PY}}{\Delta H_{VS}}$$

6.18

Y_G = Humidity of gas/air in
Y_S = Humidity of saturated air
T_G = Temperature of gas/ air in
T_S = Temperature of saturated air out
C_{PY} =effective heat capacity or humid heat (C_{PG}+$C_{PW}Y$)
ΔH_{VS} =latent heat of vaporization of water at temperature T_S

The ratio of the humid heat to the latent heat of vaporization is virtually independent of the starting conditions, and thus there is a common adiabatic saturation path for a given end temperature T_S. Above this dew-line is the relative humidity higher than 100% and dew will fall out in the air as function of temperature (Figure 64).

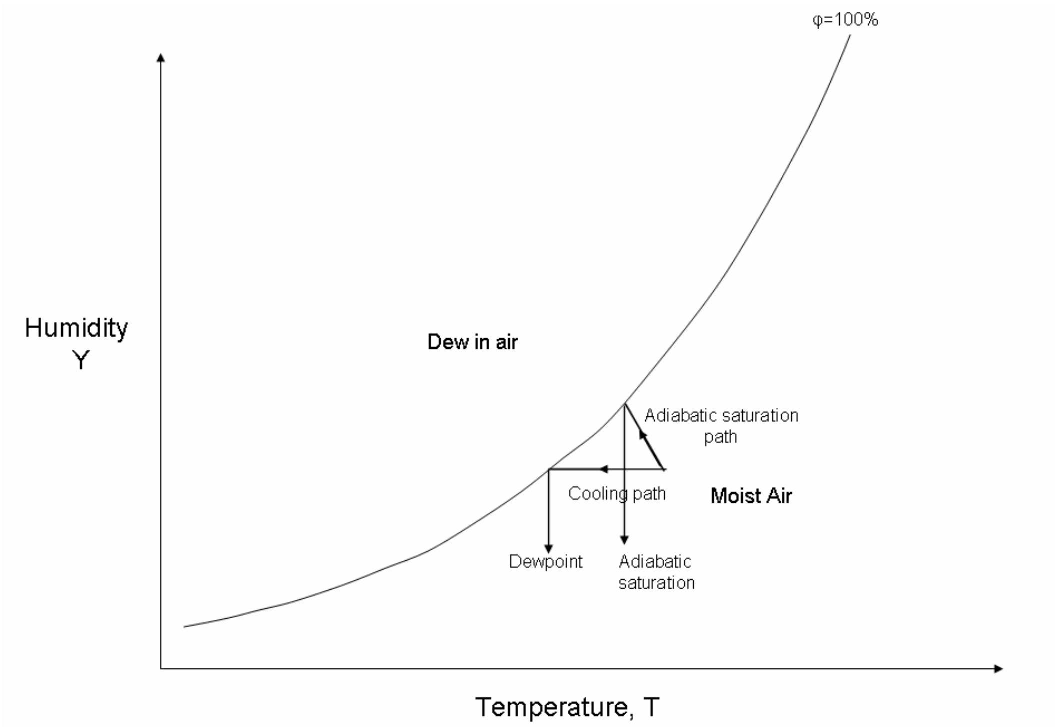


Figure 64: Adiabatic saturation and dew point temperatures

The equation (6.18) is also valid to for system of the dry bulb/wet temperature (Figure 65: Wet Bulb Thermometer Principle) under normal conditions with moist air. Dry bulb /wet bulb thermometers are normally used in wood drying kilns to control the process climate.

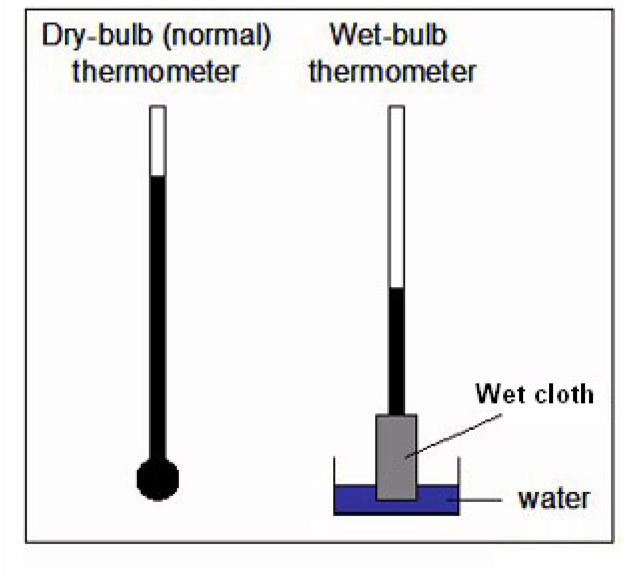


Figure 65: Wet Bulb Thermometer Principle

For other circumstances the formula (6.19) is used where the coefficient γ give a value of the thermo-physical properties of the moist gas system which heat the surface of the wet bulb convectively. Under normal conditions with moist air the coefficient γ is close to 1.

$$T_G - T_W = \gamma \frac{\Delta H_{VS}}{C_{PY}} \left(Y_G - Y_W \right)$$

6.19

T_G = Temperature of gas/ air in, the dry bulb temperature
T_W = Temperature of wet bulb thermometer
γ = coefficient, function of thermo-physical properties of gas/air medium
ΔH_{VS} =latent heat of vaporization of water at temperature $T_S = T_G$
C_{PY} =effective heat capacity or humid heat ($C_{PG}+C_{PW}Y$)
Y_G = Humidity of gas/air in
Y_S = Humidity of saturated air

Humidity charts
The properties of moist gas systems can be conveniently graphed on thermodynamic charts, humidity charts. For process design calculations and displaying of the air conditions humidity charts are still used for wood drying. They can also be useful for evaluating performance limits of the kiln.

A widely used chart is the Mollier diagram that is using a modified humid enthalpy which is linearly related to the humidity, and hence achieving important characteristics of ease to estimate properties of mixed gas streams. By convention the enthalpies of both water and dry air are defined to be zero at zero degrees Celsius in the Mollier diagram.

As shown in the equation for humid enthalpy (6.17) the humid enthalpy is the combined enthalpy of the dry air and the vapour enthalpy as a function of the humidity, which also can be expanded as shown in equation 6.20. I'_G is the modified enthalpy used in the Mollier diagrams.

$$I_G = \left[C_{PG}T_G + C_{PW}T_GY_G\right] + \Delta H_{V0} = I'_G + \Delta H_{V0}$$
6.20

I_G = Humid enthalpy of gas system
C_{PG} = Heat capacity of dry air
C_{PW} = Heat capacity of water vapour at specific humidity Y
T_G = Temperature of gas/air system
ΔH_{VO} =latent heat of vaporization of water at temperature 0°C
C_{PY} =effective heat capacity or humid heat ($C_{PG}+C_{PW}Y$)
Y_G = Humidity of gas/air system
I'_G = Modified enthalpy

The schematic sketch in Figure 66 show the physical places for different state changes of the air/vapour mixture in a wood drying kiln during the process. These changes of the air/vapour mixture in illustrated in Figure 67.

At the line from state 1 to state 2 the outside air mixes with the humid air from the wood at the temperature of state 2, resulting in a new state 3 along the mixing line with lower temperature. Then the air/vapour stream is heated by heating coils resulting in lower relative humidity which increases the potential of drying moist from the wood. The air flow passes the wood that releases moisture to the air and the air/vapour mixture reaches state 2 again.

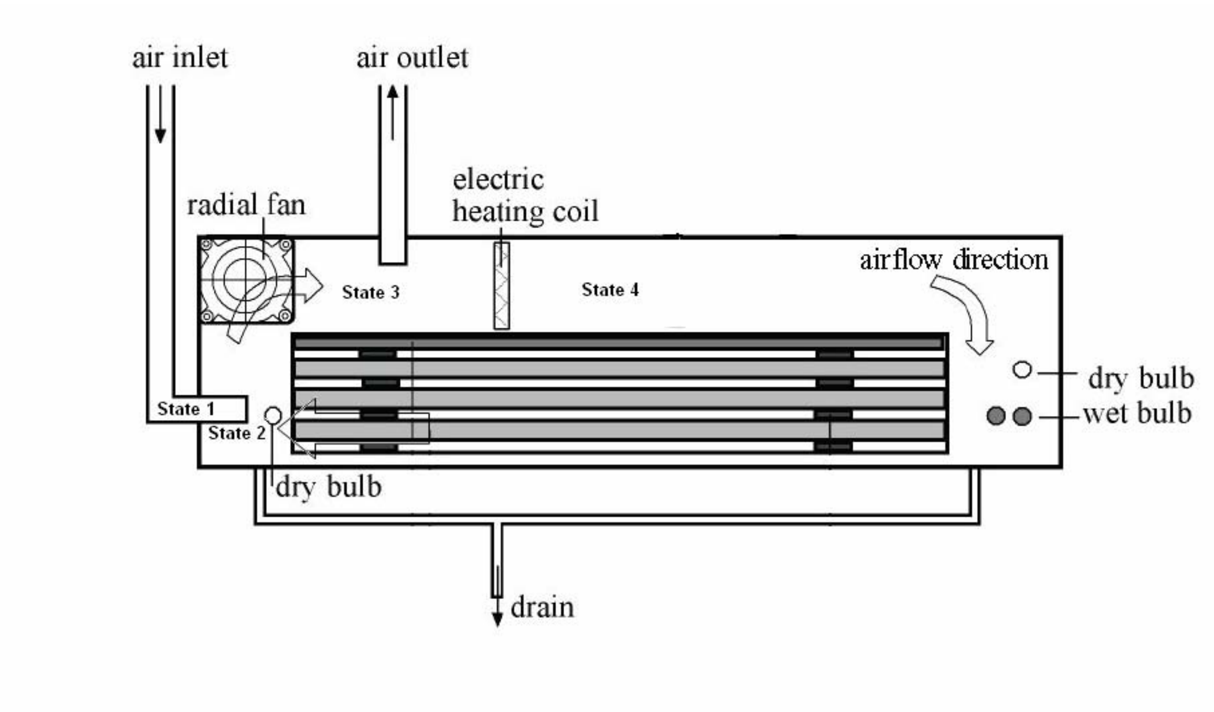


Figure 66: Wood Drying Kiln Air States

The Mollier diagram (Figure 67) illustrates relations between numbers of variables concerning mixing air and vapour. The variables in the diagram are: dry and wet bulb temperatures, relative humidity, vapour ratio and the enthalpy. By knowing only two of these variables the others can be read from the diagram. A wood drying kiln is generally equipped with dry and wet bulb thermometers.

By applying the variables on the air state changes different processes in the kiln can be analysed. The air state changes can involve:

- Heating
  Dry heating when process air passing through the heating element without changing its vapour content is visualized in the Mollier diagram as a change in upward vertical direction, showing the energy increase needed to reach a desired state. As state 3 to 4 in Figure 67

- Cooling
  with constant vapour content, the opposite of heating means a downward vertical change in the Mollier diagram showing the energy decrease needed to reach a desired state.

- Water spaying
  Moisture supply with cold water that evaporates to cool the process air, causes the temperature to decrease and the vapour ratio to increase

- Steaming
  Moisture supply from steam generator to heat the process and increase humidity

- Mixture of air streams
  Mixing of process air with outside air from the vents is shown along the mixing line and the ratio of (State 2 to State 3)/(State 1 to State 2) in Figure 67 shows the mass flux ratio

of process air stream and air from the air inlet.

- Steam absorption
  Vapour take up from the wood causes the same effect as water spraying, the temperature decreases and the humidity increases which is shown as the change from State 4 to State 2 in Figure 67

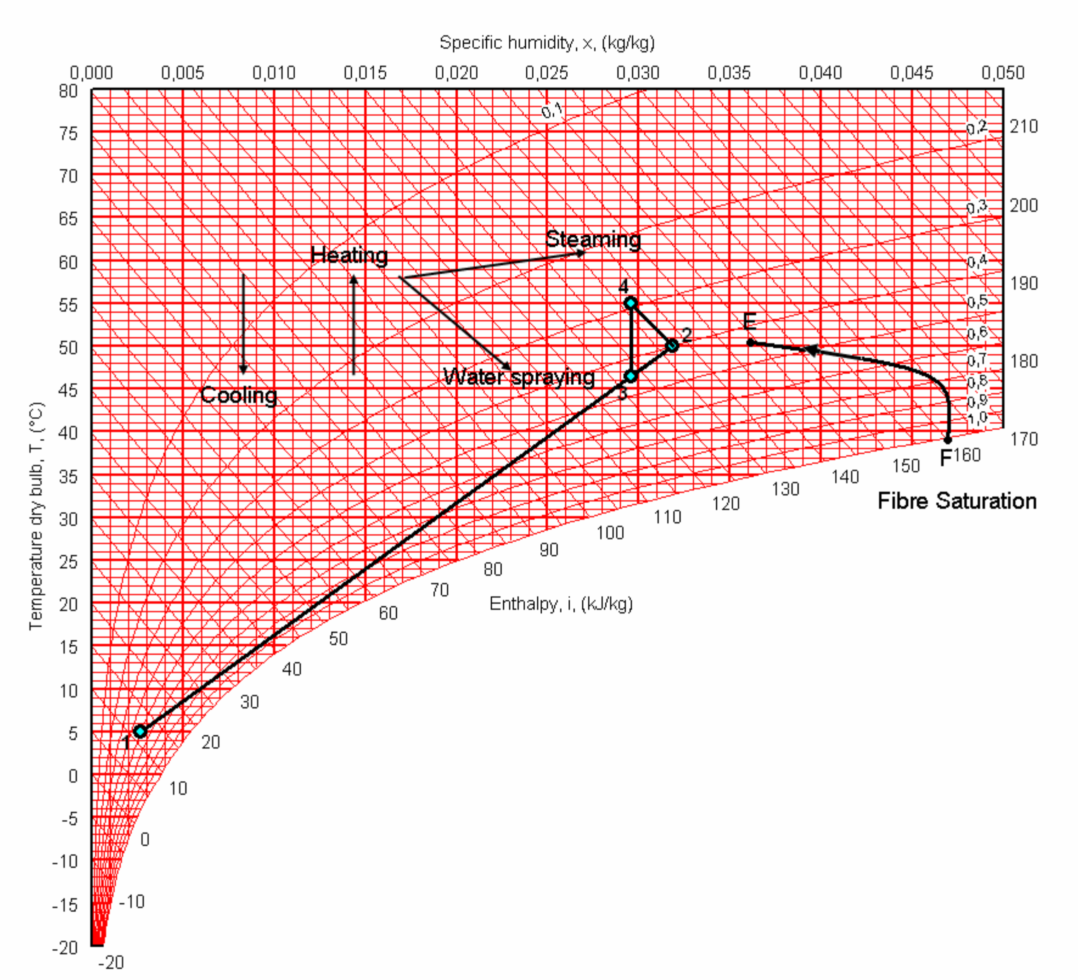


Figure 67: Mollier illustration of various air state changes in wood drying kiln

The Mollier diagram can also be used to illustrate process of drying the wood in the kiln climate exemplified as the line from State F to State E in Figure 67. (Not entirely correct positioning due to limited expansion of the Mollier diagram used in Figure 67)

The cold green wood follows the vapour saturation line until it reaches fibre saturation point and the cell walls starts to dry. Then will the wood temperature increase as the wood dries out affected by the climate in State 4. The evaporation from the wood causes decreased temperature and increase in humidity as shown in State 2. In the end of the drying process the wood surface reaches State E, which eventually will be close to state 4. Remember though that State 1 to State 4 will vary through the process as climate in the kiln varies according to the planned drying schedule.

6.3. Development of Scheduling Tool

With the background described in the chapter 6.1.1 The Kiln and chapter 6.1.2 Process regimes problems together with the theory described in chapter 6.2 there is a know a foundation for understanding the need of a tool to support the process of designing the drying schedule.

The scheduling tool in the control system provided with the kiln, the Valpas Rosterautomatik lets the user to schedule the process in terms of time, dry bulb temperature, wet bulb temperature, fan speed, and position of air outlet valve. Therefore raises a need to further understand the consequences of the settings of these process variables.

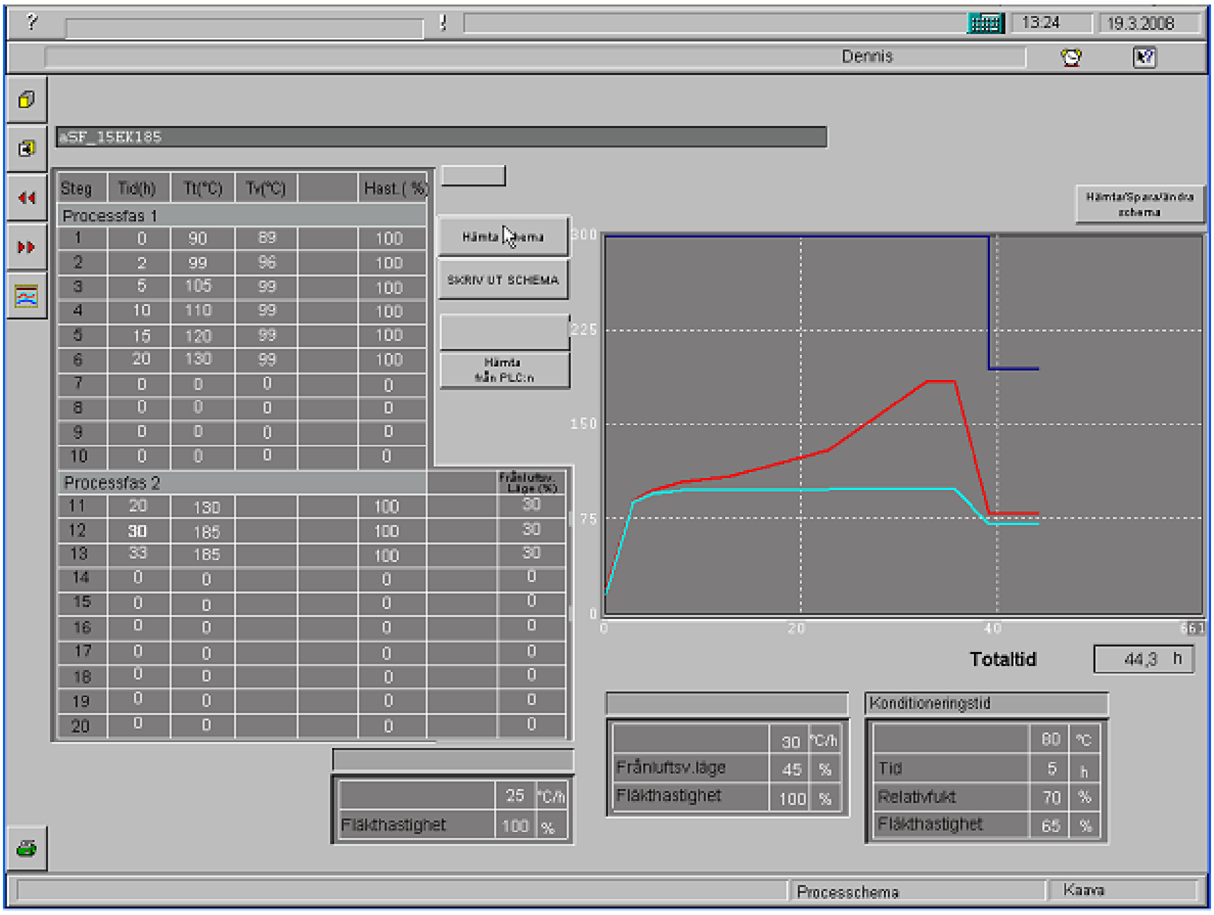


Figure 68: Process schedule view of Valpas system

In wood drying is the moisture content of the wood a key parameter of the wood to which the target of the process is set. To have accurate settings of the process is knowledge of the start value of the moisture content of importance.

$$u = \frac{(m_u - m_0)}{m_0} \, [\%]$$

6.21

$u =$ moisture content $[\%]$

$m_u =$ mass of the wet wood $[kg]$

$m_0 =$ mass of the oven dry wood $[kg]$

$m_u - m_0 = m_{H2O} =$ mass of the displaceable water $[kg]$

In heat treatment of wood the process is complicated by the additional parameters of treatment temperature and time to reach desired material property modification of the wood.

During the process of reaching target heat treatment temperature there is a need to control the moisture flow and tension build up in the wood that depends mainly on the wood response on the process climate. Because of the high treatment temperatures the climate during the heat treatment corresponds to 0% moisture content.

The temperature and time of the heat treatment also changes the hygroscopic properties of the wood and thus the equilibrium moisture content of the wood which affects the conditioning process regime.

The Mollier diagram in Figure 67 and psychrometric tables in Figure 62 are tools for evaluating the process parameter settings and the effect on the climate and on the wood drying.

The problem with Mollier diagrams and psychrometric tables is that the calculations that they are based on are not appropriate when approaching 100°C at high humidity's and is therefore seldom found in wood drying literature at higher (>100°) temperatures. When most of the heat treatment process is run at temperature well above 100°C further knowledge about high temperature behaviour of air vapour mixtures and the response on the wood where needed.

The solution to that problem where found in scientific articles of Simpson and Rosen 1980[65] and Hunter and Tamasy-Bano 2002[66], that present equilibrium moisture content tables and psychrometric charts at temperatures well above 100°C.

The articles derive the thermodynamics of the adiabatic saturation system and sorption of wood to develop their calculations.

What was of further value of these articles where that they represented formulas for calculating the relative humidity (RH) and equilibrium moisture content (EMC) of wood by knowing the dry/wet bulb temperatures.(Figure 69)

[65] W T Simpson, H N Rosen 1980 Equilibrium Moisture Content of Wood at High Temperatures

[66] A.J. Hunter, M. Tamasy-Bano 2002 Psychrometric charts for use with normal and high temperature drying of wood

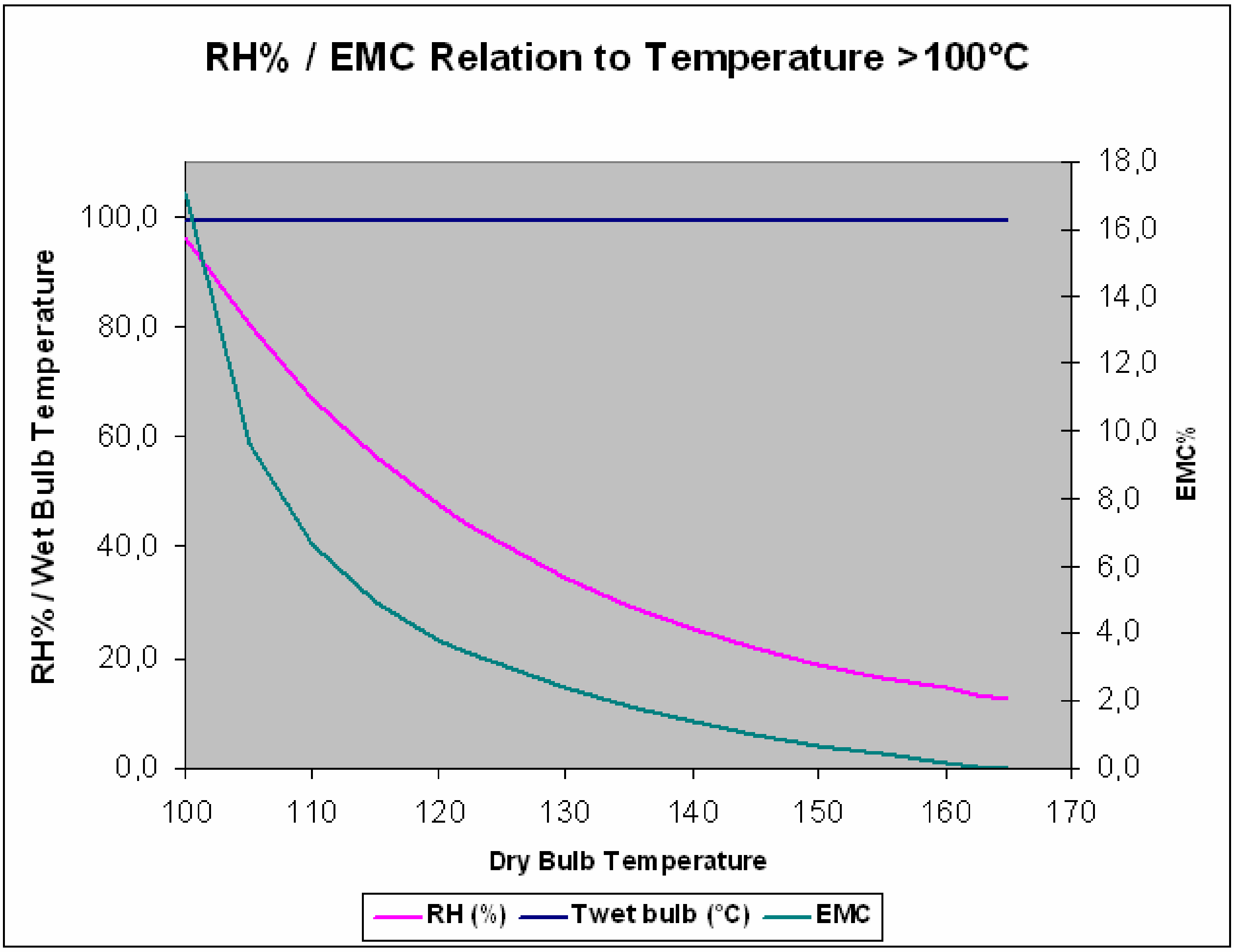
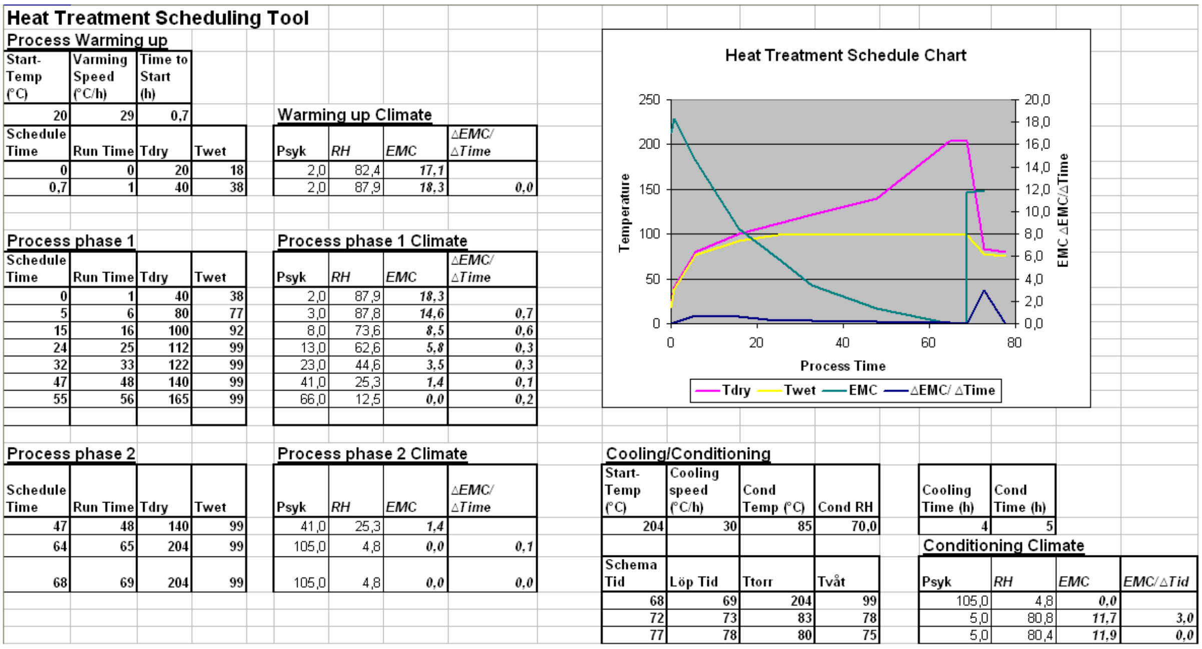


Figure 69: RH and EMC above 100°C Tdry bulb 99°C Twet bulb

The knowledge of calculating RH and EMC was been used to develop a scheduling tool to use in parallel to that of the Valpas control system of the heat treatment kiln.

The scheduling tool where realized in Excel showing the scheduling steps of the process as in the kiln control system. Then calculations of the relative humidity and equilibrium moisture content where done with use of macros in each of the steps in the process.

The idea with creating the scheduling tool was to have an indication of the affect on drying speed of the wood that the climate changes in the process created. When knowing the equilibrium moisture content (EMC) in every moment of the process, the change of EMC over time where set as that indicator. (Figure 70 and Figure 71)



Heat Treatment Scheduling Tool

Process Warming up

Start-Temp (°C)	Varming Speed (°C/h)	Time to Start (h)
20	29	0,7

Schedule Time	Run Time	Tdry	Twet
0	0	20	18
0,7	1	40	38

Warming up Climate

Psyk	RH	EMC	ΔEMC/ ΔTime
2,0	82,4	17,1	
2,0	87,9	18,3	0,0

Process phase 1

Schedule Time	Run Time	Tdry	Twet
0	1	40	38
5	6	80	77
15	16	100	92
24	25	112	99
32	33	122	99
47	48	140	99
55	56	165	99

Process phase 1 Climate

Psyk	RH	EMC	ΔEMC/ ΔTime
2,0	87,9	18,3	
3,0	87,8	14,6	0,7
8,0	73,6	8,5	0,6
13,0	62,6	5,8	0,3
23,0	44,6	3,5	0,3
41,0	25,3	1,4	0,1
66,0	12,5	0,0	0,2

Process phase 2

Schedule Time	Run Time	Tdry	Twet
47	48	140	99
64	65	204	99
68	69	204	99

Process phase 2 Climate

Psyk	RH	EMC	ΔEMC/ ΔTime
41,0	25,3	1,4	
105,0	4,8	0,0	0,1
105,0	4,8	0,0	0,0

Cooling/Conditioning

Start-Temp (°C)	Cooling speed (°C/h)	Cond Temp (°C)	Cond RH
204	30	85	70,0

Cooling Time (h)	Cond Time (h)
4	5

Schema Tid	Löp Tid	Ttorr	Tvåt
68	69	204	99
72	73	83	78
77	78	80	75

Conditioning Climate

Psyk	RH	EMC	EMC/ΔTid
105,0	4,8	0,0	
5,0	80,8	11,7	3,0
5,0	80,4	11,9	0,0

Figure 70: Heat Treatment Scheduling Tool

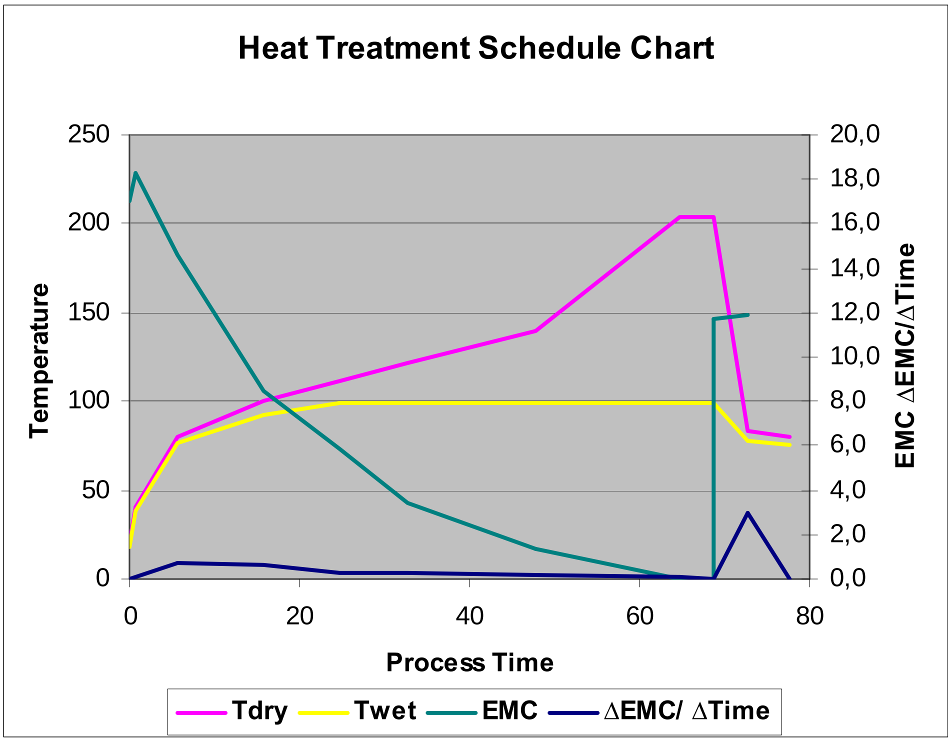


Figure 71: Chart of Scheduling Tool

Below fibre saturation point (about 30% MC) wood start to shrink as the cell wall dries out and the shrinkage causes tension/compression in the wood see Figure 60. If there are large moisture content gradients in the wood these forces increase.

The differential between the process climate and the corresponding equilibrium climate to the moisture content of the processed wood causes a moisture flow from the core of the wood to the surface; see Darcy's law in equation (6.2).

Thus by controlling the process according to the moisture content in the wood and perform the drying at a speed that minimizes moisture content gradients and the pressure differential between the core and the surface one can avoid both surface and internal checking of the wood.

Another idea with the tool was to have medium for a knowledge database on the experiences from heat treatment processes on different species and dimensions that was run in the project.

The tool gave increased insight of the climate at temperatures above 100°C and the fact that 0% EMC doesn't occur until 165°C dry bulb temperature with 99°C wet bulb temperature. Thus is a continuous change of the climate at a controlled speed a possible method to prepare the wood for the treatment regime.

6.3.1. TDL Analyses

As the process air is blowing through the pile of wood in the kiln the air is cooled by the moisture evaporating from the wood and by heat loss when heating the wood to process temperature.

The cooling of the process air as the air blows through the wood package is called temperature drop across the load (TDL). This has been an important parameter to use for analysing the heat treatment process and the experiences in the project say that the TDL shouldn't be more than about 2°C to have a successful heat treatment on more dens wood species or thicker dimension of pine and spruce.

During heat treatment there is a third parameter affecting the TDL due to exothermal reactions in the wood when some the wood constitutions decompose and releases energy which contributes to a decreased cooling of the process air. Though the decomposition of wood doesn't start until the wood temperature has reached 160°C and accelerates further at temperatures above 200°C[67].

This means that during drying wood to 0% moisture content at 165°C the release of energy due to decomposition of wood can be neglected.
Thus there are only the mass transfer of water vapour from the wood and heat transfer to the wood to take into account when considering the cooling of the process air.

Since the heat transfer rate to the surface is directly proportional to the temperature difference and by using a continuous increase of the process temperature the TDL fraction by heating of the wood will be constant. The TDL contribution from moisture evaporation gives an indication of the rate of evaporation from the wood, which increase with temperature and psychrometric difference.

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[67] Hill, Callum A. S Wood modification : chemical, thermal and other processes / Chichester, England ; Hoboken, NJ : John Wiley & Sons, c2006

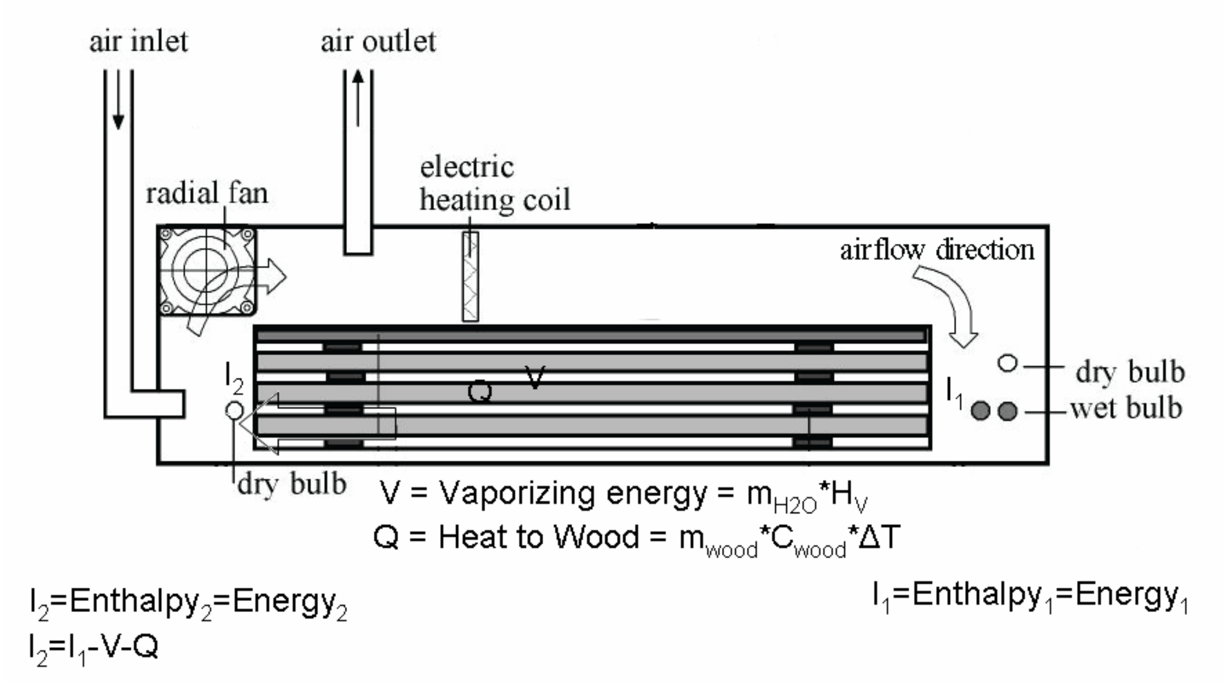

Figure 72: Energy balance in Wood Drying Kiln

By investigating the energy balance showed in Figure 72: Energy balance in Wood Drying Kiln the temperature drop (TDL) can be calculated by means of equation 6.22.

$$TDL = T_1 - T_2 = T_1 - \frac{T_1(C_{PG} + C_{PW}Y_1) - m_{H2O} * H_{V0} - m_{wood} * C * (T_1 - T_{wood})}{(C_{PG} + C_{PW}(Y_1 + \frac{m_{H2O}}{m_{air}}))}$$

6.22

T_1 = Temperature before load
T_2 = Temperature after load
T_{wood} = Temperature of the wood
C_{PG} = Heat capacity of dry air
C_{PW} = Heat capacity of water vapour at specific humidity Y
Y_1 = Humidity of air/moisture mixture as dry air to vapour mass ratio before load
H_{VO} =latent heat of vaporization of water at temperature 0°C
m_{H2O} =mass of water evaporating from wood
m_{air} =mass of dry air flow in the kiln
m_{wood} =mass of wood in the kiln

Still remains the problem of knowing the mass of water evaporating from the wood at a specific time. An estimate from a process viewed in Figure 73, Figure 74 and Figure 74 will show the level of the contribution ratio between the evaporation and the heating of the wood.

By calculating on the effect to warm the mass of the wood and compare it with the effect needed to evaporate the moisture in the wood one can get the relation of the cooling contribute of the heating in relation to the mass transfer of moisture from the wood.

From the schedule of the process are the time and temperature increase obtained and calculating with a start moisture content of 10% and that drying starts after the warming up and continues along the temperature increase to 165°C.

Such calculations give a relation of 2.8 times higher contribution to the TDL of evaporation of water vapour than from warming of the wood, the indicate that the evaporation of moisture from the wood is the main contributor to the TDL (equation 6.23 and 6.24).

$$P_{warm} = \frac{Q}{\Delta t} = \frac{m_{wood} * C_{wood} * \Delta T}{\Delta t} = \frac{102 * 1300 * (165 - 96)}{126000} = 73 \frac{J}{s}$$

6.23

$$P_{vaporize} = \frac{Q}{\Delta t} = \frac{mH2O * H_{V0}}{\Delta t} = \frac{10{,}2 * 2501600}{126000} = 203 \frac{J}{s}$$

6.24

m_{wood} = *mass of wood in the kiln*
C_{wood} = *heat capacity of wood (1300 J/kg °C)* [68]
ΔT = *Temperature increase*
Δt = *time for temperature increase*
m_{H2O} = *mass of water evaporating from wood*
H_{V0} = *latent heat of vaporization of water at temperature 0°C (2501,6 kJ)* [69]

When investigating the temperature increase from 165°C to 200°C is the question whether there is any moisture left in the wood. Assuming a 2% MC gives the relation evaporation/warming energy equal to 0,6 showing that the warming of the wood being the main contributor to the TDL in such a case.

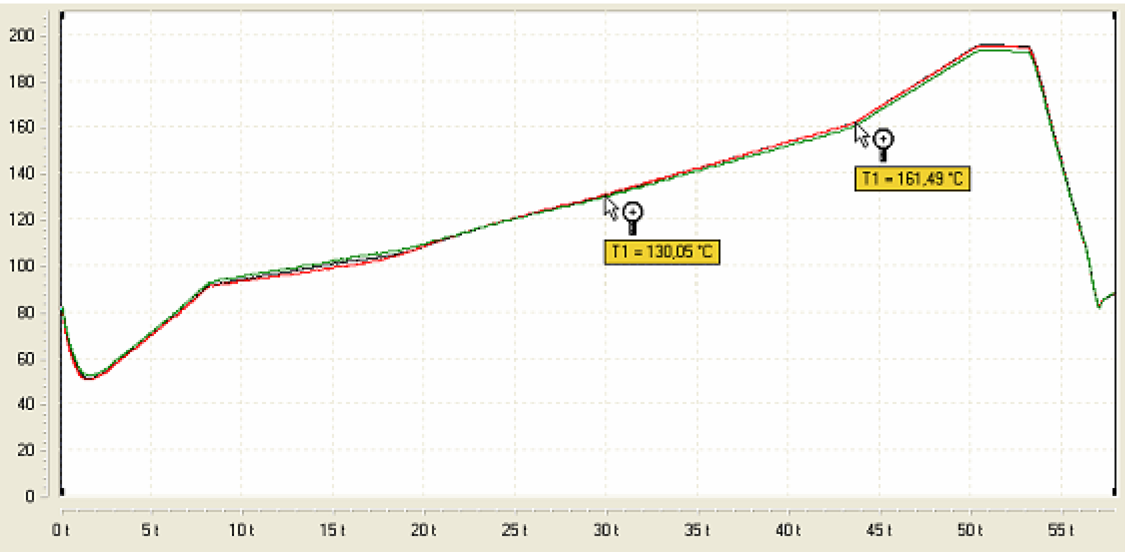

Figure 73: Wood temperature during heat treatment of Birch

[68] Träbyggnadshandbok 9 Material, sida 9 Trätek, ISBN 91-585576-20-4
[69] Tables in: Haberman William L, John James E.A 1980, Engineering Thermodynamics, Allyn and Bacon Inc

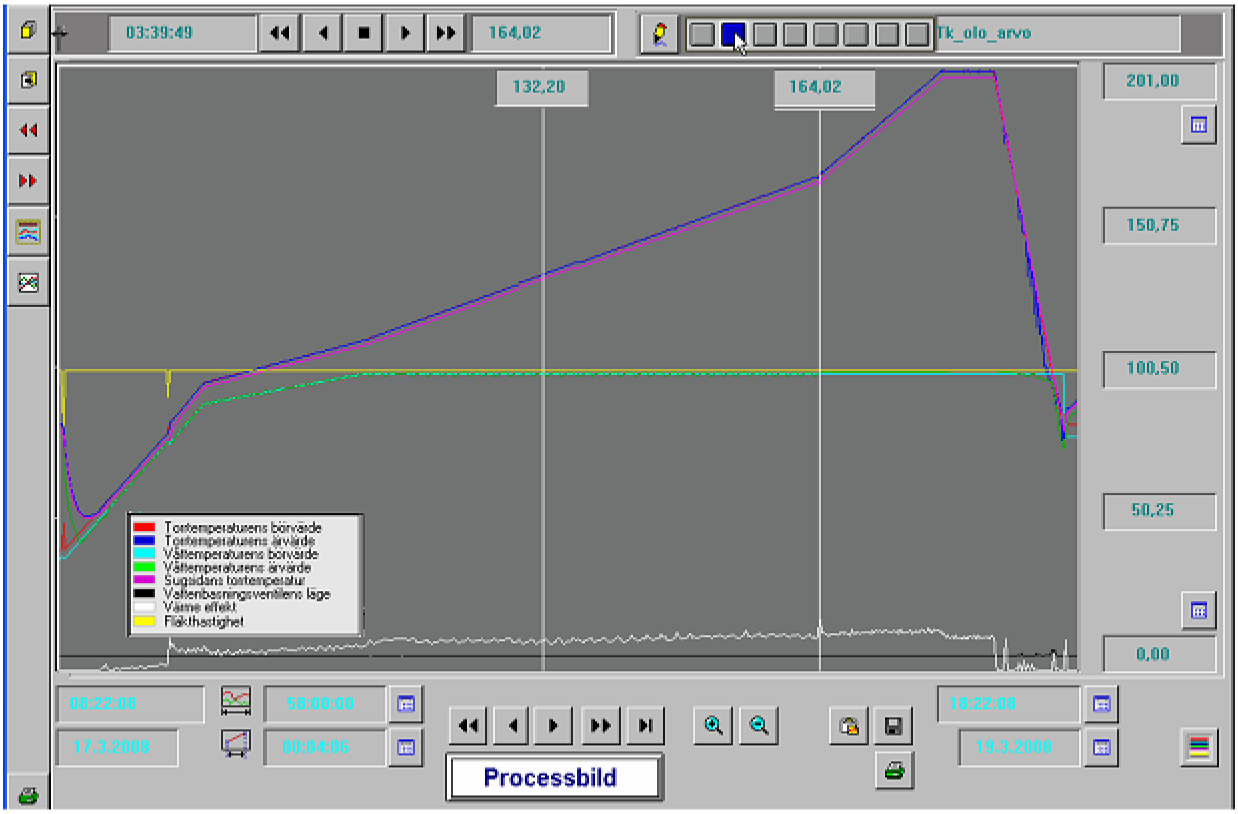

Figure 74: Process air temperature during heat treatment of Birch

By study the example of a temperature drop across the load (TDL) response in Figure 75 that represents a successful heat treatment of Birch of 40mm in thickness one can find support in the reasoning above. The process is the same as in Figure 73 and Figure 74.

During the heating with steam and electrical heat the TDL increases due to heat transfer to the wood when the temperature increase is fast. Due to high energy release when the steam condenses on the cold wood the temperature increase of the wood is quick and the TDL increase relatively small. The culminating of the TDL during the heating regime occurs when the steam no longer condenses on the wood (state A) and the moisture on the surface starts to evaporate. Due to the small amount moisture on the surface of condensed steam the TDL decreases rapidly to the level of the drying of the wood.

The TDL level is maintained due to the design of the process drying speed until the point where the process equilibrium moisture content is 0%. Then during the temperature increase to heat treatment temperature an increase in TDL is noticed that depends on heat transfer to the wood and the evaporation of moisture still present in the wood.

At state B in Figure 75 the contribution to the TDL of the heat transfer to the wood can observed when the TDL drops when the temperature increase stops. The level of TDL after state B indicates that there is still moisture in the wood evaporating.

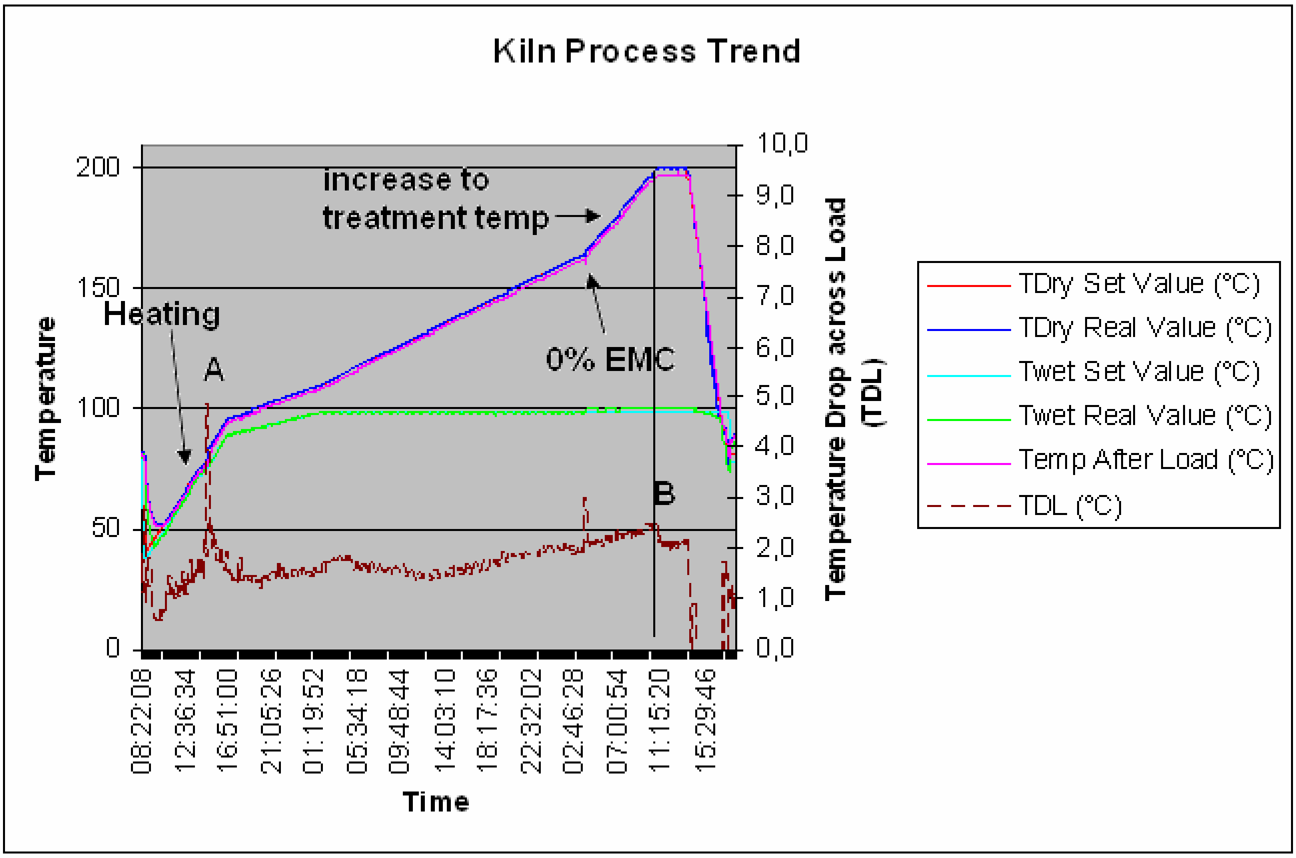

Figure 75: TDL during heat treatment of Birch

The slow drying of wood when the moisture content is near 0% is illustrated by Figure 76 that show the relation of the rate of moisture increase/decrease in wood to the increase/decrease of climate humidity. The characteristic steep curve close 0% depends on strong attraction between OH groups in the wood hemi cellulose and water molecules that are connected mono molecularly.

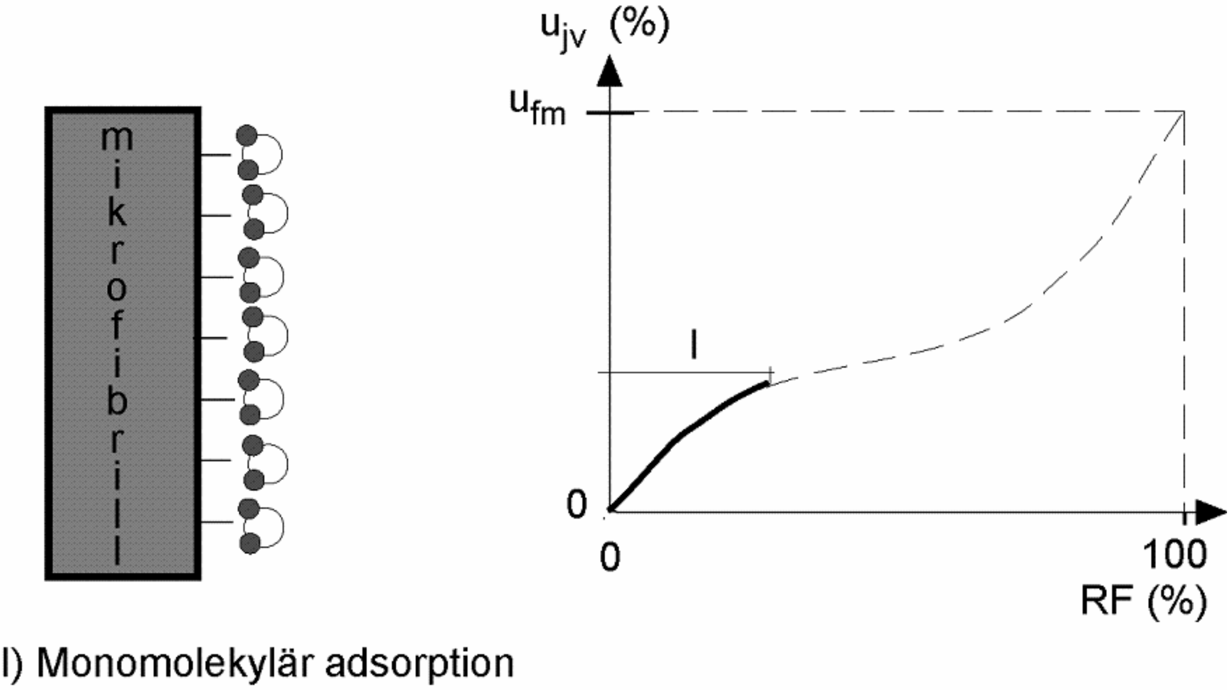

Figure 76: Wood Sorption of moisture

6.3.2. Empirical Observations

During the heat treatment process the temperatures many times are above 100°C when moisture is still present in the wood cell wall. At such temperatures the water vapour pressure increases exponentially from 1 atmospheric pressure (atm) at 100°C to 23 atm at 220°C, see Figure 77 if the volume is closed. As the moisture content is well below fibre saturation point the water is bound in the cell wall and is transported through the cell wall trough diffusion. The question is how the bound water reacts to the high temperature and if there is a high pressure build up within the cell wall or between the cell wall layers (Figure 78) or between the adjacent cell walls.

If that would be the case it would mean that a high moisture flow at high temperatures would cause very high tension in the wood that could be the cause of internal checking. The moisture flow can be indicated by the temperature drop.

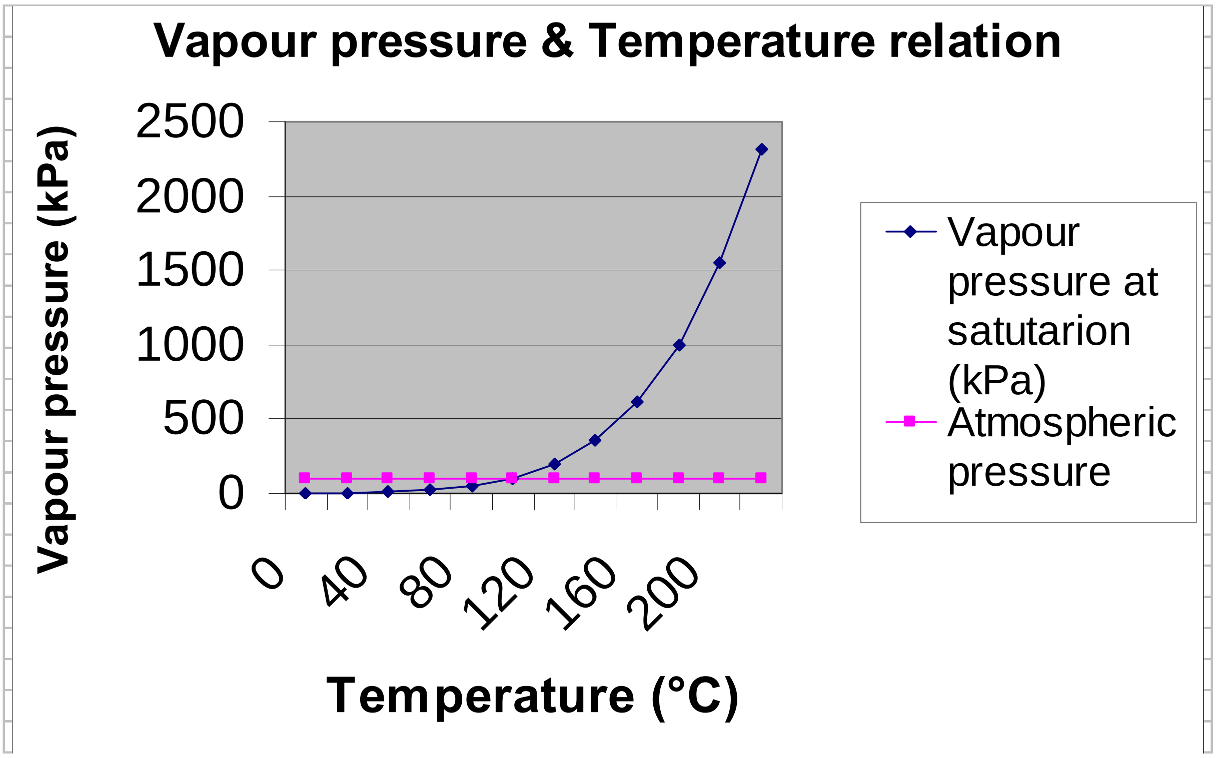

Figure 77: Vapour Pressure & Temperature Relation according to a Clapeyron calculation in a closed volume

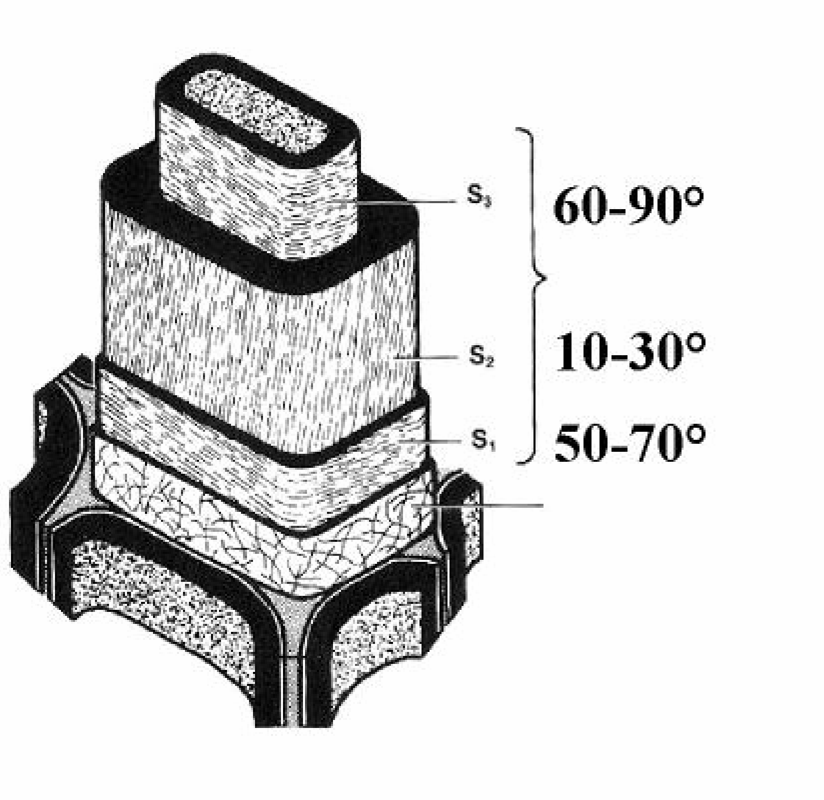

Figure 78: Wood Cell Wall Layers

The following will show some examples of heat treatment processes according to the temperature drop. The first example (Figure 79) show an experiment regarding internal checking on 50x125mm Spruce pre dried to 18%MC.

The schedule was done without the help of the tool developed in this project and the design causes an strong moisture flow in the beginning of the process and then the climate is held constant at a equilibrium moisture content of 3,8% for 60 hours. Then the temperature increases during 24 hours to 212°C and causes a steep increase in TDL at high temperatures that is likely to cause high internal pressure, which is confirmed with pressure measurements done by Johansson 2005 (Figure 80)[70]. There where internal checking within the boards in the test.

[70] Dennis Johansson – Strength and Colour Response of Solid Wood to Heat Treatment

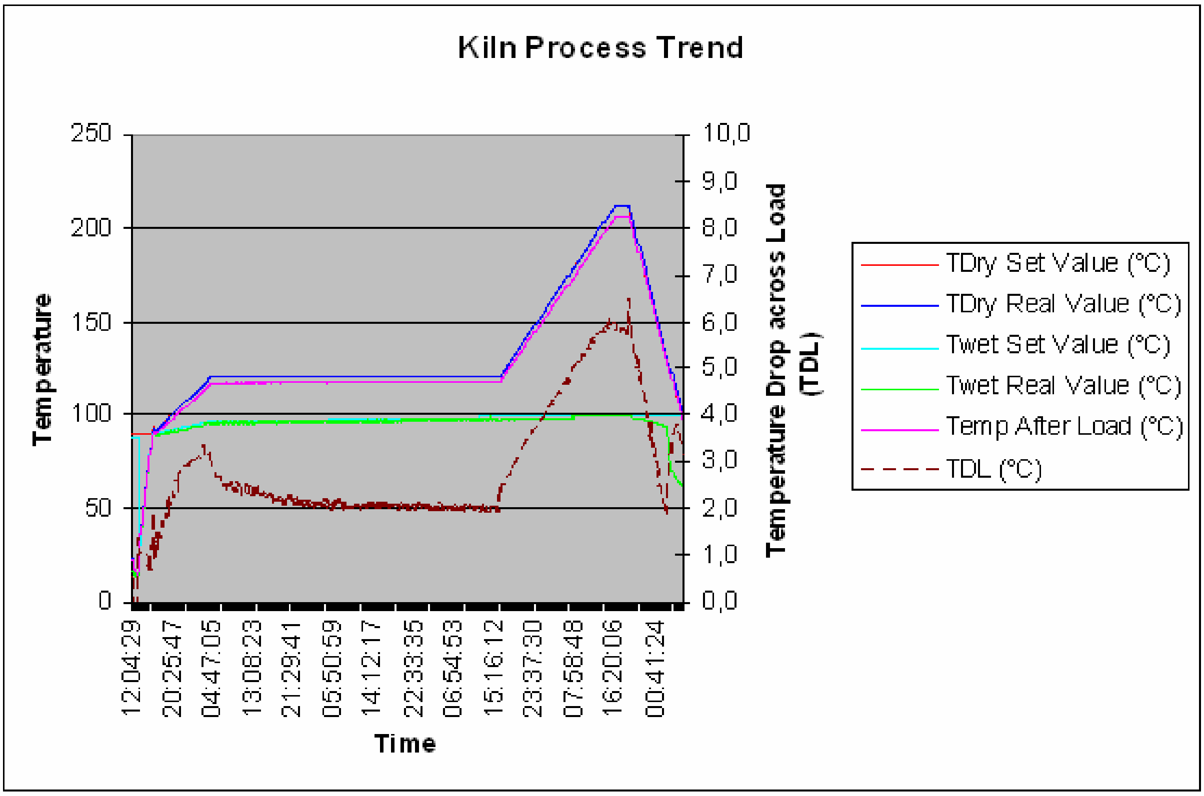

Figure 79: TDL on Heat Treatment of 50x125mm Spruce

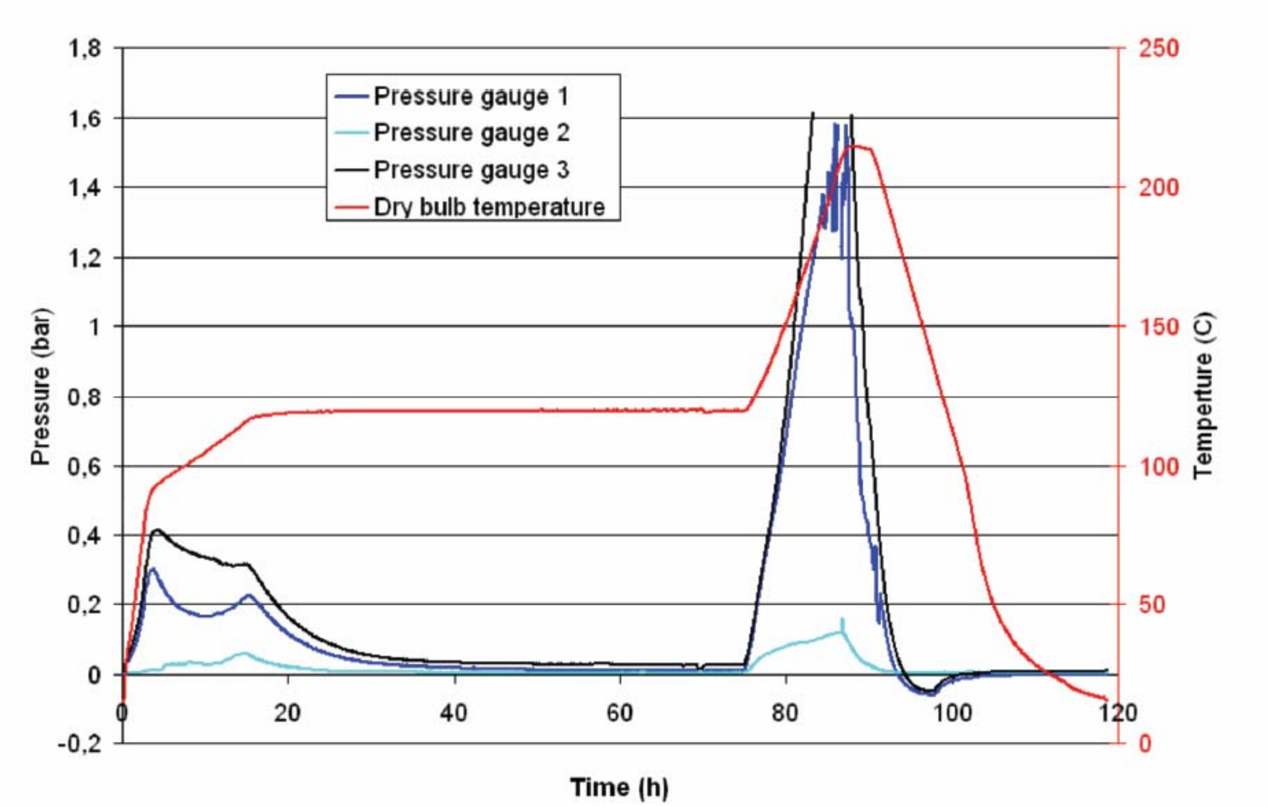

Figure 80: Pressure Response to Process Temperature

The second example show the TDL response from a process developed with developed scheduling tool for 40mm thick Oak. Despite the tool a mistake where done and the process where set with a treatment temperature of 200°C instead of 170°C without adjusting the time fore the temperature increase from 165°C to 200° which where causing a TDL peak showed in Figure 81.

When examine Figure 81 closer one can observe that the TDL never is higher than 1,5 °C until the peak at the temperature increase to 200°C. After the peak the TDL drops when the temperature flattens out at 200°C indicating a low moisture flow and that the main contribution to the TDL where warming of the mass of wood.

Oak is especially sensitive to internal checking during drying in general and even though the moisture flow in the process is low during the drying of the wood until the climate of 0% EMC at 165°C there where severe internal checking.

Figure 82 show the TDL response to the process done on a new batch that was needed due the mistake of the process in Figure 81 but now uses only 25 mm thick boards . The new process schedule is identical with the one in Figure 81until the 165°C temperature level is reached. Then the new schedule uses a plateau for 2 hours before the increase to 170°C heat treatment temperature. The result showed no internal checking.

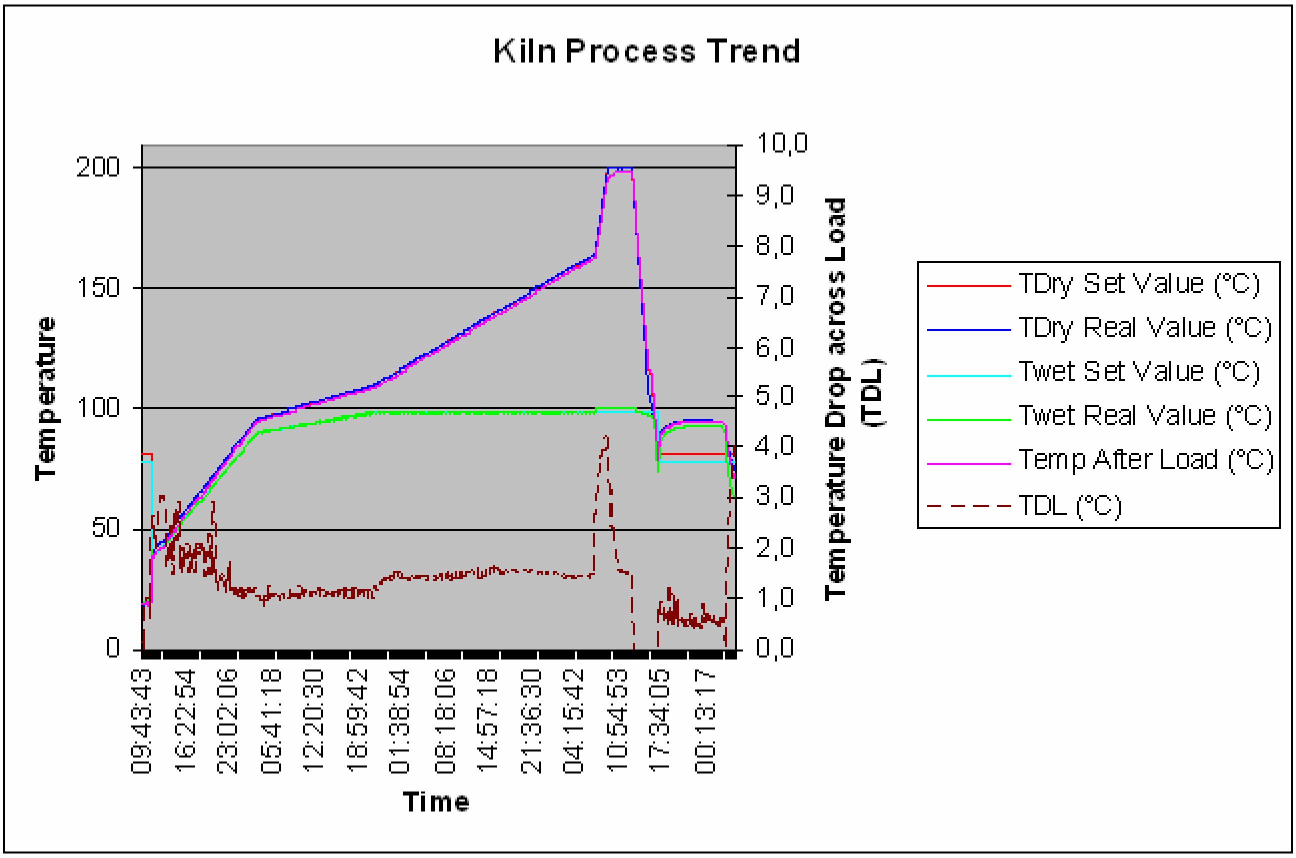

Figure 81: TDL response on 200°C Heat Treatment of 40x170mm Oak

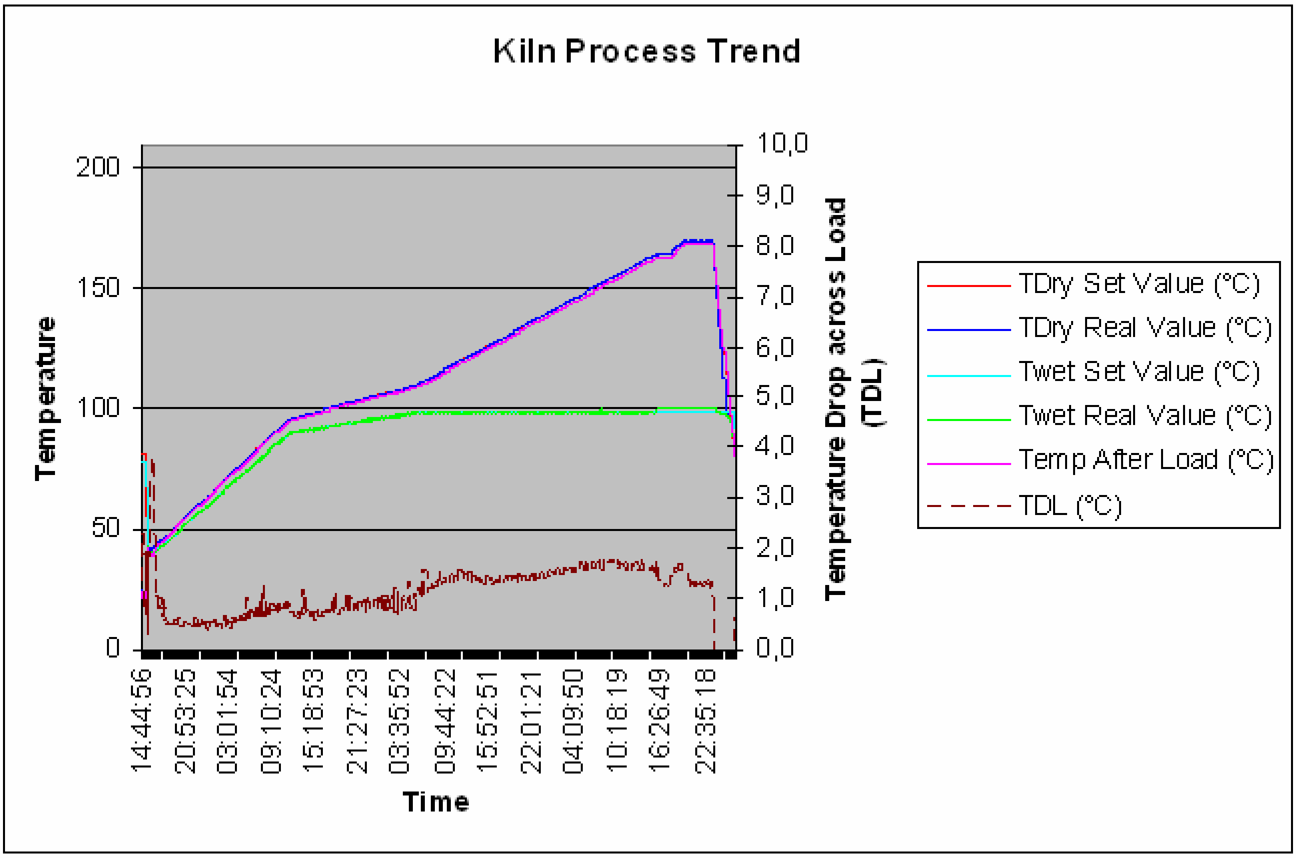

Figure 82: TDL response on 170°C Heat Treatment of 25x125mm Oak

6.3.3. Discussion on Heat Treatment Process

The original idea of using calculation models from Simpson and Rosen 1980 and Hunter and Tamasy Bano 2002 was to have a value of the change of equilibrium moisture content over time (EMC/hour) that would create an experience base for learning an appropriate drying speed during the heat treatment process.

When realizing that a climate equivalent to 0% EMC doesn't occur until the temperature reaches 165°C with a wet bulb temperature of 99°C causes a need for consideration when designing the heat treatment process. The second drying regime described by Johansson 2005 should appropriate to start at 0% EMC to avoid internal checking in the wood when increasing the temperature to treatment levels.

To start the second drying regime at 0% EMC result in a need for continuous change in process climate after the warming up in an appropriate speed. The appropriate speed where gained by analysing the temperature drop from the processes that gave useful information even at low moisture contents of the wood. The reason for having useful information during the whole drying process might be due to the continuous change to a drier climate and due to the temperatures above 100°C that causes a high diffusion flow.

As the vapour pressure increases exponentially and is above atmospheric pressure when the temperature is above 100°C this is possible cause of the problem with internal checking of wood together with induced cell collapse in the pre drying of the wood.

As the temperature drop reflects the evaporation and the warming of the wood it is likely that it also can reflect the pressure in the wood in relation to the temperature.
The use of the scheduling tool and the temperature drop would be possible to use in an adaptive control system for the heat treatment process with some further development of this work.

Perhaps causes the pressure in the wood together with the thermal degradation of the wood changes in the strength properties like the brittleness and the bending strength of the wood. Therefore it is possible that the use of better processes would give measurable improvements of results reported on the strength properties of heat treated wood.

6.3.4. Conclusion

The tool and the experiences developed in the project could be used for improving the control of the heat treatment process by adding functionality to the control system by calculating the response of the moisture content of the wood and by following and controlling the temperature drop to avoid high pressure build up in the wood due to high water vapour expand at the high temperatures used for heat treatment.

With the use of continuous change to a drier climate causes a continuous moisture flow that give ground to a measurable temperature drop at moisture contents well under the fibre saturation point that perhaps can be a possible method for controlling the diffusion regime in traditional wood drying as well.

7. Conclusion of the project

As a conclusion of a project that serve to communicate the possibilities with the technology of heat treating wood there is despite an ongoing international commercialization of the material still a number of information needed about the process as well as the material for real utilization of the technology will be found.

This lack of information is exemplified in the development of this concept house in heat treated wood, and the experiences will point at questions to raise as well as some of the development will give a start of developing solutions to some of the difficulties with the technology.

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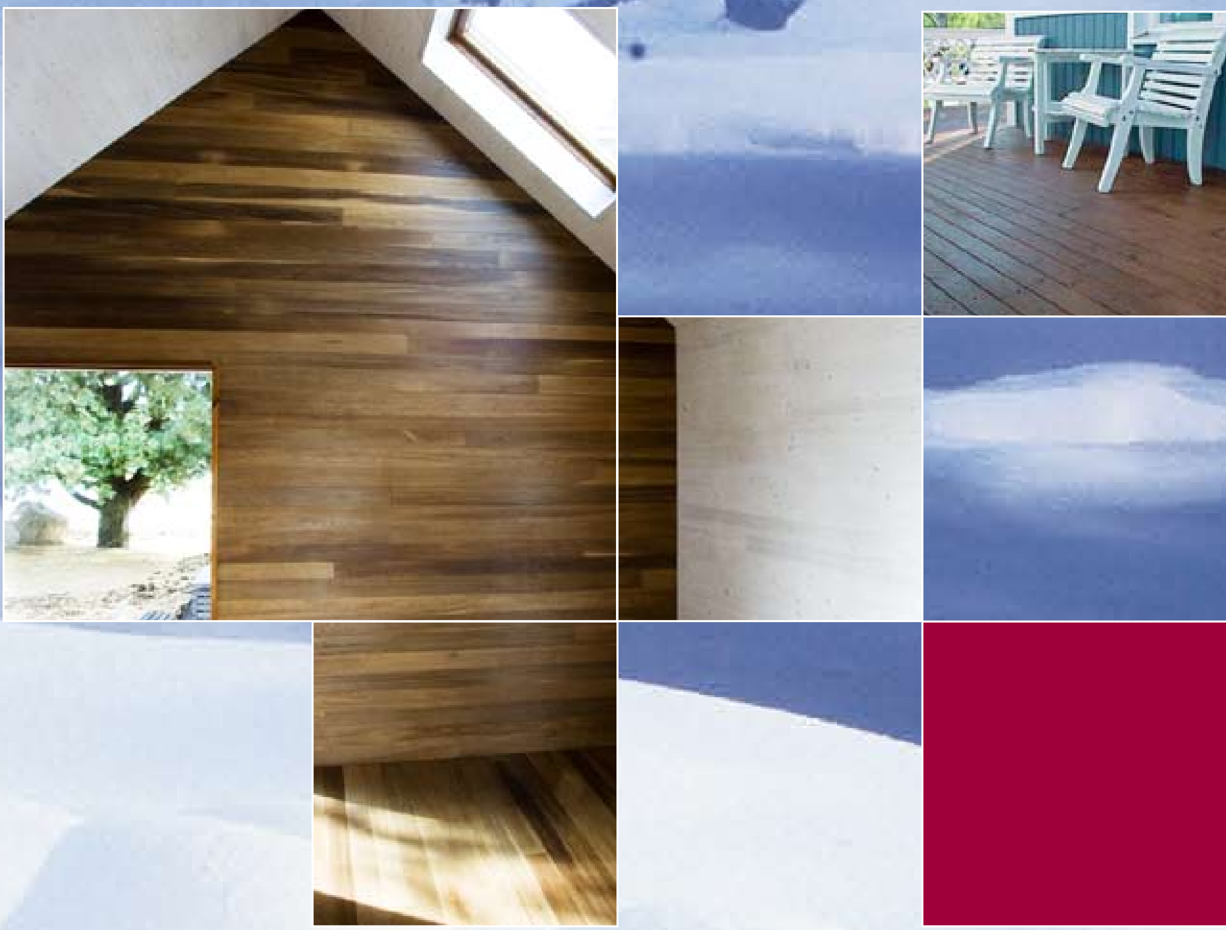
Appendix I – Information about Heat treated Wood

Skandinaviens nordligaste tekniska universitet
Forskning & utbildning i världsklass

LTU SKELLEFTEÅ

Värmebehandlat trä

Ytbehandling, egenskaper och användningsområden



LULEÅ
TEKNISKA
UNIVERSITET

Foto: Finnforest

Ytbehandling av exteriöra produkter

När det gäller ytbehandling av värmebehandlat trä för exteriör användning väcks snart frågan om hur gör man det. Värt att beakta är materialets fördelar gentemot traditionell träfasad men också dess skillnader i hantering.

Frågan är vad man vill uppnå – å ena sidan kan man tänkas vilja uppnå ett längre serviceintervall och å andra sidan vill man behålla det värmebehandlade träets estetiska värde genom att använda en transparent bestrykning.

Generellt kan man säga att traditionella ytbehandlingar för obehandlat trä har goda förutsättningar att fungera för värmebehandlat trä om man har kunskap att använda dessa enligt de förutsättningar som värmebehandlat trä har.

Fördelar

De direkta fördelar man kan se vid ytbehandling av värmebehandlat trä för exteriör användning är att man har ett mer stabilt material som är beständigt mot röta. Vidare kan man se att påväxt av mögel tenderar till att minska och att utsöndring av kåda är eliminerad på värmebehandlat trä.

Dessa egenskaper ger förutsättningar för en ytbehandling med längre hållbarhet med minskat och antagligen enklare underhåll som följd.

Problem

Liksom annat trä så grånar värmebehandlat trä och problemet är att det inverkar på materialets estetiska värde när man önskar använda en transparent ytbehandling. För att förhindra detta gäller det att välja metod utifrån de krav som ställs på applikationen där det värmebehandlade träet används.

Materialets egenskaper medför att absorption av vattenlösliga träskyddsmedel är långsammare än för obehandlat trä.

Generellt

För att ytbehandlingen av värmebehandlat trä ska få en god vidhäftning rekommenderas att ytan hyvlas eller att en sågad yta borstas så att ytlig vårved avlägsnas för att undvika att små flisor lossnar.

Utan skydd mot ljus grånar värmebehandlat trä, en metod som används för att skydda mot ljus vid användning av transparent bestrykning är att pigmentera den i samma nyans som det värmebehandlade träet.

Traditionellt görs accelererade tester med UV-ljus men erfarenheter visar på att dessa tester inte ger ett rättvisande resultat om färgförändringen på värmebehandlat trä. Det finns alltså anledning till att anta även annan typ av ljus som påverkar färgförändringar på värmebehandlat trä.

Utan ytbehandling får värmebehandlat trä ytsprickor när det utsätts för väder och vind, liksom obehandlat och impregnerat trä.

Foto: Suomen Lämpöpuu Oy

Foto: Finnforest

Som allt organiskt material kan ytan på värmebehandlat trä angripas av mögel och blånad men i en minskad omfattning jämfört med obehandlat trä.

Detta påverkar inte materialets integritet utan är enbart ett estetisk problem. Därför är det viktigt att ytbehandlingen inte tillför en grogrund för mögel och för att förhindra detta bör den innehålla antimögel-ingredienser eller vara av sådan art att den inte innehåller näring för mögelsvampar.

Erfarenheter visar på en ökad åtgång av primer vid ytbehandling av värmebehandlat trä. Genom att primen tränger in bättre medverkar detta till ytterligare förbättrat skydd.

Träfasad

Värmebehandlat trä har egenskaper som medför att materialets fuktabsorption är mindre jämfört med obehandlat trä varför vissa ytbehandlingar inte kan absorberas på samma sätt. Med rätt utförd behandling uppnås en god vidhäftning och ett beständigt resultat. För träfasader av värmebehandlat trä används idag några olika alternativ:

- **Obestruken**
  Värmebehandlat trä grånar med tiden men egenskaperna hos materialet ger möjligheter att använda det på detta sätt. Erfarenheter från långtidsanvändning saknas.

- **Lasyr**
  Detta är den vanligaste metoden på de ytbehandlade referens-objekt som visas av Thermo Wood-företagen. Lasyren kan vara transparent eller pigmenterad där den senare ger ett skydd mot gråning.

Foto: StoraEnso

Thermo-D Gran

Thermo-D Furu

Foto: Finnforest

- **Täckande färg**
  Med värmebehandlat trä och dess beständighet och formstabilitet finns förutsättningar för långa underhållsintervaller med täckande färg vilket också forskningsrapporter indikerar. Detta ger en underhållsintervall motsvarande dubbla tiden mot en pigmenterad lasyr. Under förutsättning att värmebehandlat trä kan klassas som stabilt enligt EN 927-1 kan tjockare färgfilm (100-150µm) anbringas vilket minskar kraven på underhåll.

ThermoWood Association har i samarbete med färgindustrin samlat erfarenheter av ytbehandling av värmebehandlat trä vilket resulterat i rekommenderade produkter från dessa (Teknos, AKZO NOBEL, Tikkurila, SADOLIN & SIKKENS).

Trädgård och veranda

För att skydda mot sprickbildning och kapillär fuktupptagning bör värmebehandlat trä skyddas med en ytbehandling. Till ytor med stort slitage, t ex trall används färger med hög torrhalt och hög absorptionsförmåga som ger ett tunt ytskikt. Regelbundet underhåll beroende på exponering är en förutsättning. Erfarenheter visar att dessa är effektiva med endast en strykning.

- **Olja**
  Används som för impregnerat trä med regelbundet underhåll och rengöring.

- **Pigmenterad olja**
  Pigmenteringen tillför ett skydd mot gråning.

Pigmenterad lasyr 3 år

Foto: StoraEnso

Obehandlad 3 år

Foto: StoraEnso

Foto: Union Wood

Egenskaper – värmebehandlat trä

När trä värmebehandlas sker en rad kemiska och fysikaliska förändringar av materialet som medför att dess egenskaper förändras. Egenskaperna påverkas generellt av processens tid och temperatur.

Syftet med värmebehandling har ursprungligen varit att öka den biologiska beständigheten och dimensionsstabiliteten hos trä. De processer som är utvecklade för värmebehandling kan behandla alla träslag men syftet är främst att öka värdet på de mindre beständiga träslagen.

En sidoeffekt med värmebehandling är förändringen av färg, en egenskap i sig vilken kan medföra ett ökat värde i vissa tillämpningar. Andra sidoeffekter är minskade hållfasthetsparametrar och minskad värmeledningsförmåga. Färg, beständighet och dimensionsstabilitet är de uppenbara fördelarna med värmebehandlat trä varför vi börjar med dessa.

Färg

Vid värmebehandlingen startar en nedbrytning av träet och dess beståndselar såsom hemicellulosa. Nedbrytningsprodukter reagerar sedan vidare i karamelliseringreaktioner vilket bidrar till den brunfärgning av trämaterialet som sker vid värmebehandlingen.

Färgen hos det värmebehandlade träet beror på träslag, behandlingens temperatur och tid. Med ökad temperatur och tid blir färgen mörkare vilket ger möjligheten att med ett mindre antal träslag visa upp ett bredare urval av färger i produkter utan att betsa eller på annat vis tillföra en yta i en viss kulör.

Färgen på värmebehandlat trä är genomgående genom hela materialet. Färgen har på olika djup i materialet variationer av en storlek som inte kan uppfattas med blotta ögat.

Erfarenheter av värmebehandlat trä visar att färgen kan skilja sig markant när materialet är obehandlat respektive lackat. Därför behövs det kunskap om materialets behandlingsgrad och den färg det får vid en viss behandling då detta är av betydelse för slutprodukten.

En annan viktig aspekt är färgens beständighet. Liksom för allt trä påverkas färgen på värmebehandlat trä med tiden av ljuset. För att denna färgförändring ska kunna förutspås genomförs vanligen accelererade tester med UV-ljus. Erfarenheter visar dock att dessa inte alltid ger ett rättvisande resultat när det gäller värmebehandlat trä. En förutsättning för att skydda mot oönskad färgförändring är kunskap om vad som påverkar den.

Färgöversikt

För att demonstrera förändringarna i färg hos det värmebehandlade träet visas några svenska träslag behandlade vid 185°C och vid 200°C. Dessa temperaturer motsvarar de två temperaturklasser, Thermo-S och Thermo-D för lövträ, som används av ThermoWood Association.

Färgen på exemplet för gran blir därför något missvisande då barrträ behandlas vid 190°C för Thermo-S och vid 212°C för Thermo-D. Exemplen som visas nedan har ytbehandlats med olja.

Beständighet

Den naturliga beständigheten hos trä varierar stort mellan olika träslag. De krav som ställs på beständighet hos trä varierar med den användning som det är tänkt att användas till. Standarden EN 335-1 definierar fem riskklasser med avseende på biologiska angrepp för trä eller träbaserade produkter och i EN 335-2 definieras motsvarande för massivt trä. Det är mot dessa definitioner som impregnerat virke klassas mot och för NTR klass AB avses skyddet gälla användning i riskklass 3.

Den naturliga beständigheten för olika träslag finns presenterat i standarden EN 350-2 där träslagen indelas i fem klasser från mycket beständigt till ej beständigt.

För att avgöra vilket beständighetskrav som ställs för användning i vilken riskklass används standarden EN 460. Denna nyckel behövs också för att förstå hur värmebehandlat trä ska användas.

Vid värmebehandling av trä ökar beständigheten hos det behandlade träet. Hur mycket denna beständighet ökar beror på behandlingen temperatur och tid och träslag.

Nedanstående tabell använder sig av EN 460 som nyckel för att ge en översikt över några träslag och hur de kan användas utifrån deras naturliga beständighet. Utifrån ett antagande att en värmebehandlingsklass tillför lika mycket beständighet till alla träslag kan en generaliserad översikt av hur värmebehandlat trä kan användas.

Denna generalisering är ej bekräftad på alla träslag och det finns kända undantag. För exempelvis bok finns forskningsrapporter som indikerar att den går från att vara ej beständig till att bli mycket beständig vid värmebehandling. De tester som tyder på detta har dock varit omfattande fältstudier, vilket behövs för att verifiera denna tes.

Värmebehandlat trä	Exempel på Träslag	Beständig hetsklass EN 350-1	Riskklass EN 335-1	Situations beskrivning	Fuktkvot obeh. trä
Thermo-S av al, asp, björk, lönn	Al, ask, asp, björk, bok, lönn	5 ej beständigt	1	Ovan mark (torrt)	Ständigt under 18%
Thermo-D av asp, björk	Alm, furu, gran, lärk	4, (5) något beständigt	2	Ovan mark, skyddat, risk för väta	Stundtals över 20%
Thermo-S av furu och gran (ThermoWood)	Furu (kärnved), lärk, valnöt	3 måttligt beständigt	3	Ovan mark, ej skyddat	Frekvent över 20%
Tillämplig? Thermo-D av furu, gran, ask (ThermoWood, Scheiding et al. 2005)	Ek, western red cedar	2 beständigt	4	I mark- eller vattenkontakt	Ständigt över 20%
Tillämplig? Thermo-D av bok enligt indikation av Scheiding et al. 2005	Teak, iroko, robinia	1 mycket beständigt	5	I saltvatten-kontakt	Ständigt över 20%

Dimensionsstabilitet

Trä som material är på grund av sina hygroskopiska egenskaper inte dimensionsstabilt i miljöer där luftens fuktighet varierar. När miljön är fuktig absorberar träets fibrer fukten och sväller och när det är torrt avger de fukt och krymper. Detta under förutsättning att träet är torrare/fuktigare än vad som motsvarar jämviktsfuktkvoten för den relativa luftfuktighet som råder.

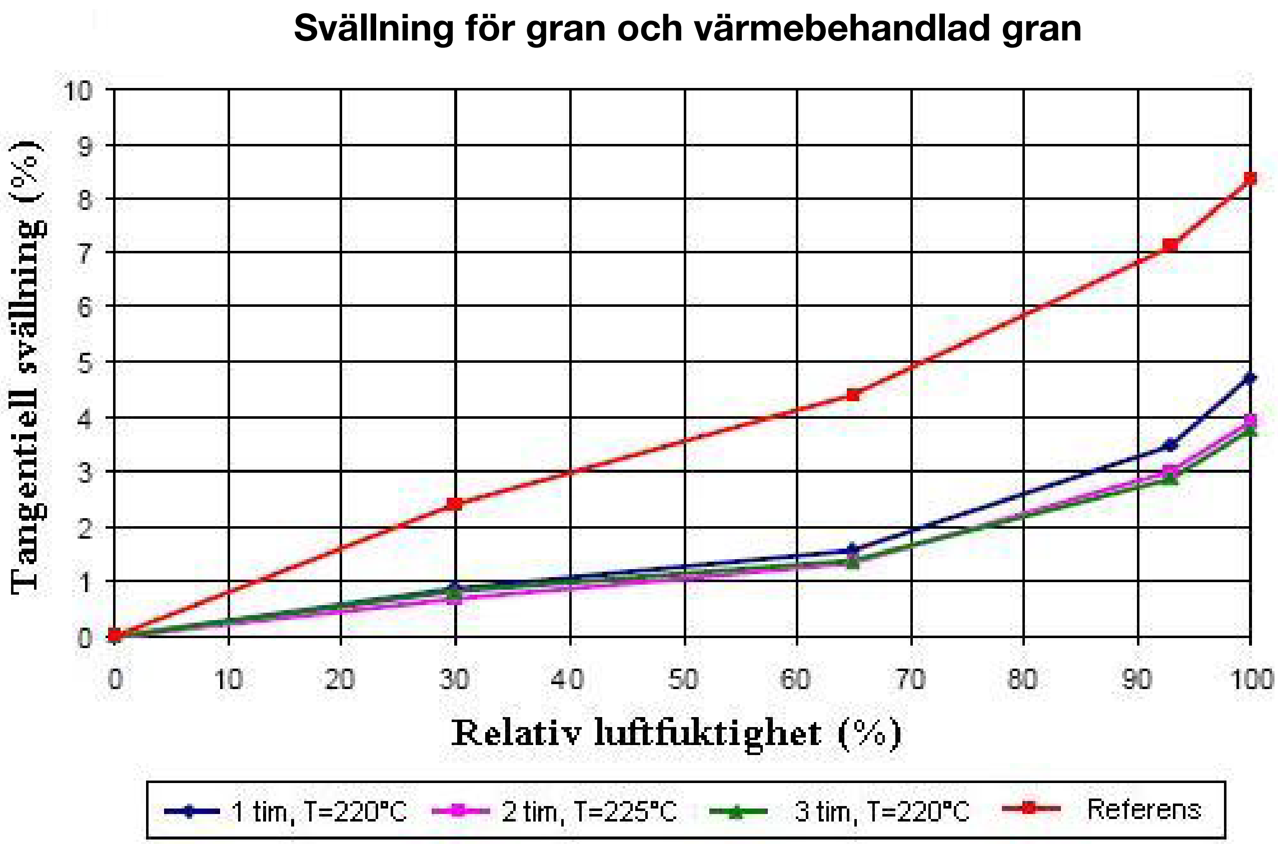
Jämviktsfuktkvoten för värmebehandlat trä beror på behandlingens temperatur och tid. Jämviktsfuktkvoten, som har ett samband med materialets dimensionsstabilitet, blir lägre med ökad temperatur och tid som behandlingen sker.

Värmebehandlat trä absorberar mindre fukt ur luften och blir därigenom mer dimensionsstabilt. Värmebehandlingsklasser som används inom ThermoWood Assosiation, Thermo-S (Stability) står för ett material med högre dimensionsstabilitet (tillsammans med färg) som en av de avgörande fördelarna. Thermo-D (Durability) som är behandlat vid en högre temperatur är mer dimensionsstabilt än Thermo-S och jämfört med obehandlat trä är det cirka 40-50% mer dimensionsstabilt. Observera att effekten på dimensionsstabiliteten kan skilja sig åt på olika träslag.

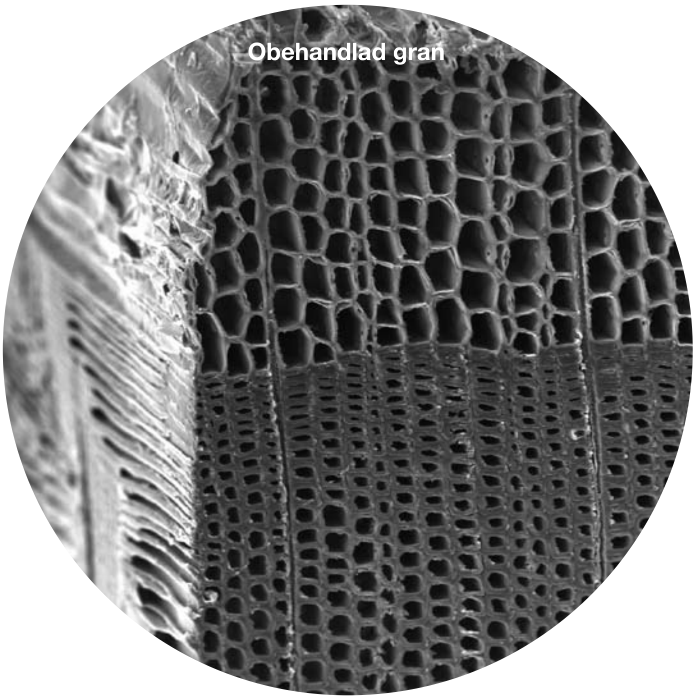
Dimensionsstabiliteten kan uttryckas ”Anti-Shrink-Efficency” (ASE) och visar på procentuell skillnad i svällning jämfört med obehandlat trä där svällningskoefficienten kan gälla antingen radiell eller tangentiell svällning.

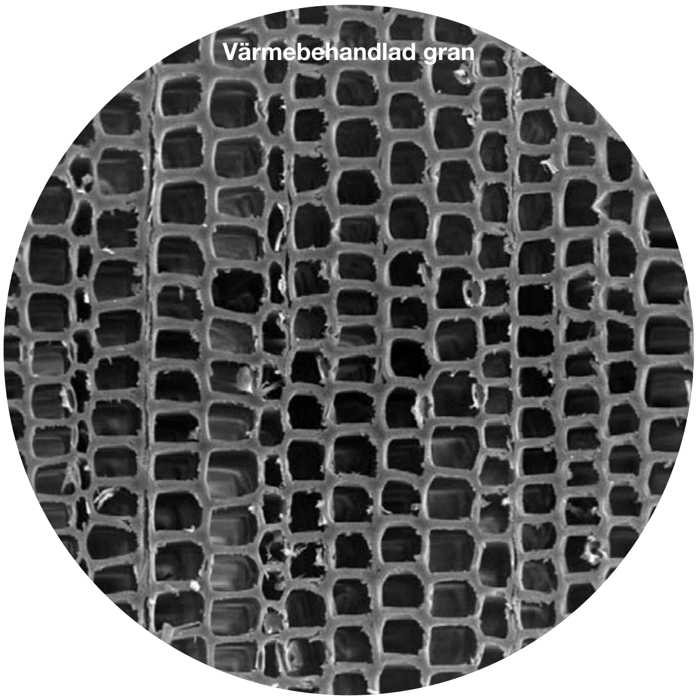
$$\text{ASE (\%)} = \frac{S_R - S_V}{S_R}$$

S_R: Svällningskoefficienten för referens, dvs. obehandlat trä.
S_V: Svällningskoefficienten för värmebehandlat trä.
Tester visar att den ökade dimensionsstabiliteten har en positiv inverkan på ytbehandlingar av värmebehandlat trä.



Källa: ThermoWood Handbook 2003 08 04





Övriga materialegenskaper

För att förstå de fysiska förändringar som värmebehandlingen medför på träet är det viktigt att relatera dessa till de kemiska reaktioner som sker under processen.

De huvudsakliga byggstenarna i materialet trä är cellulosa, hemicellulosa och lignin. När trä värmebehandlas sker en nedbrytning av dessa komponenter i olika omfattning och vid olika temperaturer.

Det är nedbrytningen av dessa byggstenar som är den huvudsakliga orsaken till att egenskaperna för värmebehandlat trä förändras. Då trä är ett komplext material är det svårt att förutsäga resultatet av processen för alla träslag varför generella uppgifter är svåra att finna.

Vid värmebehandling är det träets hemicellulosa som till största delen är den byggsten som bryts ned av processen. Nedbrytningen av hemicellulosa accelererar vid temperaturer på 200-260°C medan korresponderande temperaturer för lignin är över 200°C och för cellulosa 240-350°. för att nedbrytningen ska accelerera.

Hållfasthet

De mekaniska egenskaperna försämras i regel när dimensionsstabilitet och rötbeständighet förbättras. Nedbrytningen av hemicellulosa, lignin och cellulosa medför att densiteten för materialet minskar (5-15%) vilket har ett starkt samband med hållfastheten.

Det finns en stor variation på processens påverkan på specifika egenskaper mellan olika träslag där furu och gran är de mest utredda arterna.

Böjhållfasthet

Böjhållfastheten hos ett material påverkas mycket av fiberstörningar och värmebehandlat trä är extra känsligt för detta. Värmebehandlat trä har inte lika starka bindningar mellan fibrerna vilket gör att det spjälkas lättare vid drag vinkelrätt mot fibrerna. Denna reducerade styrka i bindning mellan fibrerna har ett starkt samband med att träets lignin bryts ned vid värmebehandlingsprocessen. Därför är virkeskvaliteten mycket viktig vid användning av värmebehandling där böjhållfastheten har betydelse.

Faktum är att värmebehandlat trä inte rekommenderas i bärande konstruktioner på grund av stora variationer i böjhållfasthet beroende på kvistarnas antal och storlek i materialet. För ett felfritt material i furu eller gran är böjhållfastheten reducerad med 10-20% för Thermo-D.

Hållfasthet

Styvhet

Styvheten för värmebehandlat trä påverkas inte i samma omfattning som många av de andra hållfasthets egenskaperna. Många av de försök som är gjorda visar på en reduktion för materialets elasticitetsmodul med cirka 5% .

Slag-, skjuv– och klyvhållfasthet

Dessa är olika mått som visar på materialets ökade sprödhet vilket är en konsekvens av den reducerade kraften i bindningen mellan fibrerna som uppstår vid värmebehandling. Vad man ser är att släpp mellan årsringarna har lättare för att uppstå. Styrkeförluster på 30-60% generellt.

Som en följd av detta rekommenderas att särskild omsorg vid skruvning och spikning av värmebehandlat trä förespråkas. Ett annat exempel är att för sågad ytterpanel rekommenderas en reducering av ytan före målning så att vårveden avlägsnas och kvar finns sommarveden som är tåligare, alternativt att ytan hyvlas. Både dessa metoder har i syfte att ge ytbehandlingen bättre fäste i materialet.

Hårdhet

Enligt ThermoWood Association ökar hårdheten för furu något när de testar hårdheten på furu, dock inte signifikant. Andra tester på gran visar på en oförändrad hårdhet och för andra träslag påvisas en reducering av hårdheten. Följaktligen finns det tydliga variationer på hur värmebehandlingen påverkar hårdheten i materialet mellan olika träslag.

Övrigt

Värmeledningsförmåga - konduktivitet

Nedbrytningen av träets byggstenar medför att strukturen i värmebehandlat trä innehåller mer luft vilket är positivt för materialets isolerande förmåga. För barrträ visar tester på en reducering av materialets värmeledningsförmåga på 20-25%.

Emissioner och lukt

Emissioner av flyktiga organiska ämnen från obehandlat trä kan ibland vålla problem. I de tester som utförts av dessa emissioner mäter man ett antal kända ämnen som avges från trä och summerar emissionen från dessa till ett begrepp, Total Volatile Organic Compound (TVOC). På Svenska betyder TVOC total avgivning av organiska ämnen, och mäts i µg/(m^2 x tim).

Tester visar på en minskning av TVOC på 40-85%, där högre behandlingstemperatur ger lägre emissioner. Av de ämnen som avges har obehandlat trä högre värden på alla utom för ättiksyra och furfural. Det är furfural som bidrar till den karaktäristiska röklukten hos värmebehandlat trä, som dock avtar snabbt.

Kåda

Under värmebehandlingsprocessen smälter träets kådämnen och flyter ut eller förångas. Detta medför att värmebehandlat trä inte utsöndrar någon kåda vid användning.


Foto: SWM-WOOD


Foto: Suomen Lämpöpuu Oy


Foto: SWM-WOOD

Värmebehandlat trä

Vackert, modifierat och miljövänligt

Varför värmebehandlat trä?

- Modifiera egenskaperna
- Miljövänligt träskydd
- Gynnar användandet av trä
- Öka värdet på råvaran
- Bevara naturresurser
- Ersätta tropiska träslag

Egenskaper värmebehandlat trä

- Färg: Mörkare rakt igenom
- Beständighet: ökar 1-3 klasser enligt EN 350-1
- Slaghållfasthet: ökar 30-50%
- Konduktivitet: minskar 10-30%
- Jämviktsfuktkvot: minskar 50%
- Emissioner: minskar 45-85% för furu
- E-modul: minskar 4-30%
- Hårdhet: minskar 0-30%
- Dimensionsstabilitet: minskar 30-60%
- Vikt: minskar 10-15%
- Böjhållfasthet: minskar 0-30%
- Saknar kåda

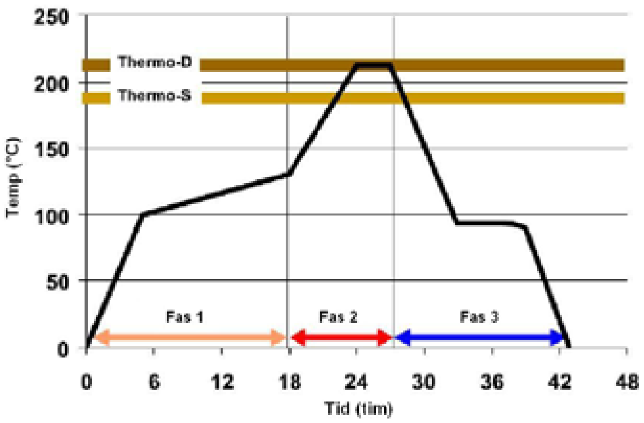
Metoder för värmebehandling

Egenskaperna påverkas av processens temperatur och tid. Likartade resultat och alla träslag är behandlingsbara.

LTU använder en metod med överhettad vattenånga. Två klasser Thermo-S (Stability) och Thermo-D (Durability)

Processmetod:

1. Torkning vid temperaturer över 100°C
2. Värmebehandling vid 190-212°C (lövträ 185-200°C)
3. Svalning och återfuktning till 4-6% fuktkvot



Värmebehandlat trä - användning

Exteriört

Miljövänligt, beständigt och dimensionsstabilt.

- Dörrar
- Fönster
- Fasadbeklädnad
- Trädäck
- Utemöbler
- Staket
- Skärmar
- Lekparker
- Etc.

Interiört

Utseende, dimensionsstabilitet, avsaknad av kåda och låga emissioner.

- Möbler
- Golv
- Köksinredningar
- Badrums- och bastuinredningar
- Invändiga paneler
- Musikinstrument
- Etc.

Kommersialisering

Värmebehandlat trä har funnits på marknaden i 10 år.

- Försäljning på 50 till 100 tusen m3 årligen och under tillväxt
- 20-30 olika tillverkare i Europa – huvudsakligen i Finland, Holland, Tyskland och Frankrike
- Nästan hälften av allt värmebehandlat trä vidareförädlas
- Vanligaste träslagen är gran, furu, björk och asp
- 70% av virket behandlas med den högre värmetemperaturen (212°C)

Mer information:

www.ltu.se

SAMARBETSPARTNERS:

ThermoWood

www.thermowood.fi
www.storaenso.com
www.swm-wood.com
www.tekmaheat.fi
www.lunawood.fi
www.suomenlampopuu.com

Värmebehandlade prod.

www.kahrs.se
www.unionwood.se
www.rappgo.se
www.bitus.se
www.essemobel.fi

LULEÅ TEKNISKA UNIVERSITET

Appendix II – The Concept House Folder

Koncepthus i värmebehandlat trä.
Ett uttryck för nya sätt att tänka.

BESTÄLLARE:
Luleå tekniska universitet
genom Samuel Forsman

ARKITEKT:
Nilsson & Sahlin Arkitekter AB
genom Ove Nilsson, ark SAR/MSA
Kristina Sahlin, ark SAR/MSA

MÖBELDESIGN:
Nilsson & Sahlin Arkitekter AB

BYGGÅR: 2007

Huset är en flyttbar, 20 m² stor utställningsbyggnad som visar hur värmebehandlat trä kan se ut och användas. Alla synliga ytor, interiört och exteriört, är utfört i värmebehandlat virke. Stommen består av massiva förtillverkade limträelement.
Byggnaden är till största delen tillverkad på fabrik, för att senare monteras på plats. Furu, gran, ek, björk och bok samt olika värmebehandlingstemperaturer har givit en rad olika färgtoner och ytstrukturer vilket utnyttjats i utformningsarbetet. Vi har velat ge byggnaden ett modernt uttryck för att visa på nya sätt att tänka och använda trä. Parallellt med husprojektet har en serie möbler i värmebehandlat trä också tagits fram.

SKER I SAMARBETE MED
NILSSON & SAHLIN ARKITEKTER

LULEÅ
TEKNISKA
UNIVERSITET








VARFÖR KONCEPTHUS?

När man ska introducera ny teknik och nya material är det effektivaste sättet oftast att visa på verkliga ting, produkter och tillämpningar som gör det uppenbart vari nyheterna består. Med vårt koncepthus vill vi visa upp produkter i värmebehandlat trä.

Projektet har genomförts i nära samarbete med Nilsson & Sahlin Arkitekter. Det är också del i ett internationellt samrbete inom forskning och utveckling, tillsammans med en satsning från LTU inom entreprenörskap och samverkan med näringsliv och samhälle.

PLANERAD FORTSÄTTNING

LTU:s engagemang i FoU-projekt inom värmebehandling av trä har redan lett till en industriell utveckling. En etablering av företag som tar upp produktion av värmebehandlat trä är en direkt följd av detta projekt. Vår ambition är att stödja den fortsatta utvecklingen av värmebehandlade träprodukter och konstruktioner, tillsammans med en industrigrupp i regionen. Både det regionala strukturfondsprogrammet ”Mål 2” och ett EU-projekt riktat till bl a norra Sverige, öppnar möjligheter för sådant fortsatt engagemang.

MATERIAL OCH PRODUKTION

Värmebehandling av trä medför förändrade egenskaper i materialet. De främsta fördelarna är en ökad formstabilitet, förbättrad beständighet, mörkare färg och miljövänlig framställning. Dessa förändrade egenskaper gör det möjligt att anpassa och diversifiera råvaran till en mängd nya och befintliga produkter. Inom den värmebehandlande industrin används två standardklasser av värmebehandling; Thermo-S och Thermo-D (Stability & Durability), vilket motsvarar 190°C och 212°C för barrträ. Materialsammansättningen i koncepthuset speglar produkter från den svenska skogs- och träbearbetande industrin, för att visa hur den nya teknologin kan ha värden för hela den industriella kedjan.

MATERIAL UTVÄNDIGT

Fasadsystem där brädor med Thermo-D behandlad gran hängs upp och kläms fast med klämlister.

Taket använder också Thermo-D behandlad gran som yttertak i ett system utan synliga genomföringar.

Pergolan över entrén använder Thermo-D limträ i furu, vilket är en helt ny metod som skapar ökade möjligheter att använda värmebehandlat trä i bärande konstruktioner.

Husets entré är tillverkad av Thermo-D bok vars egenskaper avseende svällning har utvärderats i klimatkammare för att avgöra materialets lämplighet för tänkta konstruktionsmetoder.

Husets fönster är alla tillverkade i Thermo-D furu med en ytbehandling som ger ett synligt trä. Det har krävts processutveckling för att kunna tillhandahålla lämpliga ämnen för fönstertillverkning.

Terrassen framför huset är Thermo-D gran i en spårad profil som är vanlig på den finska marknaden. För att åstadkomma ett unikt uttryck har trallen anbringats med ett system för dolt montage.

MATERIAL INVÄNDIGT

Invändigt är husets alla ytor Thermo-S material i furu och ek. Alla ytor, tak, väggar och golv är massiva träskivor som bildar husets bärande stomme. För att kunna använda värmebehandlat trä till detta har det varit nödvändigt med metod- och teknikutveckling, både vad gäller process och produktion. Huset innehåller också en möbelgrupp i värmebehandlat trä.

MER INFORMATION

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