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Wood Modification in Europe

a state-of-the-art about processes, products and applications

edited by
Dennis Jones, Dick Sandberg,
Giacomo Goli, Luigi Todaro

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Front cover: Lookout tower Pompejus in acetylated radiata pine, Fort De Roovere, Halsteren, The Netherlands.
The watch tower is also used as an open-air theatre, and an information point for tourists. The facade of the watchtower has been designed according to the principle of the Voronoi diagram, a mathematical design principle, which enables the triangles of the steel construction to be used to have windows and openings in the facade. By using this design principle, it allowed the facade to be divided into elements that could be prefabricated and transported, and at the same time, add an additional layer to the facade to break the dominance of the triangular steel structure. Architects: RO&AD Architecten

This report was made possible through the generous funding from COST through their granting of the Action COST FP1407, which is hereby acknowledged.

This report is based on responses collected from a questionnaire in COST FP1407 and subsequent discussions. Whilst every effort has been made to identify all current wood modification practices across Europe and those research groups active in these fields, there may be circumstances where some information has not been provided or collected. The authors are not responsible for any future activities that impact the information within this report.

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Summary

On 28 November 2018, the European Commission adopted the long-term strategic vision for a climate neutral economy by 2050. Europe shall lead the transition to climate neutrality by investment in realistic technical solutions while ensuring social fairness[1]. This press release, in conjunction with the EU's strategy for sustainability[2] means that Europe will lead the transition to climate neutrality by investment in realistic technical solutions while ensuring social fairness. One of the seven strategic building blocks identified to reach net-zero emissions is to fully utilize the benefits of the bioeconomy, where improved utilization of the biobased resources will be necessary. A transfer from carbon-intensive raw materials creates a large climate benefit as wood used in construction which will not only replace carbon-intensive materials, but also function as carbon storage. The EU strategy also points out how an increased bio-economy can create up to one million new jobs in EU until 2030. This policy also requires greater resource efficiency and improving opportunities for lesser-used timber stands.

The ambitious aims of climate neutrality come at a time when political drivers are also aiming to minimise increasing global temperatures resulting from human activities, with the increasing population becoming more urbanised – indeed, it is projected that 70% of the global population will live in urban conglomerations by the same 2050 deadline.

Timber construction has long been recognised as a means of achieving low-carbon solutions for construction, and an increased understanding from architects and specifiers has led to many believing timber to be the material of choice for the 21st Century. Hence, there is a growing need for timber-based solutions, preferably in ways susceptible to discolouring and degrading organisms. Discolouration by stain and mould fungi as well as fungal, bacterial, and insecticidal decay is limiting the performance of bio-based building materials. Likewise, mould plays an important role not only in outdoor environment, but also in the building envelope with partly drastic impact on the indoor air quality and thus on the health of human beings. Furthermore, the aesthetical appearance of building components (e.g. window frames, cladding) can be compromised by stain, which becomes an increasing issue across Europe and worldwide. The timber industry is now seeking for effective methods and treatments to protect wood and other bio-based building materials from surface mould growth and fungal disfigurement because of the perceived threat of losing costumer preference. Previously this has been achieved through the use of wood preservation, but changes in legislation and increasing understanding of toxicity has led to the commercial developments of alternative methods.

Wood modification processes are industrial processes that result in wood-based material that is non-toxic in service and when disposed at the end of life does not result in the generation of any toxic residues. This means it can be disposed at the end of a product´s life cycle without presenting any environmental hazards greater than those associated with the disposal of unmodified wood. A wood-based material is hereby understood to be a wide range of wood products that have their technical, aesthetical or tactile characteristics improved or that new functions have been added by the use of modification. Bended, densified and moulded wood are examples of modified wood that have been available on the market for at least 150 years. Thermal modified timber, acetylated and furfurylated timber are examples of modified wood more recently available on the market. As the environmental concerns have grown considerable since several decades, the interest in biobased solutions in different areas of the society has increased and new modification processes and materials are constantly under development around the world.

1 http://europa.eu/rapid/press-release_IP-18-6543_en.htm
2 https://ec.europa.eu/commission/news/new-bioeconomy-strategy-sustainable-europe-2018-oct-11-0_en

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This report is a result of a questionnaire and subsequent collation of data within the frame of *COST Action FP1407 Understanding wood modification through an integrated scientific and environmental impact approach – ModWoodLife*, which outlines the current status of wood modification across Europe in terms of national inventories and groups that have reported current activity in the respective research areas covered in this report.

Based on the production volumes that were reported in COST FP1407 and subsequent investigations, the annual production volumes for the nearest coming year have been estimated and are presented below. Thermo-hydro (TH) and thermo-hydro-mechanical (THM) methods such as steaming, softening for veneer production, solid wood bending, veneer moulding are hereby recognised as being a form of wood modification, but are not included within data compiled here.

Estimated production volumes for the nearest coming years for some specific types of modified wood

Type of wood modification	Estimated annual production (m^3)
Thermally modifed timber incl. aged timber	535,000
Densified wood	2,000
Acetylated timber incl. production under development in UK	120,000
Furfurylated timber incl. production under development in Belgium	45,000
Other chemical methods	35,000

FP1407
ModWoodLife

Different appearance of an exterior shingle façade of larch wood after two years of exposure, Vorarelberg, Austria

Preface

Wood modification (chemical, thermal, impregnation) represents an assortment of innovative processes currently being adopted in the wood protection sector. It has gained commercial interest as a result of the wood protection sector undergoing several changes in recent years, such as:

- Restriction of conventional biocidial products used for wood preservation;
- Demand for more environmentally benign treatments;
- Greater use of locally sourced timber species with known limited durability;
- Increasingly demanding design criteria and customer requirements.

Though many aspects of these wood modification treatments are known, the fundamental influence of the process on product performance, the environment, and end of life scenarios remain relatively unknown. It is essential to integrate interactive assessment of process parameters, developed product properties, and environmental impacts. To optimise modification processing to minimise environmental impacts, much more information must be gathered about all process related factors affecting the environment (VOC, energy use, end of life use, etc.). To this end, COST Action FP1407 (Understanding wood modification through an integrated scientific and environmental impact approach - ModWoodLife) was initiated in 2015, with its 4-year programme aiming to investigate modification processing and products design with emphasis on their environmental impacts. This will require analysis of the whole value chain, from forest through processing, installation, in service, end of life, second/third life (cascading) and ultimately incineration with energy recovery. Over the four years of COST Action FP1407, the Action brought together more than 317 researchers and industry members from across Europe and beyond. Network participants participated in many activities organised or supported by the COST Action. COST FP1407 has been the latest in a series of Europe-wide Actions focussing on varying aspects of wood modification. These Actions have included:

- 508: Wood Mechanics (1990-1994)
- E2: Wood Durability (1994-1998)
- E8: Mechanical Performance of Wood and Wood Products (1996-2000)
- E22: Environmental Optimisation of Wood Protection (1999-2003)
- E37: Sustainability Through New Technologies for Enhanced Wood Durability (2004-2008)
- FP0904: Thermo-Hydro-Mechanical Wood Behaviour and Processing (2010-2014)
- FP1303: Performance of Bio-Based Building Materials (2013-2017).

A recent task within COST FP1407 was to re-evaluate the current status of wood modification across the member countries, tasks previously undertaken within COST Actions E22 and E37 respectively and reported in several papers within several of the previous European Conferences on Wood Modification (ECWM). Whilst the early projected advances anticipated for various types of modified wood has not been as previously reported. During a COST FP1407 meeting in Florence, Italy, the national status of wood modifications in 18 different European countries was presented, and the findings will be presented herein. However, given there were 29 EU members within COST FP1407, considerably more information could be gathered in terms of national activities and production levels, so providing a truer overview of the commercial progress of wood modification. These findings are reported herein. COST FP1407 over its four years contributed to the development and expansion of the use of emerging environmental-friendly processes of wood modification, the use of materials produced by these processes, and the environmental impact. COST Action members continue to develop new ideas, uses and documentation supporting the correct use of modified wood. Most importantly, members of COST Action FP1407 have developed strong and lasting relationships and networks that have and will continue to allow for successful collaboration and scientific innovation in the greater field of wood modification and environmental impacts. Many members of the COST Action are involved in scientific endeavours that will continue and would not be possible without the support and framework of the COST programme.

These results were only possible through the continued collaborative activities of the Action partners from participating countries, for which the Action Chair, Vice-Chair and authors of this book are extremely grateful.

Andreja Kutnar – Chair FP1407

Dennis Jones – Vice Chair FP1407

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Content

Thermally modified and fire retardant impregnated Scots pine
at Valle Wood, Helsfyr, Oslo, Norway

Background

Wood modification represents an assortment of innovative processes currently being adopted in the wood protection sector. Though many aspects of these treatments are known, the fundamental influence of the process on product performance, the environment, and end of life scenarios remain relatively unknown. It is essential to integrate interactive assessment of process parameters, developed product properties, and environmental impacts. To optimise modification processing to minimise environmental impacts, much more information must be gathered about all process related factors affecting the environment (VOC, energy use, end of life use, etc.). To this end, COST Action FP1407 "Understanding wood modification through an integrated scientific and environmental impact approach – ModWoodLife" and led by the University of Primorska, Slovenia, was initiated in 2015, with its 4-year programme aiming to investigate modification processing and products design with emphasis on their environmental impacts. This required analysis of the whole value chain, from forest through processing, installation, in service, end of life, second/third life (cascading) and ultimately incineration with energy recovery.

A recent task within COST FP1407 was to re-evaluate the current status of wood modification across the member countries, tasks previously undertaken within COST Actions E22 and E37 respectively and reported in several papers within several of the previous European Conferences on Wood Modification (ECWM). The early projected advances anticipated for various types of modified wood have not been as previously reported. During a COST FP1407 meeting in Florence, Italy in February 2018, the national status of wood modifications in 18 different European countries was presented (Goli & Todardo 2018). These findings have been complemented with information from the countries not attending the Florence meeting, and a short information about COST FP1407 and wood modification in general. The Florence meeting abstracts and additional information herein provide a summary of the state-of-the-art of research, development and industrial use of wood modification, across EU.

Figure 1: *COST Action 1407 working groups (WGs 1 and 2) meeting at University of Florence in February 2018*

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Charred wood,
Café Birgitta, Helsinki, Finland

COST and COST Action 1407

Founded in 1971, COST – European Cooperation in Science and Technology – is the first and widest European framework for the transnational coordination of nationally funded research activities. It is based on an inter-governmental agreement and comprises currently 38 European Member Countries plus one Cooperating State (Israel) as shown in Figure 2.

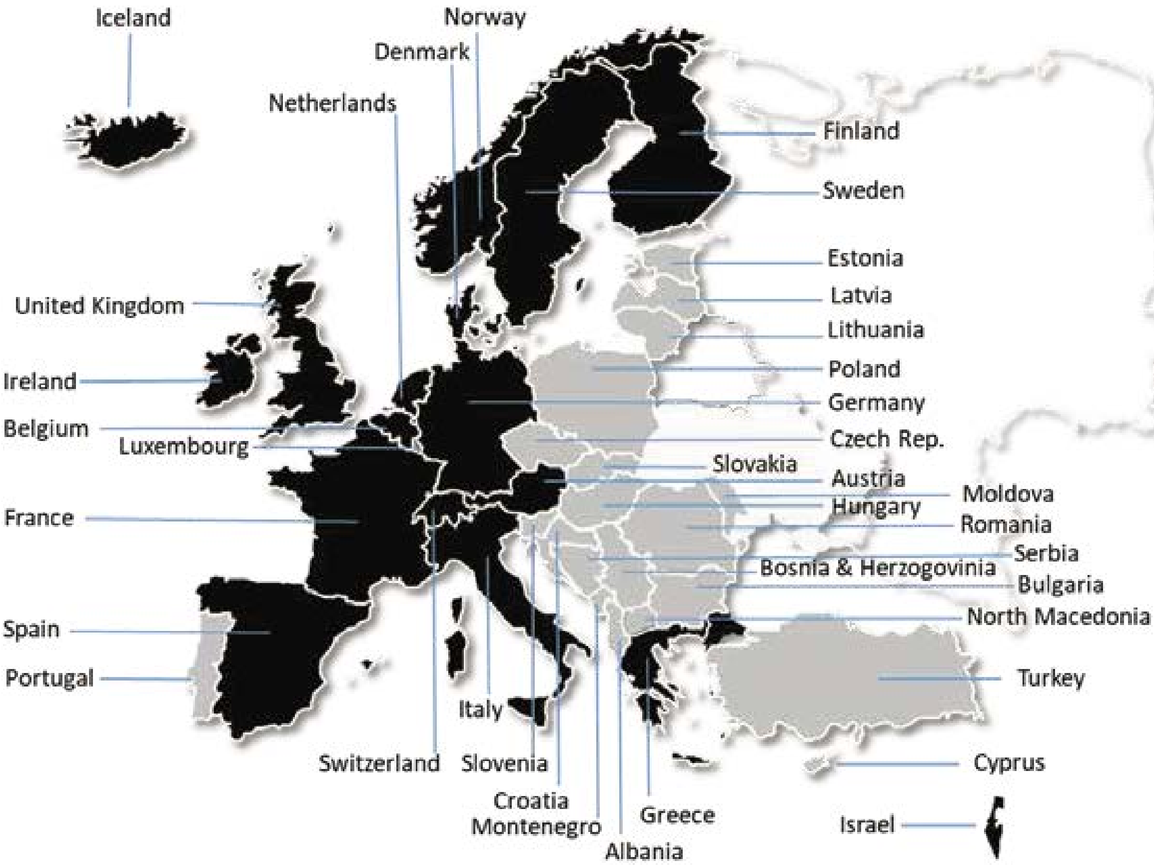

Figure 2: *Countries funded under the COST scheme*

COST's mission is to strengthen Europe's scientific and technical research capacity by supporting cooperation and interaction between European researchers, covering from basic to applied or technological research and including research addressing issues of pre-normative nature or of particular societal importance. It anticipates and complements the activities of the EU Framework Programmes, constituting a "bridge" towards the scientific communities of COST Inclusiveness Target Countries (shown in grey in Figure 2). It also increases the mobility of researchers across Europe and fosters the establishment of scientific excellence.

The former science organisation, which was structured into nine science and technology domains, has been replaced by a new organisation aiming at guaranteeing a fully open and bottom-up approach through the establishment of a single Scientific Committee. This also includes a renewed evaluation and selection procedure aiming at identifying breakthrough ideas and favouring interdisciplinary and multidisciplinary projects.

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COST FP1407

The COST FP 1407 Memorandum of understanding take lead on EU Roadmap 2050 and state that the forest-based sector can become a leader in achieving the European Commission's ambitious target of reducing CO_2 emissions with innovative production technologies, reduced energy consumption, increased wood products recycling, and reuse. Apart from these undoubted environmental benefits, the use of forest products in long life products, such as built environment applications, allows for the possibility of extended storage of atmospheric carbon dioxide. As already mentioned here, though many aspects of wood modification treatments are known, the fundamental influence of the process on product performance, the environment, and end of life scenarios remain relatively unknown. It is essential to integrate interactive assessment of process parameters, developed product properties, and environmental impacts.

COST Action FP1407 "Understanding wood modification through an integrated scientific and environmental impact approach, ModWoodLife" had as aim to investigate modification processing and products design with emphasis on their environmental impacts. This included the development and optimisation of modified processing and quantification of the impacts of emerging treatment technologies compared to traditional processing and alternative materials to maximise sustainability and minimise environmental impacts. This also required analysis of the whole value chain, from forest through processing, installation, in- service, end of life, second/third life (cascading) and ultimately incineration with energy recovery, Figure 3.

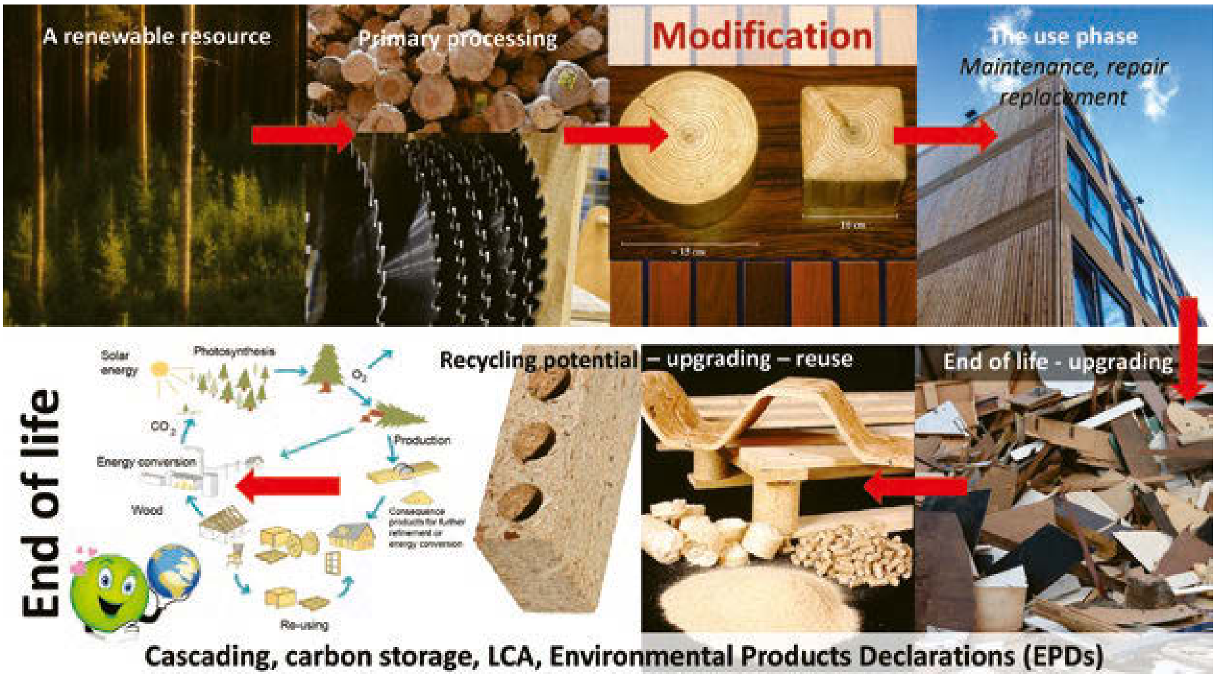

Figure 3: *Schematic of the aims within COST Action FP1407*

Forest-based industries are continually developing advanced processes, materials and wood-based solutions to meet evolving demands and increase competitiveness. Several emerging environmental-friendly processes of *wood modification (chemical, thermal and impregnation/polymerization)* have been developed, which can improve the intrinsic properties of wood, and provide desired form and functionality. However, a more detailed consideration reveals several issues that lead to the question: *Is the global environmental impact of wood modification processing and further uses of the resulting products comparable with the impact of native, untreated wood?* To address this question the COST Action FP1407 applied the 'cradle to cradle' (C2C) concept to the development of products based on wood modification processes. This paradigm values new advanced wood-based materials with improved intrinsic properties that promote *efficient product reuse, recycling and end-of-life use, and pave the way to a low carbon economy*.

Different modification processes, with possible variations in their parameters, result in modified wood with different properties, thusly enabling the creation of different product lines. However, they also have different environmental impacts, which are consequently transferred into materials, elements, and final products. *Interactive assessment of process parameters, product properties, and environmental impact* should be used to aid development of innovative modification processes and manufacturing technologies, existing and planned, which embrace the 'cradle to cradle' paradigm. Recycling, up-cycling and end-of-life disposal options need to be integrated in a fully developed industrial ecology. Intelligent material reuse and up-cycling concepts could reduce the amount of waste destined for landfills or down-cycling. In order to develop and/or optimize wood modification processing to minimize environmental impacts, *much more information must be gathered about relevant process factors*. This includes the development of chain of custody procedures throughout the entire life cycle. The COST Action FP1407 also supported national and international research efforts by gathering an interdisciplinary research team to reduce CO2 emissions, and the Action supported the definition and dissemination of Life Cycle Assessment (LCA) studies of wood modification processes and modified wood products, which are currently relatively limited.

The COST Action FP1407 provided the foundation for verification of the research implemented in the COST countries and beyond. The Action also enabled that the same system boundaries in environmental assessments methods will be used across COST countries, which requires an integrated pan-European approach. The Action resulted in enhanced contributions from the forest-based sector to sustainable development of COST countries. Furthermore, the Action supported the achievements of the goals given in the European Strategies and Directives, goals that can only be achieved by collaborative research between different EU countries, which is the greatest advantage that arises from carrying out the activities of this Action within the COST framework.

Networking within the Action was the *most productive, proficient and enduring* tactic to build sustainable relationships among Action-related researchers from COST countries. The COST Action FP1407 improved innovativeness and secure competitiveness of forest-based sector. The activities also supported by inform the development of new standards. It is also essential to be aware of wider developments in other industrial sectors and provide this information to the forest sector.

Thermally modified ayous (Triplochiton scleroxylon) wood
at Castellum Hoge Woered, Utrecht, The Netherlands

Wood modification

As a natural renewable resource, wood is in general a non-toxic, easily accessible and inexpensive biomass-derived material. Nevertheless, as wood is a natural product that originates from different individual trees, limits are imposed on its use, and the material needs to be transformed to acquire the desired functionality. *Wood modification* is implemented to improve the intrinsic properties of wood, to produce new materials and to acquire a form and functionality desired by engineers without changing the eco-friendly characteristics of the material.

Nowadays, wood modification is referred to as a process used to improve the physical, mechanical, or aesthetic properties *of sawn timber, veneer or wood particles used in the production of wood composites*. Wood in this context still has is character of natural wood, i.e. wood modification do not include modification of dissolved wood or wood fibres. Modified wood is non-toxic in service and that disposal at the end of life does not result in the generation of any toxic residues, i.e. can be disposed at the end of a product´s life cycle without presenting any environmental hazards greater than those that are associated with the disposal of unmodified wood. Wood modification is applied to overcome weak points of the wood material that are mainly related to:

- low resistance to bio-deterioration against fungi, termites, marine borers,
- moisture sensitiveness,
- low dimensional stability,
- low hardness and wear resistance,
- low resistance to UV irradiation and weathering in general, and
- to improve aesthetic properties.

The reasons for wood modification

The main reasons for the increased interest during the last decades in wood modification with regard to research, the industry, and society in general can be summarised as:

1) a change in wood properties as a result of changes in silvicultural practices and the way of using wood (e.g. in construction),
2) awareness of the use of rare species with outstanding properties such as durability and appearance,
3) awareness and restrictions by law of using environmental non-friendly chemicals for increased durability and reduced maintenance of wood products,
4) increased interest from the industry to add value to sawn timber and by-products from the sawmill and refining processes,
5) EU policies supporting the development of a sustainable society, and
6) the international dimension on climate change and related activities mainly organised within the frame of the United Nations (UN), such as the Paris Agreement under the United Nations Framework Convention on Climate Change (United Nations 2015).

Wood modification has, however, a much longer history and the reasons for its use have of course varied over time. Examples of wood preservation to improve the decay resistance can be found in the in the old testament in the Bible, and in ancient Egypt as well as in Scandinavia where wood was modified to increase the bendability for several thousand years ago (Navi & Sandberg 2012). Considerable more recent, the need to treat wood to extend its service life by minimising threats from biological attack has come into focus. As such, wood has been historically treated with preservatives to increase its resistance to decay caused by insect attack, micro-organisms and damage caused by marine wood-boring animals (Larsson-Brelid 1998), with commercial activities since the 1830s, when sleepers and poles of railroads were pressure impregnated by a heterogeneous mixture of

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polycyclic aromatic hydrocarbons PAH, creosote (Rowell 2005). However, concerns over the toxicity of traditional preservatives in use and in residuals led to the withdrawal of many of these products, to be replaced with less toxic preservatives. This also allowed an opportunity for alternative treatments to gain a market entry, among these being wood modification. Today, some specific types of wood modification (e.g. acetylation, furfurylation, thermal modification) that are an alternative to conventional preservation for the protection of wood are on the market.

By definition, wood modifications do not have a toxic mode of action as is the case for preservative treated wood (Hill 2006). Similarly, the modified wood should itself be non-toxic under service conditions, and there should be no release of any toxic substances during service, or at the end of service life (Hill 2006). As a result of the modification process, the wood constituents can be physically altered, and/or the wood structure can be chemically altered, such that these changes can result in more durable wood or a material with reduced hygroscopicity.

The increased use of fast-grown low-density species from plantation forestry, but also a need to find new uses for the boreal softwood forest has created an interest to find different methods to compress wood in its transversal direction to achieve permanent deformation of wood cells and, thereby, to increase its hardness and abrasion resistance. A significant amount of research and some commercialization has occurred in Europe and the United States during the 20th century based on compression of wood in the transverse direction (Kollman 1936, Morsing 2000, Sandberg *et al*. 2013). Kollman (1936) even mentioned some investigations in Germany in the late 19th century. Most of these commercialized products were resin-impregnated presumed for dimensional stabilization. Typical products on the market were formaldehyde-impregnated laminated veneer with about 50% degree of compression and designed for the hub of aircraft propeller blades, sport goods, bobbins, tooth picks, and shuttles used in the textile industry, as well as machine dyes, antenna masts and knife handles.

Principal mechanisms of wood modification

Modification of wood can involve active modifications, which result in a change of the chemical nature of the material, or a passive modification, in which a change in properties results without altering the chemistry of the material. Most active modification methods investigated to date have involved the chemical reaction of a reagent with cell-wall polymer hydroxyl groups. These hydroxyl groups play a key role in the wood-water interaction while simultaneously being the most reactive sites (Figure 4). In moist wood, the water molecules settle between the wood polymers, forming hydrogen bonds between the hydroxyl groups and individual water molecules. A change in the number of these water molecules results in shrinkage and swelling of the wood. All possible types of wood treatments affect the wood-water interaction mechanism. The main wood-treatment interaction mechanisms that

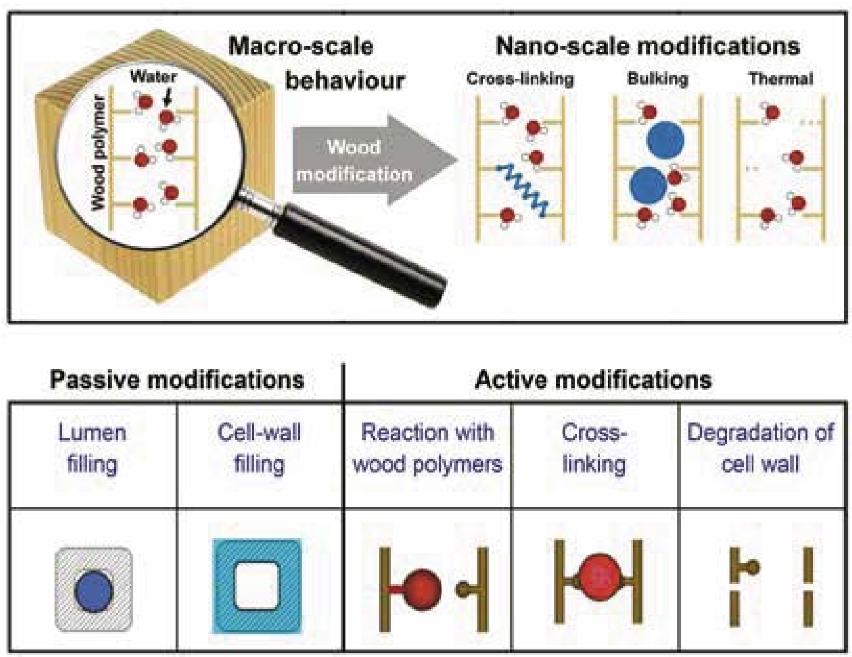

__Figure 4:__ Schematic diagram illustrating the effect of chemical modification (courtesy: Emil Engelund Thybring, University of Copenhagen)

Several wood-treatment interaction mechanisms tend to occur at the same time. In thermal modification, as one example, parts of the cell-wall polymers are altered, which may lead to cross-linking, reduction of OH-groups, and undesired cleavage of the polymer chains.

The above mentioned modification mechanisms are mainly related to what is called chemical modification (see also under processes below), but wood modification can also include other types of mechanism that result in a modified wood material. That can include treatment with heat and moisture to soften the lignin and make it possible to shaping and forming the wood in a way that is not possible for unmodified without serve damage. The wood cells can be compressed in the longitudinal direction to make the wood more flexible in bending, or compressed in the transverse directions (as already mentioned) so the lumen volume decreases and the density increase. Most of these modification techniques are combined with a treatment with heat, moisture and/or different chemicals to achieve the desired properties. Electromagnetic irradiation of different wavelengths, laser and plasma can also be used for changing the chemical and microstructural characters of the wood surface or for softening the wood.

Most types of wood modification processes cannot prevent photo-degradation (see e.g. Feist & Rowell 1982, Hon 2001, Evans 2009), but in particularly increased dimensional stability combined with high durability can significantly enhance the performance and the lifetime of wood under outdoor conditions.

Wood modification processes

Wood modification can be classified based on the type of process used to achieve the property change of the wood. Figure 5 show the most common classification of processes used for wood modification: chemical, thermo-hydro-mechanical, and physical processes. There are also modification techniques that may in the future be useful for wood, but today are only used in other fields of processing, mainly in the agricultural, energy conversion or food industries. Here these process is classified under "other processes" and will not be further described.

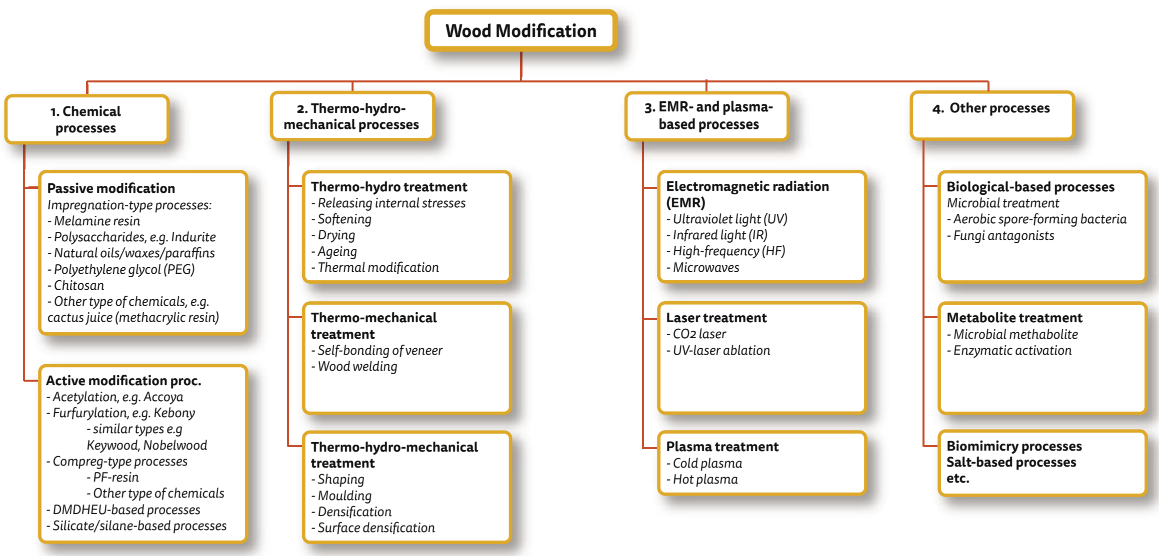

Figure 5: *A diagram of the various wood modification processes (after Sandberg & Jones 2018)*

Chemical modification processes

There are several ways to chemically modify the wood cell wall polymers and the most abundant single site for reactivity is the hydroxyl groups. The hydroxyl groups in the wood polymers (i.e. cellulose, hemicellulose and lignin) are the most reactive sites in the wood (though there are differences in their relative reactivity). They are also responsible for the dimensional instability through their hydrogen bonding to water. Chemical modification of the wood by reacting the hydroxyl groups with a stable, covalently bounded, less hydrophilic group, leads to an increased dimensional stability. Chemical modification requires the penetration of the modifying chemical into the microstructure of wood. Wood species, which are difficult to impregnate, are therefore not suitable for chemical modification, at least at greater dimensions. Penetration generally proceeds much easier into sapwood than into heartwood. Therefore, sapwood usually exhibits higher weight gains than heartwood after chemical modification.

Modification of wood can involve active modifications, which result in a change of the chemical nature of the material through the formation of new covalent bonds between the modification chemicals and the cell wall polymers (Rowell 1983a), or a passive modification, in which a change in properties results without altering the chemistry of the material. A clear differentiation between the two types is not always possible.

Further reading: Rowell (1983b, 2005), Hill (2006), Sandberg et al. (2017)

Acetylation

The main form of chemical modification has been acetylation (Rowell 2014). Despite being a known reaction for several decades, it was not until improvements in chemical engineering allowed for the commercialisation of the process in The Netherlands in the early 2000s (Sandberg *et al*. 2017). The reaction (Figure 6) involves the reaction of wood with acetic anhydride up to temperatures of around 140°C, since the additional exothermicity of the acetylation process can lead to excess temperature build-up within larger scale operations.

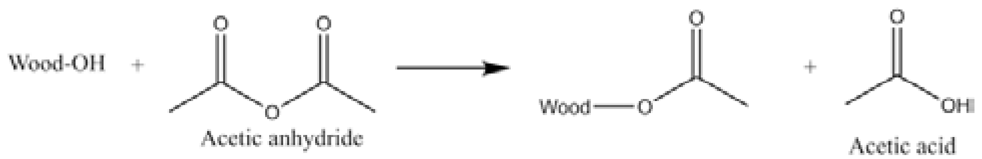

Figure 6: *Acetylation of wood with acetic anhydride*

The release of acetic anhydride as a by-product was seen as a limiting factor until commercial post-reaction techniques were developed for the removal of this by-product. Alternative methods for acetylating wood have also been attempted, particularly through the use of ketene (Morozovs *et al*. 2003) or diketene (Figure 7, Hill 2006), reaction with acetic acid under harsh conditions, or reaction with acetyl chloride, though this latter method resulted in the release of hydrochloric acid as a by-product.

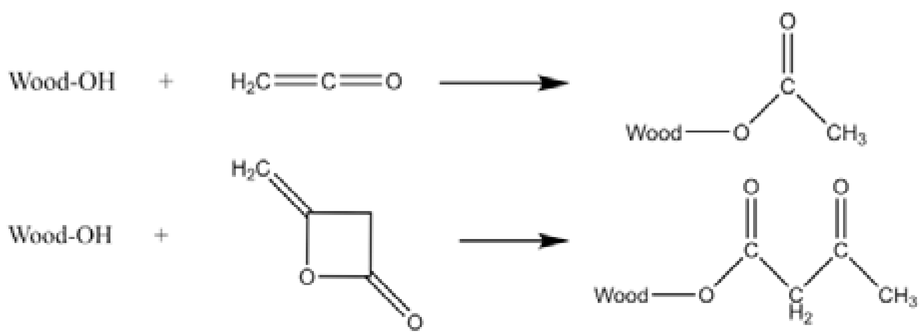

Figure 7: *Reaction of wood with ketene and diketene (Hill 2006)*

Another method that has gained scientific interest is the use of vinyl acetate (Jebrane & Sèbe 2007), in an attempt to avoid secondary processing for the removal of odorous components (as is the case with the removal of acetic acid with conventional acetylation). Experiments using vinyl acetate (Figure 8, where R=CH_3) showed moderate yields of acetylated material could be achieved at a temperature of 90°C.

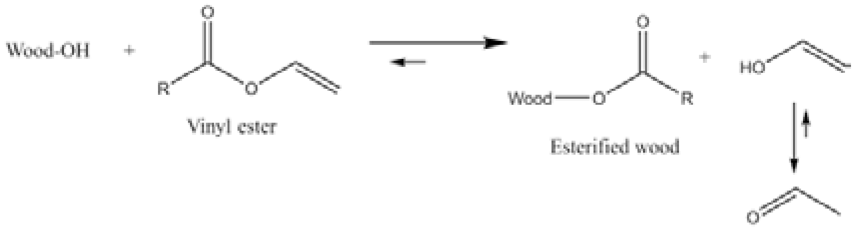

Figure 8: Acetylation of wood with vinyl acetate

Further reading: Rowell (2014), Sandberg et al. (2017), Mantanis (2017)

Modification with DMDHEU

Originally used within the textile industry, 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU) has been found to be a suitable reagent for use in wood modification (Figure 9). Based on early work by Militz (1993). Subsequent work has shown that the process requires aqueous-based impregnation under high pressure, followed by polymeric curing at temperatures typically around 100-120°C under humid conditions. This causes the agent molecules to cure by polycondensation, after which water is released (Krause *et al*. 2003, Krause & Militz 2009).

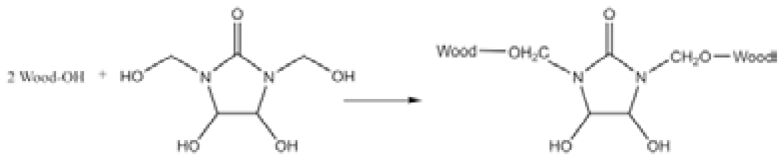

Figure 9: Modification of wood with DMDHEU

Further reading: Emmerich et al. (2019)

Furfurylation

The furfurylation process is based on the impregnation of furfuryl alcohol into the wood structure. The polymerisation of furfuryl alcohol in wood is more complex than suggested in Figure 10, with two possible processes postulated. One possibility is that furfurylation comprises a chemical modification process, since the furfuryl alcohol polymer reacts with itself and possibly reacts with the lignin in the cell walls (Lande *et al*. 2008, Nordstierna *et al*. 2008, Gérardin 2016, Li *et al*. 2016). Thus, the furfuryl alcohol complexes are deposited in the wood cavities and cell walls. Polymerisation takes place in microscopic cell cavities and is easily detected using optical microscopy. This suggests that furfurylation leads to a permanent “bulking” of the cell wall, meaning that the cells are swollen in a permanent way. One possible explanation is that the furfuryl alcohol polymer inside the cell wall occupies some of the space normally occupied by water molecules when wood is exposed to humid conditions (Lande *et al*. 2008). Various scientists consider wood furfurylation as an impregnation modification process, in which the properties of the furfurylated material appear more like those of a polymer-filled cell wall rather than a reacted cell wall (Rowell 2012, Larsson-Brelid 2013). However, it is likely the overall process will be a combination of both reactions.

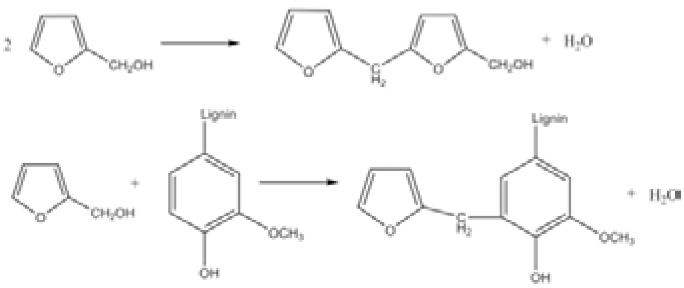

Figure 10: Mechanism for the furfurylation of wood

A key development aspect of the furfurylation process has been the sourcing of furfuryl alcohol from lesser-used biomass such as corn-cobs. This has allowed the furfurylation process to be recognised as an environmentally-friendly modification, as demonstrated with the "Swan" ecological label for the furfurylation process adopted by Kebony ASA in Norway.

Further reading: Lande *et al*. 2008, Mantanis 2017.

Resin impregnation/polymerisation

Initial research work at the Forest Products Laboratory, Madison USA impregnated wood with phenol-formaldehyde resins up to 100% resin addition, which resulted in an improved dimensional stability (anti-shrink efficiency, ASE, up to 58%) and improved resistance to biodeterioration against fungi, termites, and marine borers. Initial experiments using wood veneers by applying impregnation with phenol-formaldehyde (PF) resins, heat, and compression were implemented by Stamm & Seborg (1955), leading to the production of products called Compreg® and Impreg®.

Research on the impregnation modification of wood with melamine-formaldehyde (MF) resins has increased in recent decades, especially in Europe, with positive results with respect to dimensional stability and biological resistance to brown-rot fungi (Sandberg et al. 2017). Formulations of PF resins penetrate and polymerize in the cell wall resulting in cell wall bulking greater than other thermosetting resin (Stamm & Seborg 1936, Furuno *et al*. 2004, Shams & Yano 2011). In addition, PF resin is also deposited on the lumen surfaces (Hosseinpourpia *et al*. 2016). The PF resin is fixed in the wood by formation of a three-dimensional network and only a minor part might react with lignin.

Further reading: Kielmann *et al*. 2017, Stefanowski *et al*. 2018.

Modification with silicon compounds

In recent years, there has been an increase in interest in finding alternative treatment methods for modifying wood. Since around 2000, there has been activity in the treatment of wood with inorganic silicon compounds (Mai & Militz 2004a). Such systems are mainly based on condensation products of silicic acid (colloidal silicic acids, silicates, ''water glass'') or tetraalkoxysilanes which undergo hydrolysis and condensation steps to form sols and finally gels (sol-gel technology). When the sol-gel process is completed, an inorganic silicate free of organic groups is formed (Mai & Militz 2004b). "Water glass", an alkali silicate, has been shown to enhance the durability of wood though some important drawbacks were noted during subsequent analysis. Because of its high hygroscopicity and its high pH values, increased moisture absorption and strength loss of wood was frequently observed.

Wood treated with tetraalkoxysilanes showed an enhanced dimensional stability, especially when the hydrolysis and the condensation of the silanes was controlled to react within the cell wall. Similarly, treatment with siloxanes increased the water repellency of wood (Donath *et al*. 2006, 2007), but did not considerably influence the sorption behaviour of wood. Siloxanes containing amino-functional groups showed protective effectiveness against wood destroying basidiomycetes particularly the brown rot fungi Coniophora puteana and Gloeophyllum trabeum in laboratory durability tests according to EN 113 (Donath 2004).

Much of the commercial development has been based on the early treatment methods, with aqueous solutions being sold commercially for do-it-yourself application, or by vacuum impregnation using conventional treatment facilities. However, there has been a trend in recent years to investigate combining silicon-based treatments with further functionalisation, such as the use of epoxysiloxanes (Meints *et al*. 2018) and aminosilicones (Weigenard *et al*. 2008).

Further reading: Mai & Militz 2004a,b.

Thermo-hydro-mechanical modification processes

This modification approach involves the combined treatment of wood at higher temperature in presence of moisture and/or external compression forces, and is classified as thermo-hydro (TH) and thermo-hydro-mechanical (THM) processes. When no moisture is added during modification process, the process is sometimes called thermo-mechanical (TM). The general expression for all these process is THM processing. There are numerous THM processing techniques, some of them in use for a very long time, others are on a development stage.

In a broad definition of wood modification, TH processing may include different method for releasing stresses in wood by expose the wood by hot steam or boiled water, a typical process uses in veneer production. By the same treatment, the wood starts to get softer and under specific conditions the material (the lignin) plasticize making the wood possible to form by an externa force. Wood drying in kilns may also been considered as a mild type of modification, especially when temperature reach above 100°C. These different modification techniques we will not consider further in this report, as these are conventional techniques used in the wood industry for a long time.

Thermal wood processing (thermal treatment) involves temperatures of 100-300°C and can have two distinctly different purposes:

a) softening the wood in steam or water to release internal stresses and make the wood easier to further process, or
b) controlled degradation of the wood involving temperatures between 150 and 260°C with the purpose of improving shape stability and decay resistance.

Thermal treatment of wood at greater than 300°C is of limited practical value because of the severe degradation of the wood material (Sandberg *et al.* 2013). Wood aging is a further development of the classic thermal modification processes currently used industrially. Wood aging operates in a temperature range between wood drying and thermal modification (100-150°C), and the negative effects that a classic thermal modification normally has on strength and brittleness of wood are therefore decreased.

Thermally modified timber (TMT) is, according to CEN (2007), wood at which the composition of the cell wall material and its physical properties are modified by exposure to temperature greater than 160°C and conditions of decreased oxygen availability. The wood is altered in such a way that at least some of the wood properties are permanently affected through the cross section of the timber. This product is sometimes related to *heat-treated wood*, but to distinguish it from heat sterilization at lower temperature (≈55°C) with the purpose of killing pests in solid wood materials and preventing their transfer between continents and regions, the terms thermal modification is to prefer. TMT is characterised by the wood specie, grading, its manufacturer, procedures and stages of treatment and has a specific property profile. Compared to un-modified timber, TMT distinguishes by an increased resistance against wood-destructive fungi, by improved dimensional stability, lower equilibrium moistures as well as darker colour shade. As a rule, an increased intensity in the modification treatment (raised temperature and duration of treatment) will result in improved dimensional stability and increased resistance to biodeterioration.

Further reading: Hill (2006), Navi & Sandberg (2012), Sandberg *et al.* (2013, 2017), Gerardin (2016).

Wood modification processes based on electromagnetic radiation (EMR) or plasma

This type of wood modification is referred to as a process used to change the chemical composition or the cell-wall structure by different types of *electromagnetic radiation* or *plasma*, and without using additional chemical or biological agents, or any mechanical force.

Classically, *electromagnetic radiation* consists of electromagnetic waves such as radio waves, visible light, and gamma rays, which are synchronized oscillations of electric and magnetic fields that propagate at the speed of light. *Laser* treatment uses electromagnetic radiation that is optical amplified by a device (the laser) so it emits light coherently. The laser beams can be focused to very tiny spots, achieving a very high irradiance, or they can have very low divergence in order to concentrate their power at a great distance. The term “laser” originated as an acronym for “light amplification by stimulated emission of radiation”.

The physic definition of *Plasma* is an ionised gas with an essentially equal density of positive and negative charges. It is constituted by particles in permanent interaction; the particles include photons, electrons, positive and negative ions, atoms, free radicals and excited or non-excited molecules. Plasma can exist over an extremely wide range of temperature and pressure, but for technical purpose, it is most often limited to low-pressure. The plasma state is in an extremely high energy level compared with solid, liquid, and gas state. There is no limitation regarding the concentration of charged particles and electrons in plasma state. In plasma treatment of materials, all significant reactions are based on free-radical chemistry.

Wood modification processes based on electromagnetic radiation (EMR) or plasma is commonly used in the food and agricultural sectors for the modification of particles of different compounds such as starch and can improve e.g. water solubility and reduce particle size. The processes could be generally classified into thermal and non-thermal modification. Beyond heating or curing wood by EMR and surface activation by plasma or corona discharge treatments, these group of processes are not common in the wood industry.

Further reading: d´Agostino *et al.* (2008), Volokitin *et al.* (2016)

Research activities in wood modification

Research activities in wood modification within COST FP 1407 countries are described in the appended country information. Table 1 gives a summary of the information that can be extracted from there and some additional information. Since mid of last century, wood modification has provided many opportunities for the science, research, and testing community, and the activities has strengthened the wood research as field of science and research. Research on wood modification gained many new findings on physical and chemical micro- and nanostructure of wood, relationship between structure and properties, and interaction between material and external influence factors.

Table 1: *Overview of research activities in the area of wood modification in European countries based on responses to the COST FP1407 questionnaire and subsequent correspondence. Note: This table is indicative of current research of respondents only and does not aim to cover past research activities, nor studies into performance of modified wood. TH - Thermo-hydro and THM - Thermo-hydro-mechanical modification*

Country	TH / Thermal modification	TH / ageing	THM / densification	Other TH or THM processes	Acetylation	Furfurylation	Silicate / Silanes	Resins	Waxes / Oils / extractives	Mixed anhydride	Other processes
Austria											
Salzburg University of Applied Sciences Kuchl	X										X
KPLUS in cooperation with BOKU	X										X
Belgium											
Ghent University, WoodLab	X				X	X			X		X
Croatia											
University of Zagreb	X										
Czech Republic											
Czech University of Life Sciences Prague (CULS)	X								X		X
Mendel University, Brno	X	X	X	X	X				X		X
Denmark											
University of Copenhagen											X
Estonia											
Tallin University of Technology		X		X			X			X	X
Estonian University of Life Sciences	X										
University of Tartu											X
Finland											
Aalto University	X		X	X				X	X		X
University of Eastern Finland (UEF)	X								X		X
Natural Resources Institute Finland (Luke)			X								X
France											
Lab. de Mécanique et Génie Civil de Montpellier (LMGC)	X	X									
Arts et Metiers, LaBoMaP	X										
Institut Pascal, University Clermont Auvergne		X									
CIRAD, the French Agricultural Research Centre for International Development	X										X

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Country	TH / Thermal modification	TH / ageing	THM / densification	Other TH or THM processes	Acetylation	Furfurylation	Silicate / Silanes	Resins	Waxes / Oils / extractives	Mixed anhydride	Other processes
France											
INRA, French National Institute for Agri.l Res.										X	
INP, Grenoble Institute of Technology										X	
ENSIACET, École nationale supérieure des ingénieurs en arts										X	
Germany											
Georg-August-University of Göttingen	X				X		X	X		X	X
University of Dresden			X								
Eberswalde University for Sustain. Dev. (HNE)			X								X
Greece											
Forest Research Institute 'Demeter'			X						X		X
TEI of Thessaly / WFDT Dept.					X	X			X		X
Institure of Mediterranean Forest Ecosystems and Forest Products Technology	X		X								X
Hungary											
University of Sopron	X		X		X				X		X
Ireland											
Italy											
University of Florence (DAGRI)	X	X						X			
University of Basilicata (SAFE)	X								X		
CNR-IVALSA	X										
University of Tuscia (DIBAF and DAFNE)	X								X		X
University of Turin (DISAFA)	X										
CATAS SPA					X						
Latvia											
Latvian State Institute of Wood Chemistry	X							X			
Latvia University of Life Sciences and Technologies						X					
Lithuania											
Lithuanian Research Centre for Agriculture & Forestry											X
Netherlands											
SHR b.v.	X				X	X					X
Saxion University of Applied Sciences									X		
North Macedonia											
Norway											
Norwegian Institute for Bioeconomy Research (NIBIO)					X	X					X
Norwegian Institute of Wood Technology (Treteknisk)											X
Norwegian University of Science and Technology (NTNU)											X
Sintef											X
Poland											
Warsaw University of Life Sciences (SGGW)			X								X
Poznan University of Life Sciences			X								X
Portugal											
Polytechnic Institute of Viseu	X					X			X		
Forest Research Centre (CEF)											X

Country	TH / Thermal modification	TH / ageing	THM / densification	Other TH or THM processes	Acetylation	Furfurylation	Silicate / Silanes	Resins	Waxes / Oils / extractives	Mixed anhydride	Other processes
Portugal											
National Laboratory in Civil Engineering (LNEC)	X	X	X								X
Minho University	X										
Romania											
Petru Poni Institute of Macromolecular Chemistry	X										X
Transilvania University Brasov	X										X
Russia											
Serbia											
University of Belgrade, Faculty of Forestry	X										
Slovakia											
Technical University in Zvolen	X								X		X
Slovenia											
University of Ljubljana	X										
InnoReNew/University of Primorska									X		X
Spain											
University of the Basque Country	X										X
University of Santiago de Compostella											
University of Lleida	X										
CIFOR-INIA											X
CSIC											X
Sweden											
Luleå University of Technology (LTU)	X		X	X						X	X
Swedish University of Agricultural Sciences (SLU)	X						X		X		
RISE, Research Institutes of Sweden						X	X	X	X		
Linnaeus University	X										
KTH				X	X						
Switzerland											
BFH AHB in Biel			X	X				X	X		X
ETH			X	X	X						X
EPFL										X	
Turkey											
Karadeniz Technical University, Faculty of Forestry	X				X				X		
Istanbul University-Cerrahpasa, Faculty of Forestry	X						X		X		
İzmir Katip Çelebi University, Faculty of Forestry					X	X				X	
Kahramanmaraş Sütçü İmam University, Faculty of Forestry					X			X		X	
Bursa Technical University, Faculty of Forestry	X										X
Bartin University, Department of Forest Products Engineering	X										
Duzce University, Faculty of Forestry	X		X								
Ukraine											
Ukrainian National Forestry University	X		X								
Kyiv National University of Civil Construction & Architecture											X
UK											
BRE	X				X						
Biocomposites Centre, Bangor	X		X	X			X	X	X		X

Wood modification in scientific publications

The studies related to thermal modification and chemical modification have been increasing over the past decade. Figure 11 shows the number of articles found in a search among article titles, abstracts and keywords in the Scopus database of peer-reviewed literature using the keywords “thermo-hydro-mechanical treatment” and “wood”, “thermo-hydro treatment” and “wood”, and “thermo-mechanical treatment” and “wood”. The time frame of the search was 1990-2016 and resulted in 100 publications. However, the first peer-reviewed article with keywords “thermo-hydro-mechanical treatment” and “wood” and “thermo-hydro treatment” and “wood” dates to 2000. In recent years, increased number of publications is indicating the development of the thermal modification treatments.

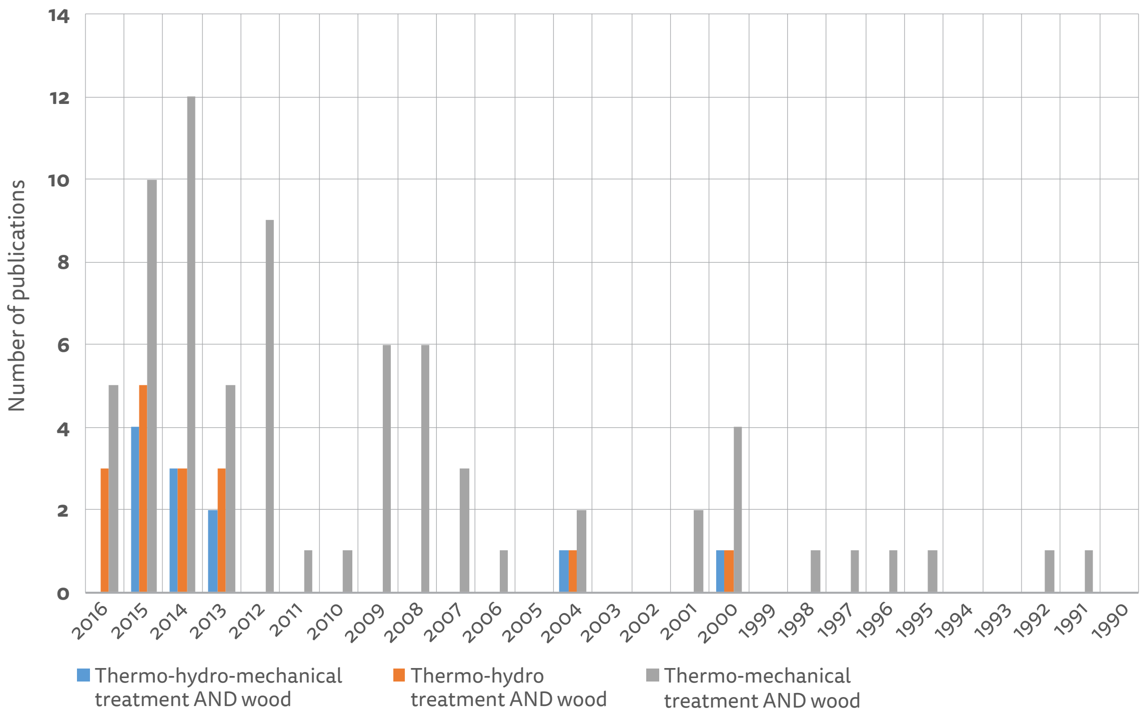

Figure 11: *Number of publications found in a search among article titles, abstracts and keywords, in the Scopus database of peer-reviewed literature 15th of January 2017, using the keywords “thermo-hydro-mechanical treatment” and “wood”, “thermo-hydro treatment” and “wood”, and “thermo-mechanical treatment” and “wood”*

As indicated in Figure 12, the chemical modification of wood was studied much wider in the last years. The keywords “chemical impregnation” and “wood”, “chemical modification” and “wood”, and “wood preservation” resulted together in 5124 publications. In the searched timeframe, 2982 publications were found with keywords “wood preservation”. The number of publications sharply increased until 2014, while in the past three years decreased number of publications can be seen. On the other hand, publications with keywords “chemical modification” and “wood” have been increasing throughout the analysed timeframe. In the timeframe 1990-2016, the search resulted in 1615 publications. The publications in the field of chemical impregnation have been relatively constant in the past 26 years. The search with the keywords “chemical impregnation” and “wood” resulted in 527 publications.

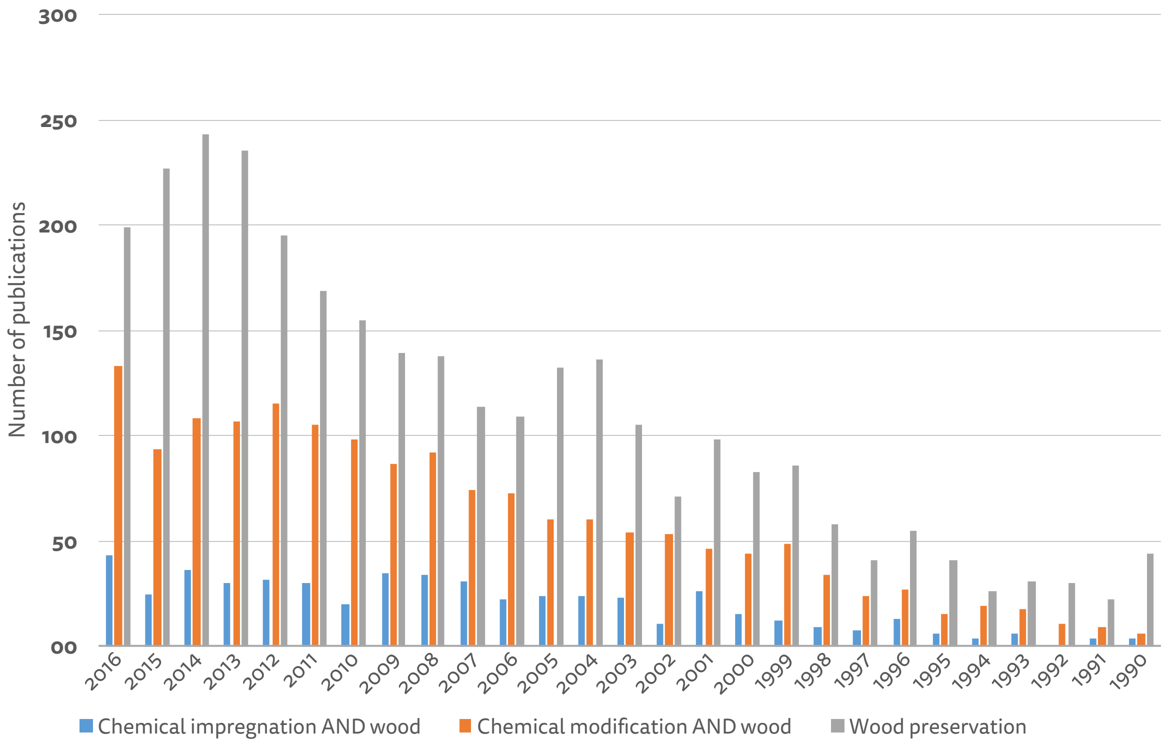

Figure 12: *Number of publications found in a search among article titles, abstracts and keywords, in the Scopus database of peer-reviewed literature 15th of January 2017, using the keywords "chemical impregnation" and "wood", "chemical modification" and "wood", and "wood preservation"*

This review of the Scopus database shows that wood modification area is receiving an increased interest in the scientific community, which to a great extent is driven by environmental concerns and increased wood use in novel applications to replace the fossil-based materials. However, it is important that also environmental impact assessment, like life cycle assessment (LCA), of wood products, especially of modified wood is included in the development of new treatments, wood-based materials and products. Figure 13 shows the number of articles found in a search among article titles, abstracts and keywords in the Scopus database of peer-reviewed literature using the keywords "wood" and "LCA" and "modified wood" and "LCA". The time frame of the search was also here 1990-2016, however the first peer-reviewed article found with keywords "wood" and "LCA" dates to 1992. Until 2008 a slow increase in number of publications can be seen, while after 2008 there is a sharp increase. Increased involvement of LCA in research studies has been the consequence of the standardized requirements and guidelines for life cycle assessments. The analysis of number of publications including the keywords "modified wood" and "LCA" shows that first publication dates back to 2005. In the whole search timeframe there were only 15 publications that included the keywords "modified wood" and "LCA". To optimize modification processing to minimize environmental impacts, much more information must be gathered about all process-related factors affecting the environment (volatile organic compounds, energy use, end-of-life use, etc.).

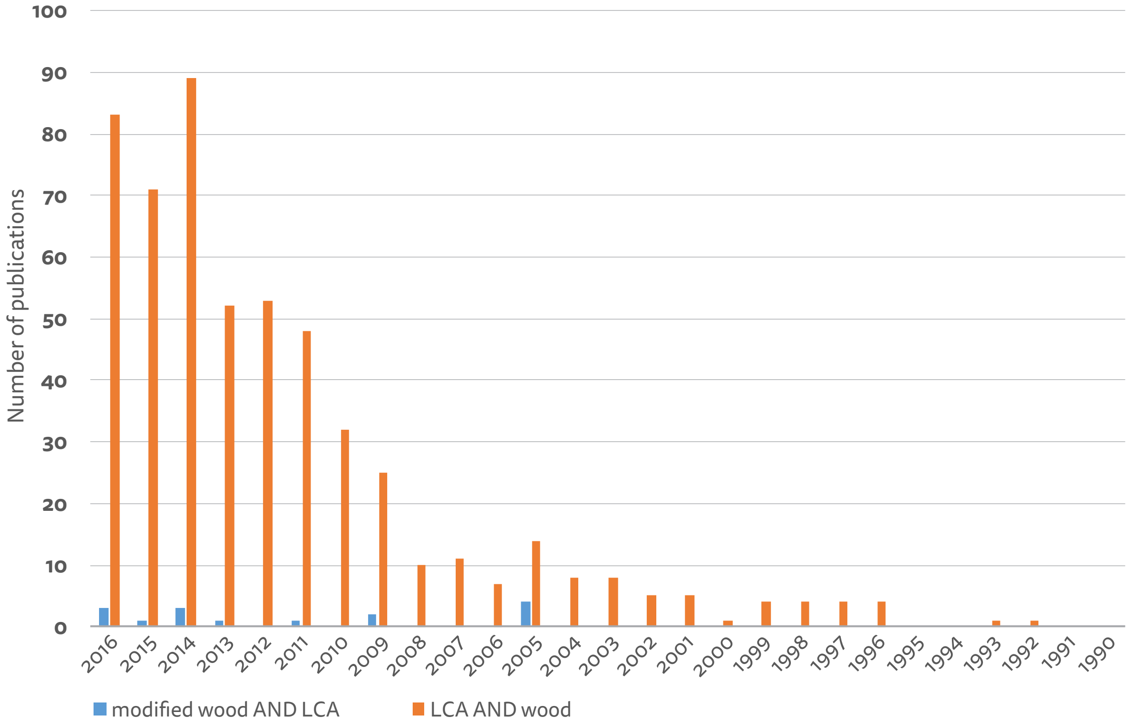

Figure 13: *Number of publications found in a search among article titles, abstracts and keywords, in the Scopus database of peer-reviewed literature, 15th of January 2017, using the keywords "modified wood" and "LCA" and "LCA" and "wood"*

Industrial wood modification

There are or have been several examples of commercial wood modifications (with some of the original scientific publications) in recent years: thermal modification (Tjeerdsma et al. 1998, Sailer *et al.* 2000), furfurylation (Schneider 1995, Westin 1996, Lande *et al.* 2008), modification with DMDHEU (dimethylol dihydroxy ethylene urea) (Militz 1993) and acetylation (Militz 1991, Larsson Brelid *et al.* 2000). The role of wood modification has gained significant interest and research over recent years, as demonstrated through the European Conferences on Wood Modification (an outcome from the European Thematic Network on Wood Modification which ran between 2000-2003), and the regular sessions within the annual International Research Group on Wood Protection (IRG) conferences.

Since the Thematic Network of Wood Modification, where the emphasis was on the development of three processes (acetylation, thermal modification and furfurylation), there has been a steady growth in the transfer of laboratory-based studies to industry. This was clearly shown in a review by Militz (2015), where the progress of additional methods was presented (Figure 14).

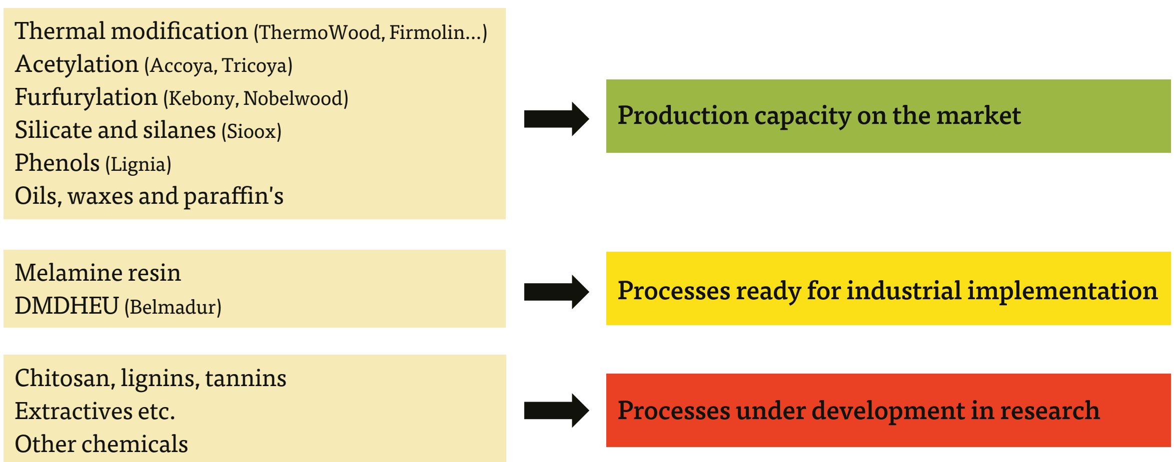

Figure 14: *Overview of extent of commercialisation of modified wood processes in Europe with some examples of commercialized products (after Militz 2015)*

Overview of current production levels

In this review (Militz 2015), it was estimated that there was approximately 350,000 m^3 of modified wood produced per year, dominated by thermal modification (estimated at 300,000 m^3, of which approximately half could be assumed to be from the ThermoWood Association (Dagbro 2016). As a part of COST Action FP1407, it was decided to review the production values across Europe, whereby each national production level was determined. Table 2 provides an overview of the types of modification being commercially produced in each country that responded to the questionnaire.

As listed within Table 2, there are a few examples of processes under development. In Belgium, there are plans to develop a new furfurylation plant in a collaboration between Kebony (Norway) and Transfurans Chemicals (Belgium) and Foreco (Netherlands), with initial productions volumes estimated at 20,000 m^3.

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Table 2: *Overview of responses to levels of commercialised wood modification in European countries within the COST FP1407 questionnaire. Legend: + Commercial production under 10,000 m^3/year, ++ Commercial production over 10,000 m^3/year. u.d. production under development.*

Country	**TH / Thermal modification**	**TH / ageing**	**THM / densification**	**THM / Solid wood bending**	**Acetylation**	**Furfurylation**	**Silicate / Silanes**	**Resins**	**Waxes / Oils / extractives**	**Mixed anhydride**	**Other processes**
Austria	++										
Belgium	++					++ u.d.	+ u.d.				
Croatia	+										
Czech Republic											
Denmark	+										
Estonia	++										
Finland	++			+			+				+
France	++							+		+	+
Germany	++		+						+		
Greece											
Hungary			+								
Ireland	+										
Italy	+		+				+	+			
Latvia	++										
Lithuania											+
Netherlands	++			+	++	+					
North Macedonia	+										
Norway	+					++					
Poland	+	+	+	+							+
Portugal	+										
Romania	+										
Russia	++		+	+				+	+		+
Serbia	+										
Slovakia	+										
Slovenia	+										
Spain	++										
Sweden	+			+			+				+
Switzerland	+		+	+							
Turkey	++										
Ukraine	++			+							
UK	+				++ u.d.		+	++			

The development of organosilicon compounds by Dow Construction Chemicals at their R&D site at Seneffe, Belgium, based on successful results from the EU Life+ project SILEX. In the U.K., there are plans to develop new acetylation plant for producing wood chips for the manufacture of Tricoya®. Work has already begun on the construction of a plant at Hull in a collaboration between B.P (UK), Accsys Technologies (UK/NL) through its subsidiary Tricoya Technologies Limited (TTL, UK) and Medite Europe (Ireland), which will ultimately produce 30,000 tonnes of acetylated wood chip (Figure 15). This material will help serve manufacturing rights with Medite, as well as in a new commercial venture with FINSA (Spain).

Figure 15: *Breaking of soil for new acetylation plant for wood chips at Hull, UK*

From Table 2, it can be seen that there has been a considerable increase in recent years in the range of treatments being commercially produced across Europe, and whilst production figures at these new sites remain fairly low (often around 1,000 m^3 a year), it demonstrates the desire of companies to provide local solutions to architects and specifiers.

Whilst outside the scope of this study within COST FP1407, an overview of the Russian wood modification market was recently undertaken. In this (Kiseleva *et al.* 2017), the classifications of modified wood according to Russian standards were identified within four different classes (Table 3). Of these classifications, it is the Thermomechanical processing that is most common within Russia, since it includes conventional thermal modification. It was reported (Kiseleva *et al.* 2017) that there were some 20 companies producing TMT in 2010, with a maximum production capability of around 60,000 m^3. In addition, it was reported (Kiseleva *et al.* 2017) that there were enterprises active in other classifications of modified wood. A reasonable estimation of thermal modification volumes 2018 indicate a total production of 75,000 m^3.

Table 3: *Overview of wood modification classifications (State Standard of USSR 1980)*

Modification approach	Explanation
Thermomechanical	Pressure modification of pre-heated, steamed, dried or impregnated wood with further high temperature drying and thermal modification
Chemo-mechanical	Pressure modification with preliminary or simultaneous wood plastification by ammonia or urine or impregnation with resins or lubricants and further thermal modification
Thermochemical	Impregnation with monomers, oligomers, or resins with further thermal modification in order to polymerise or polycondensate the impregnated compound in the wood structure
Chemical	Impregnation with ammonia or acetyl oxide in order to change the chemical composition of the wood
Radiation chemical	Impregnation of wood with monomers, oligomers or resins with further polymerisation of those under the influence of ionising radiation

The ease of modification, and in particular thermal modification has occurred as a result of several equipment manufacturers diversifying from conventional kiln and impregnation vessel manufacturing to produce small scale reactors, such as that produced by ISVE in Italy, who have sold several reactors internationally in addition to three being used within Italy for local production (Figure 16).

Figure 16: *Example of a small scale thermal modification plant (ThermoWood)*

Based on the production volumes that has been reported in COST FP1407 and further investigations, the annual production volumes for the nearest coming year have been estimated and are presented in Table 4. Thermo-hydro (TH) and thermo-hydro-mechanical (THM) methods such as steaming, softening for veneer production, solid wood bending, veneer moulding are hereby recognised as being a form of wood modification, but are not included within data compiled here.

Table 4: *Estimated production volumes the nearest coming years for some specific types of modified wood*

Type of wood modification	Estimated annual production (m^3)
Thermally modifed timber incl. aged timber	535,000
Densified wood	2,000
Acetylated timber incl. production under development in UK	120,000
Furfurylated timber incl. production under development in Belgium	45,000
Other chemical methods	35,000

Uses of modified wood

Decking for terrace, balcony, platforms and similar is the most important application for modified wood such as thermally modified timber, acetylated and furfurylated timber, followed by façade cladding including shading elements. These applications are well established and the main sales for modified wood products (Scheiding 2018). The use of modified timber for window scantlings has been introduced by some suppliers, but current data on real sales are not available. Considerable amounts of thermally modified timber are used for sash cores of polyurethane-coated windows. Modified wood is also used for garden furniture, playground devices, or other gardening and landscaping purposes, like fences, poles, or screens. Thermally modified timber is because of its aesthetic appearance also used for interior applications, mainly for flooring and panelling, which is not the case for acetylated and furfurylated timber. For interiors, existing requirements on emission should be considered for thermally modified timber.

Modified wood has gained market entry across a range of Use Classes, depending on the levels of treatment and how they alter the durability and moisture exclusion levels of the treated material. Some examples of these modified wood in Use Classes are given in Figure 17.

In the country information about modified wood in this report, more examples on products of modified wood can be found.

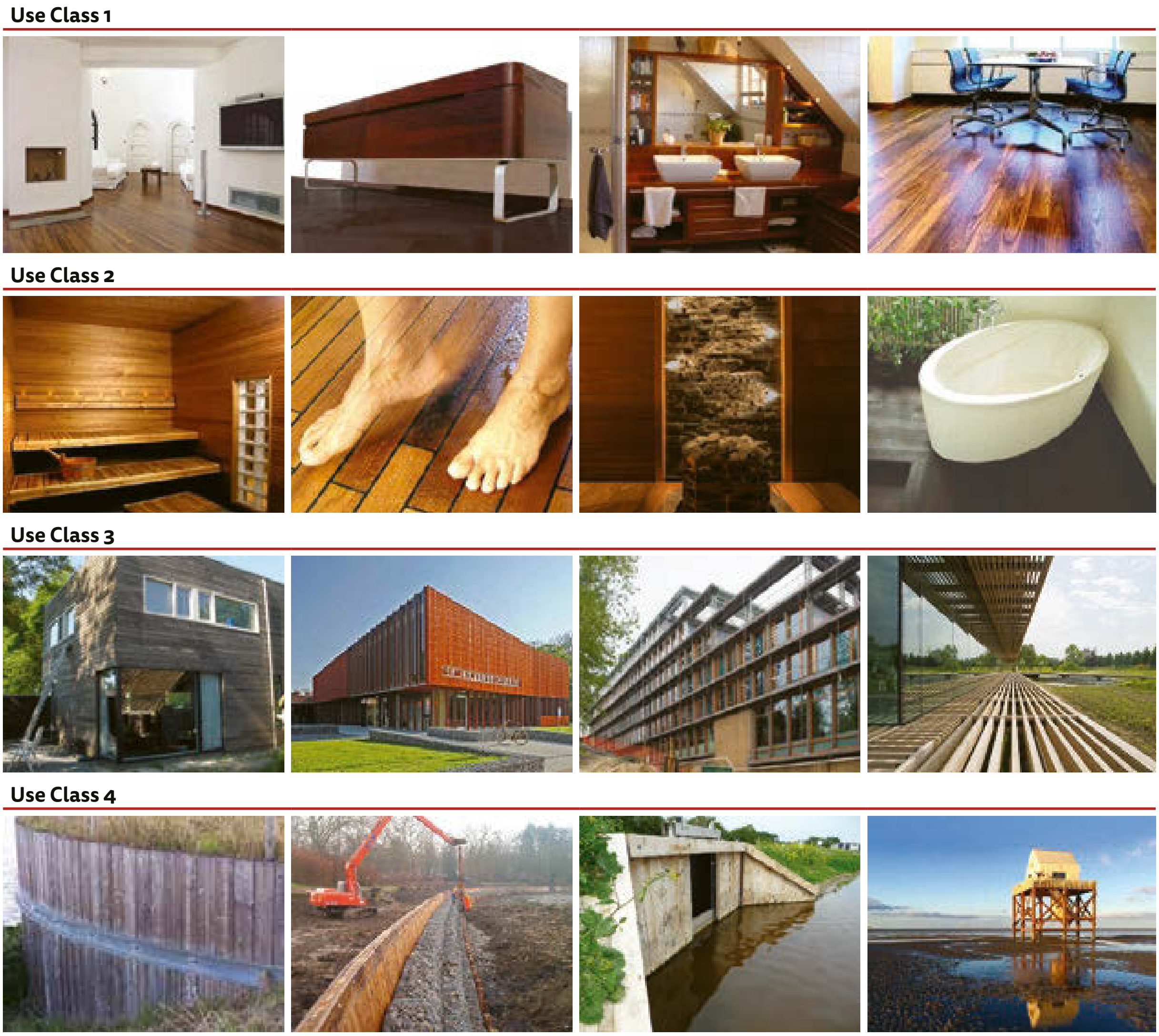

Figure 17: *Examples of modified wood in Use Classes 1-4*

Accoya and Tricoya at the Accsys headquarters,
Arnhem, The Netherlands

Performance of modified wood

The BIO4ever project - how to convince people to use bio-based building materials?

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Introduction

Today's bio-based building materials, even if well characterized from the technical point of view, often lack reliable models describing performance during their service life. The overall goal of the BIO4ever project is to contribute to public awareness, by demonstrating the environmental benefits to be gained from the knowledge-based use of bio-based materials in buildings.

Modification technologies tested within the BIO4ever project

Performance of 120 selected façade materials provided by over 30 industrial and academic partners from 17 countries is under evaluation. The experimental samples were classified in seven categories, according to treatment applied: natural wood (or other bio-based materials), chemical modification, thermal modification, impregnations, coatings and/or surface treatments, composites, and hybrid modification, that include combination of at least two different treatments (Table 4).

Table 5: *Categories of bio-based facade materials tested within BIO4ever (Sandak et al. 2018)*

Wood modification technology	Samples examples	Number of tested materials
natural chemical composites	wood, bamboo	19
coating & surface treatments	acetylation, furfurylation	5
impregnation	panels, bio-ceramics, tricoya, wood plastic composites	7
thermal modification hybrid	different coatings, carbonized wood, nanocoatings	16
modification	DMDHEU, Knittex, Madurit, Fixapret	28
	vacuum, saturated steam, oil heat treatment	20
	thermal treatment + coating, thermal treatment + impregnation, acetylation + coating etc.	25

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Performance of investigated samples

All bio-materials are under extensive characterization before, during and after degradation by biotic and abiotic agents (natural weathering in San Michele, Italy, 46°11'15''N, 11°08'00''E), in order to provide experimental data to be used for better understanding the bio-materials performance/degradation as a function of time. The appearance change, being result of the progress of natural weathering is presented on Figure 18.

The experimental data, acquired during BIO4ever project duration are used for development of the numerical models simulating the material degradation in a function of time and exposure. The weather data calculated according to the ASHRAE 2013 database allows numerical simulation of cumulative radiation on building facades, situated in 6000 locations all over the world. Dedicated algorithms simulating material deterioration by taking into account specific material characteristics, kinetic and intensity of weathering process as well as specific architectonic details are extensively tested. The main project output is a software simulating biomaterials aesthetic performance integrated with LCA interactive calculation. The tool, dedicated for investors, architects, construction engineers, professional builders, suppliers and other relevant parties, including also final customers is now under validation and integration with the BIM software.

a) **b)**

Figure 18: *The appearance change, being result of the progress of natural weathering. Appearance of investigated samples at a) the beginning of the test, and b) after 12 months of natural weathering at the southern exposure*

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Conclusion and outlook

Multi-family living is becoming the norm with the continued urbanisation of populations increasing the need for mid- to high-rise buildings, due to lack and cost of prime city land. With the growth in such buildings comes an increased need for higher performance in exterior products with greater importance placed on cost over life cycle, limited need for maintenance, homogenous and pleasing appearance, high durability and in many cases fire resistance. Many of these key requirements are extremely challenging for standard wood products to meet and thus there continues to be a growing contradiction between the impacts of global trends and the current technical capabilities of wood-based products. Other challenges such as increased constraints to use of efficient chemicals for durability and protection are making the competitiveness of wood products even more challenged.

However, even in the face of these obstacles, considerable design innovation has taken place in recent years in the use of bio-based products in construction, with a number of international architects and engineers acting as enthusiastic trailblazers in the development of new building types and construction components and systems made principally from wood but and other naturally occurring materials. Most influential amongst these innovations to date has been the development of new engineered wood products together with the increasing emergence of economically viable wood modification processes, focussing on areas where the use of wood products in certain performance situations requires high levels of durability.

Given this recognition, the use of modified wood continues to increase across Europe. In addition to the three main wood modification processes (acetylation, furfurylation, thermal modification), there has been a recent increase in the number of alternative processes being commercialised. In addition, there has been an expansion of the number of companies producing thermally modified wood, particularly for local use in a given country. The findings in the present study appear to show increased volumes to those estimated in 2015 (Militz 2015). One reason is that the European production levels has been further increased through the inclusion of an estimate of Russian production volumes, but considerable volumes are also under development for acetylation (UK) and furfurylation (Belgium). The demand for wood for exterior applications is increasing continuously. Here, terrace decking is the most important application, followed by façade cladding. Within the decking market, the share of wood-plastic composites (WPC) and natural fibre composites (NFC) has increased considerably (Scheiding 2018). Among the alternatives to preserved or tropical timber, acetylated and furfurylated timber has become more important. Furthermore, compressed and thermally modified bamboo products are to be found more frequently (when used for outdoor application, the bamboo is usually thermally modified). This continued demand for modified wood is despite the slow-down within the construction sector. This suggests that modified wood is gaining more favour with architects, specifiers and end-users as indicated earlier, which suggests a continued success for modified wood across Europe.

Though many aspects of these treatments are known, the fundamental influence of the process on product performance, the environment, and end of life scenarios remain relatively unknown. It is essential to integrate interactive assessment of process parameters, developed product properties, and environmental impacts. To optimize modification processing to minimize environmental impacts, much more information must be gathered about all process related factors affecting the environment.

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Walkway of thermally modified Norway spruce,
Grado, Italy

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A wooden church in the shape of a Sami goahti, a tent cot, painted with traditional "Swedish red coating". The architect was Gustav Wickman. The church was built between 1909-1912, and will be relocated as part of the ongoing city transformation; scheduled to be moved around 2025-2026

Oil treated Scots pine,
Grythyttan Steel Furniture, Sweden

Country information about wood modification

There are 44[1)] countries in Europe 2019, according to the United Nations. Country names in **Bold** type, more information is attached, and for the other countries are no information available.

A

Albania
Andorra
Austria

B

Belarus
Belgium
Bosnia and Herzegovina
Bulgaria

C

Croatia
Czech Republic

D

Denmark

E

Estonia

F

Finland
France

G

Germany
Greece

H

Hungary

I

Iceland
Ireland
Italy

L

Latvia
Liechtenstein
Lithuania
Luxembourg

M

Malta
Moldova
Monaco
Montenegro

N

Netherlands
North Macedonia
Norway

P

Poland
Portugal

R

Romania
Russia

S

San Marino
Serbia
Slovakia
Slovenia
Spain
Sweden
Switzerland

T

Turkey [1)]

U

Ukraine
United Kingdom

V

Vatican City (Holy See)

1) *Turkey is here counted as a European country, so 45 countries in total.*

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The Moses Bridge in acetylated radiata pine,
Fort De Roovere, Halsteren, The Netherlands

Wood modification in Austria

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A summary of wood modification activities

There are different applications for thermally modified wood produced in Austria. Thus thermally modified timber (TMT) occupies a special position. In Austria actually there exist four production sites for thermal modification with an estimated total annual production of about 15,000 m³ (2013). There also exist traditional wood bending (see biegeholz.com/ for examples of products), Table 6.

In Austria there was an increase in research and technology in wood modification in the years around 2000. Mitteramskogler (MIRAKO) was one of the leading companies, and BOKU had research projects, and the school in Kuchl/Salzburg had a "Competence Centre for Wood Modification" at that time (Teschinger & Stingl 2002). There was however never a real market break through - Mitteramskogler went bankrupt (today Heussermann) and the current volume of modified wood is very low. The main importance is in parquet flooring (Stia, Mafi) for colour management.

Today, frequently asked research questions are mainly related to the stabilization of the modified wood colour for different applications. There are primary two research institutes in Austria that deal with wood modification as needed, i) Department of Forest Products Technology & Timber Constructions at Salzburg University of Applied Sciences in Kuchl and ii) wood KPLUS in closely cooperation with BOKU in Tulln.

Mirako is a sawmill and thermal modification plant in Gaflenz. In 2011, the Häussermann Group took over the business operations of Mirako GmbH. Häussermann, with its headquarters in Sulzbach/Murr (Baden-Württemberg), founded in 1899.

Mirako has four chambers for thermal modification with a batch capacity of 10 m³ to 36 m³. Typical products are wooden flooring for bathrooms, frames for pools, balcony floors, noise barriers, musical instruments such as oboes and organ pipes, but also building system such as wooden facade system. Mirako follow the pre-standard ÖNORM CEN/TS 15679 for their TMT, Figure 19.

Table 6: Wood modification in Austria (Thermal modification from Holzkurier - Reitberger 2013)

Company	Trademark	Production	Capacity	Products	Process	Webpage
MIRAKO	ThermoHolz	7,500 m³	10,000 m³	Deliver TMT, decking	No info.	www.mirako.at www.haeussermann.de
Mafi	Vulcano	6,000 m³	No data	Flooring	No info.	https://mafi.com/en/action/Vulcano_s12930
Stia*	Admonter Mocca	No data	No data	Flooring	No info.	www.admonter.eu/
Aberger	Thermoholz	1,400 m³	1,400 m³	Decking	No info.	www.thermoholz-aberger.at/
SCHNEEWEISS AG	BRAUN Lockenhaus	--	--	Furnishing	Wood bending,veneer moulding	https://www.braunlockenhaus.at/en/company/

* Stift Admont Holzindustrie

Mafi is a flooring manufacturer and their flooring is exclusively produced in Austria - from the tree to the flooring. They operate two plants for their production; Steindorf processes the tree up to the slats, and in Schneegattern the slats are then processed into floorings, Figure 19.

Stia is a flooring manufacturer. The Admonter Mocca represents a product range of flooring which includes dark colours achieved by thermal modification. By regulating the temperature and the duration of the heat, different colour shades can be achieved. TMT also allows the manufacture of Mocca flooring suitable for rooms with a higher humidity and for under-heated floors.

Figure 19: *An example of thermally modified timber in Austria*

BRAUN Lockenhaus focuses on the manufacturing of seating furniture made of solid wood, bentwood, decorated wood laminate and tubular steel. BRAUN Lockenhaus is one of a very few companies in Austria being expert in the area of the old craft of bending wood. Since 2005, BRAUN Lockenhaus is a subsidiary of the German Hiller group, known today as Schneeweiss AG Interior. The enterprise is a market leader in the production of tables and seating solutions made of wood, tubular steel, stainless steel and plastic at European level, Figure 20.

Figure 20: *Bentwood products from BRAUN Lockenhaus: CO03 chairbed (left) and the more traditional M99 chair (right). The furniture's are designed by Adolf Krischanitz*

Reference

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Wood surface densification of Scots pine, Sweden

Wood modification in Belgium

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Introduction

Wood modification has for several decades been important in Belgium and this was underlined by the organization of the first European Wood Modification Conference in Ghent in 2003 by the European Thematic Network for Wood Modification. The presence of several production plants in The Netherlands definitely delayed the start of specific production sites in Belgium. Today we still see this is an ongoing process and both the use of tropical wood species and the presence of international harbours like Antwerp seem to be drivers in this respect.

There seems to be similarities in the approach in The Netherlands and developments in Flanders, the northern part of Belgium. Both have low forest cover and depend largely on import of timber and forest products. Import of tropical timbers is significant and there is tradition of trading forest products. Open border systems existing since the introduction of the BeNeLux in 1958 allowed since long to transfer raw materials up to finished products between The Netherlands and Belgium. Today we can observe a clear presence of modified wood from The Netherlands on the Belgian market, but we also observe that specific companies provide treating products in opposite direction. Additionally also products from the main countries involved in producing modified timber are present on the Belgian market and competing for specific markets related several commodities and applications, mainly cladding and decking but also for exterior joinery.

Modification technologies and production volumes

Actually at this moment there are only a few companies producing modified wood in Belgium. As you can see from Table 7 only thermal wood modification is present and relates primarily to modification of (tropical) hardwoods alongside common softwood species.

Table 7: *Wood modification technologies, producers, companies and production volumes in Belgium*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
ThermoWood	LDCwood ThermoWood process https://ldcwood.com/en/	Estimated capactity 20,000 m³
Thermo VacWood	Debeuckelaere Gebroeders nv ThermoVuoto process http://www.debeuckelaere.com/	Estimated production 1,500 m³

Besides the producers of thermally modified wood LDCwood (joint venture of the timber importing companies Lemahieu en Decolvenaere) and Debeuckelaere there are also some companies active in promoting and interacting on the Belgian market with specific products based on production sites in other countries. The company SWP (Stockmans Wood Products - http://www.swp-timber.com) is commercializing ThermoDUR products, which are linked to Smartheat products (https://www.lignius.nl/, the Netherlands). The company Carpentier (http://www.carpentier.be) sells amongst others HOTwood ash. Often focus is on decking and cladding but also window frames (e.g. so-called TMT Fraké based on *Terminalia superba*), insulating wood materials (e.g. products based on low density hardwoods like Thermo Ayous, *Triplochiton scleroxylon*) and other high end products often originating from specific treating facilities that are using vacuum plate systems as part of the process.

Besides TMT (Thermally Modified Timber) there is also scope for chemically modified wood. Accoya products from the Accsys acetylation plant in Arnhem, The Netherlands (https://www.accoya.com/) are since long present on the Belgian market and available from the distributor company Hout van Steenberge nv (https://www.vansteenberge.be) that also is selling the Medite Tricoya wood based panel. Originating mainly from The Netherlands modern window frames based on finger-jointed laminated beams are not only using thermally modified wood species often in combination with spruce, but also acetylated radiate pine is used in combination with Scots pine (www.ibrid.nl).

The company TFC (Transfurans Chemicals - https://www.polyfurfurylalcohol.com/building-construction) is a main producer of furfuryl alcohol used for the chemical modification called furfurylation and also producer of the Biorez resin used for treatment of the Nobelwood products by Foreco in The Netherlands (http://www.foreco.nl/nobelwood.html). The construction of a new production plant for furfurylated wood was started in 2017 by Kebony Belgium (https://kebony.com/sv/blog/second-factory-belgium/) as a second factory envisaging an initial capacity of 20,000 m³ with potential to increase to 40,000 m³.

Alongside thermal and chemical wood modification, there has been an interest in hydrophobation of wood with organosilicon compounds since beginning this century by the company Dow Construction Chemicals having their research facilities in Seneffe, Belgium. They just finished successfully an EU Life+ project SILEX showing the potential of some of their formulations.

This is a compilation of info available beginning 2018 for Belgium and it is expected that additional wood modification plants will be functional later that year and the coming years especially when considering all innovative technologies being introduced as indicated by Sandberg *et al*. (2017) and linked to the impact of high ranked publication(s) appearing recently (Song *et al*. 2018).

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Wood modification in Croatia

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Introduction

In Croatia, forests and forest land cover 46% of total land area which amounts to 56,594 km² and makes Croatia one of the countries with the highest forest cover in Europe. State forests account for 80% of the total forest area in the country, whilst the privately-owned forests are often small individual areas of land (under 1 ha.). The amount of forests and forest land per inhabitant is 6,000 m². The main species present are beech and oak (common and durmast), common hornbeam, and combined fir/spruce. The desire to use local materials has helped define a wood modification programme at the University of Zagreb, particularly with thermal modification and chemical modification via the use of compounds such as citric acid.

Wood Modification in Croatia

Currently, the majority of modified wood used in Croatia is imported from the major manufacturers, such as ThermoWood. However, there is growing interest to locally produce modified wood, with two companies to date undertaking small-scale production (Table 8).

Table 8: *Summary of companies producing modified wood in Croatia*

Wood modification technology	Producer, process short description and website	Products
Thermal modification	PPS Galeković. Treatments in water vapour atmosphere. https://pps-galekovic.hr/en/	cladding, decking and interior floorings
Thermal modification	Evolen d.o.o. http://evolen.hr	cladding, decking and interior floorings

As architects learn more about the properties of modified wood, its use in new projects will increase.

Exterior cladding of Norway spruce coated with nano-technology based wax.
Kamppi Chapel, Helsinki, Finland

Wood modification in Czech Republic

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A summary of wood modification activities

Wood modification production is rare in the Czech Republic. Since 1861, solid wood bending has been applied for furniture production by the former Michael Thonét owned factory TON in Bystřice pod Hostýnem. The principles of bending wood were adopted by TON in 1953 after several changes of property rights and company names. The factory in Bystřice pod Hostýnem is the oldest in the world where this manufacturing technology is still used, Figure 21. The most frequently processed wood is beech as it has the best characteristic features for wood bending. Although TON has implemented modern machinery to the manufacturing process, some operations are still done manually and are unlikely to be substituted by machinery.

The veneer producer Danzer also apply different methods for staining and modification of veneer.

Other than the above mentioned modification processes, there are no other types of wood modification processes applied in the Czech Republic, but there also exists one producer of thermal modification kilns. Katres drying technology (KATRES spol. s.r.o.) is a Czech producer of drying equipment for sawmills that also produces and sell chambers for thermal modification according to the ThermoWood process (Table 9).

Table 9: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Wood bending	TON produce furniture by steaming, bending and staining processes; high-frequency based bending process (www.ton.eu/en/)	Not available
Thermal modification kilns	KATRES spol. s.r.o. (Katres drying technology) is a producer of thermal modification kilns - ThermoWood (www.katres.cz/)	No wood modification production
Densification and moodification of veneer	Danzer Bohemia-Dýhárna employs more than 600 people at the sites Křivenice near Mělník and Frýdlant near Raspenava. (https://www.danzer.cz/cz/)	Not available

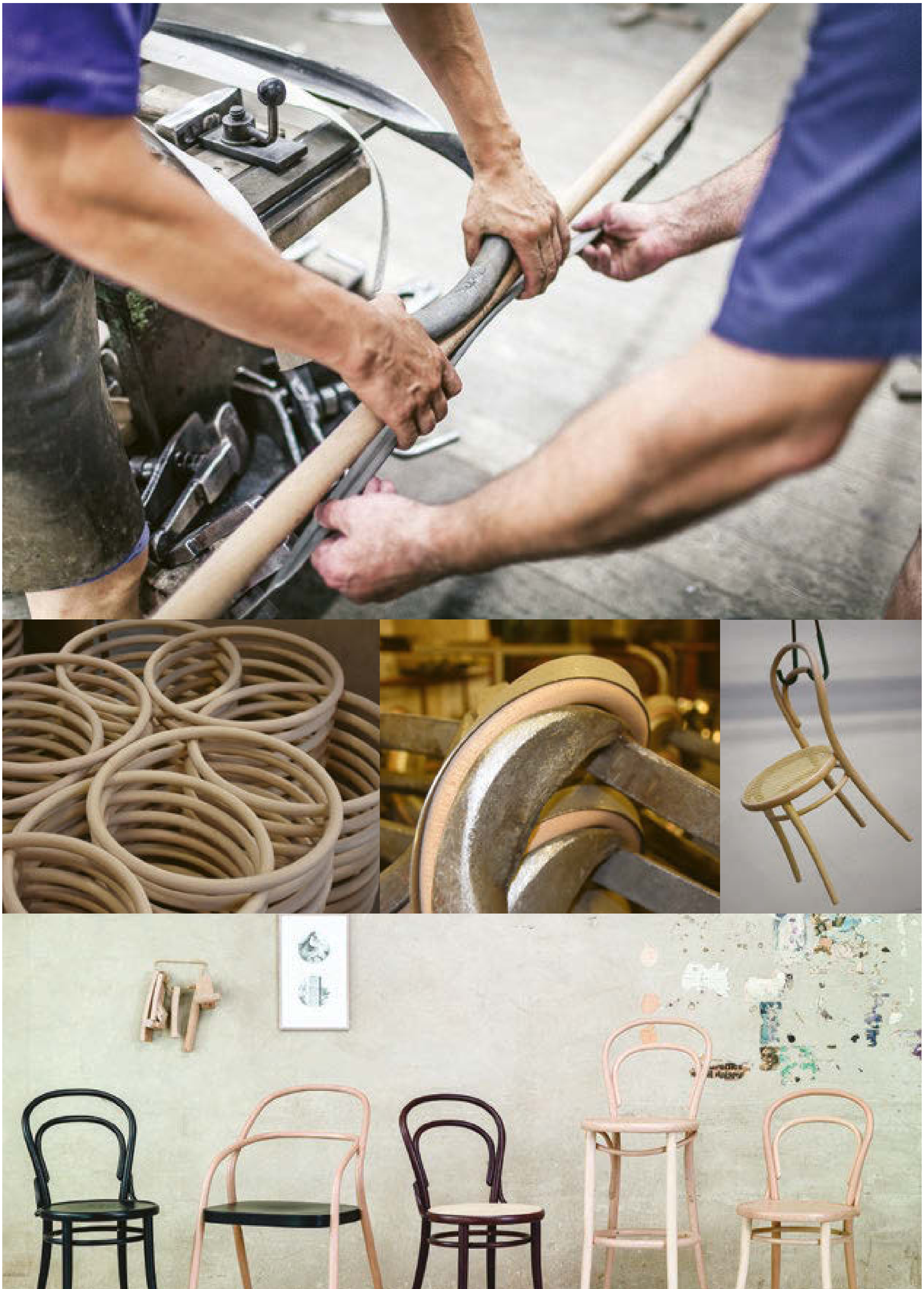

Figure 21: *Wood bending of furniture components at the TON company, and examples of the Thonét chairs*

Wood modification in Denmark

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A summary of wood modification activities

The majority of research into wood modification in Denmark has to date focussed on the treatment of wood fibres. The majority of this research has been conducted on enzyme modification, particularly on the use of laccase to increase the cross-linking of lignin (Felby *et al*. 2002), though the treatment concept was applied to solid wood (Felby & Hansen 2000). Much of this work was undertaken within the BioMat project in Denamrk, at the same time as studies into the hygrothermal treatment of wood and plant fibres (Hoffmeyer *et al*. 2003). Besides that no academic community really on this topic.

Modification technologies and production volumes

There were previous attempts to undertake semi-commercial acetylation of wood fibres, with plans announced at the Fourth European Conference on Wood Modification in 2009 by DanAcell Denmark A/S (Jones et al. 2009). However, attempts to generate sufficient financial backing failed to achieve commercial development.

Currently there are two companies producing thermally modified timber (Table 10).

Celloc undertakes thermal modification procedures using its own kilns for local markets and merchants. ThermoTreat 2.0 is a process and technology patented by Wood Treatment Technology. ThermoTreat 2.0 is approved by the Nordic Wood Preservation Council as first non-biocide containing treatment process ever. The process utilizes a closed autoclave system with inert gas heating. The process time less than 10 hours.

Table 10: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Thermal modification	Celloc (www.celloc.dk) does thermal modification of wood for clients in two own produced kilns	Not available
ThermoTreat 2.0	Sagawood (www.sagawood.dk) produces thermally modified siding and decking boards. The finished products are treated with Royal (linseed-based) hot oil.	Not available

In addition, wood from different commercialised modification processes (e.g. ThermoWood, Kebony, Accoya, Organowood) are imported directly into Denmark for use.

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Wood modification in Estonia

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Introduction

According to the national statistics of 2016, the direct added value arising from the forest and wood sector for Estonia was 5.3% of the total GDP. Of this, the percentage of wood, paper, and furniture industry in manufacturing industry was 35%, with the revenues from sales totalling € 3.3 billion. Timber products have always been an important export commodity for Estonia over the centuries. Today, exports from Estonian timber companies consist of a wide range of different product groups as sawn and planed timber, pre-fabricated structural details for construction and for furniture manufacturers, or element and modular buildings. During the last decade, there has been a substantial increase in the number of products with higher added value included in these exports (EMPL 2017).

Modification technologies and production volumes

Current wood production volumes by categories are shown in the Table 11 (EMPL 2017).

Table 11: *Wood production volumes (total) in Estonia 2016*

Wood modification product	Year 2016	Unit
Sawn timber	2,183,000	m³
Glulam and CLT	359,600	m³
Wood pellet	1,166,514	ton
Thermo-mechanical pulp	172,900	ton
Unbleached paper	65,300	ton
Plywood	55,700	m³
Veneer	108,400	m³
Chipboard	120,000	m³
Fibreboard	7,123,800	m²

Main producers of wood modified products are shown in Table 12.

Table 12: *Wood modification technologies, main producers, companies and production volumes in Estonia*

Wood modification technology	Producer, process short description and website	Annual volume production
GL, GL-panels, finger-jointed structural timber, DUO-TRIO, CLT	Peetri Puit OÜ. GL: length 1.0-29.5 m, max height 2.3 m. CLT: max measurements 3.5x15 m, thickness of panels 60-300 mm. http://www.arcwood.ee/en	
Finger jointed timber, GL components	Lemeks AS (Pinest AS). GL components glued into blocks, L and T profile. Length up to 6 m. http://www.pinest.ee/en/you-have-discovered- pinest-welcome.html	
Finger jointed timber, GL pine	Barrus AS. http://www.barrus.ee/en/	60,000 m^3 (80% export)
Vacuum-pressing treatment, finger-jointed timber	Tapa Mill OÜ. http://www.tapamill.ee/	
Treatment	Lotus Timber OÜ. Deep-impregnated wooden poles, fire protection. http://www.lotustimber.ee/en	
Pressure treated timber	Imprest AS. Machine rounded timber products, outdoor playgrounds, preservative - treated wood. http://www.imprest.ee/EN/company/introduction/	(95% export)
Hot oil treatment	Hansacom OÜ. Deep impregnation of timber (Koppers). http://www.hansacom.ee/en/	
Timber strips, colouring	Trives OÜ. Production of strips and components made of softwood, coloring. http://trives.ee/en/	
Timber strips, colouring	Combiwood OÜ. Wooden mouldings finished with primer and surface paint. http://www.combiwood.ee/en/node/9	
Birch veneer, plywood	Kohila Vineer OÜ. Production of birch veneer and plywood. http:// kohilavineer.ee/	45,000 m^3
Veneer, plywood	UPM-Kymmene Otepää AS. Uncoated and coated WISA birch plywood for construction, furniture and transport industries. http://www.wisaplywood.com/Contacts/production- units/otepaa/ Pages/Default.aspx	90,000 m^3
Birch veneer, plywood	Tarmeko Spoon AS. Production of rotary cut birch veneer. http://tarmeko.ee/companies/veneer/production	
Veneer (mainly birch), plywood	Valmos OÜ. Rotary cut veneer and sliced veneer, but also plywood veneer and formatted veneer of various thicknesses. http://www.valmos.ee/en/	10,000 m^3
GL components of timber, planned timber products	Stora Enso Eesti AS (Imavere, Näpi). http://www.storaenso.com	

Recently, Thermory and Ha Serv merged to become the largest producer of thermally modified wood and Sauna materials in Europe, with unconfirmed production volumes of 19,000 m^3/year.

Practical examples

The Winner of Wooden Buildings 2016 in Estonia was Arcwood`s new office and industrial building, made of their own produced CLT (walls, ceilings, stairs, commercial stend etc.) and GL details (columns, beams, railings). The use of Thermory (Figure 22) is increasing in popularity with architects and specifiers.

Figure 22: *Example of Thermory cladding in Estonia*

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Wine barrels, Iasi, Romania

Wood modification in Finland

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Introduction

Information in this report is based either on personal communications between the author and company representatives or websites of the companies. Prognosis regarding the ThermoWood® production in 2018 is a subjective estimate of the author.

Thermal modification

The ThermoWood® process (www.thermowood.fi) was developed in Finland in the 1990s. Nowadays the International ThermoWood Association, founded in year 2000, has 16 member companies in eight countries. Production of ThermoWood has been increasing steadily for over 15 years. ThermoWood is a registered trademark owned by the International ThermoWood Association. The Finnish members of the International ThermoWood Association (Table 1) have eight production units with total production of 170,000 m³ of ThermoWood in 2017. Since there was a fire in the biggest ThermoWood production unit (Lunawood Soinlahti) in November 2017, resulting in a long production break, the volume of ThermoWood produced is expected to grow only slightly in 2018.

In addition to the registered ThermoWood producers, there is one company (www.rakennuspuu.fi/en) producing approximately 2,000 m³ thermally modified timber per year, but it does not belong to the International ThermoWood Association.

Thus, the total production of thermally modified wood in Finland was approximately 172,000 m³ in 2017.

Other modification methods

The following points present other modified wood products commercialized in Finland. All products are rather new, and due to confidentiality issues the information is on rather general level:

- Kivipuu (trademark Siligna® in German speaking markets, and Silica® in French speaking markets) silica impregnated wood, a joint effort of Lapuan Saha Ltd., Aureskoski Ltd., and Tammiston Puu Ltd. Product launched into markets in 2018. Maintenance free product, fire retardancy class Bs1d0. Estimated product sales approximately 1,000 m³ for 2018, production capacity approximately 20,000 m³/a. (http://aureskoski.fi/wp-content/uploads/2017/09/kivipuu_esite_A4_ENG_v2.pdf)
- Waurum, a brand for modified wood produced by Paattimaakarit Ltd. Estimated production of Waurum is approximately 1,000 m³ for 2018. Chemical free property improvements especially in hydrophobicity, durability (both biological and weather resistance), dimensional stability, and hardness (www.waurum.com).
- Thermo-mechanically modified timber with TMTMTM technology by KWS Timber Tech Ltd. (technology provider). Production volume some hundreds of cubic metres per year, mainly for product and process testing with several different species (www.finestwood.fi).

Table 13 summarizes the production of modified wood products in Finland.

Table 13: *Wood modification technologies, producers, estimated production volumes (2017 or 2018), and production capacities in Finland in November 2018*

Technology / Brand	Producer	Production (2018)	Annual Capacity
ThermoWood®	Finnish members of the International	170,000 m³	170,000 + m³
	International ThermoWood Association		
	• Ekosampo Oy Ltd		
	• HJT-Holz Oy Ltd		
	• Oy Lunawood Ltd		
	• Stora Enso Wood Products Oy Ltd		
	• Suomen Lämpöpuu Oy Ltd		
	• Oy SWM-Wood Ltd		
Thermally modified wood	Pieksämäen rakennuspuu Ltd.	2,000 m³	2,000 m³
Waurum®	Paattimaakarit Ltd.	1,000 m³	10,000 m³
Kivipuu (Siligna®, Silica®)	Aureskoski Ltd. / Lapuan Saha Ltd.	1,000 m³	20,000 m³
Thermo-mechanical timber modification	KWS Timber Tech Ltd.	<500 m³	3,000 m³
TMTMTM technology			
Finestwood®			

Wood modification in France

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Introduction

As a result of increasingly stringent constraints, biocidal restrictions and costly investments, the European regulations has imposed a reduced flexibility for wood preservative manufacturers. It is therefore necessary today to diversify the types of wood modification processes. The concept of modified wood in France has attracted considerable interest over the lasts years both with industry and academia, with activities in several modification methods, Table 14.

French activities in thermal modified timber (TMT) were studied since the 80s, and were mainly conducted in collaboration between universities and industries. Improvements of existing processes and material studies were focused in this research. The thermal modification is now well established in France with about 13 companies, working on various processes (retication®, WTT®, ThermoWood®, Thermostabilisation and Inductive heating), representing an annual production of heat modified woods around 35,000 m³/year. Actually, the studies are mainly focused on (i) the quality control of the produced thermal modified wood materials (Candelier *et al*. 2016) and on (ii) the combination between thermal modification and biocide agents (Salman *et al*. 2017).

Alongside thermal and chemical wood modification, there has been an interest in hydrophobation of wood. Academic and industrial companies from France, Switzerland and Austria just finished an EU WoodWisdom-Net project (BioCoPol – Enhancing wood durability and physical properties through innovative bio-based sustainable treatments), showing the potential of some of their formulations.

Acylation of wood has been extensively studied using a wide range of chemicals, among them, acid anhydride, acyl chloride, ketene or even carboxylic acid. Even if no acetylated wood producer is present in France, the commercialization of Accoya® wood products in France has increased by 20% in 2017-2018.

Mixed acetic-fatty esters preservatives have been also recently developed by Lapeyre® industry and INP Toulouse. This method permits the grafting of acyl groups on wood leading to dimensionally stable treated wood bearing acetyl and fatty acid acyl chains, showing improved water repellence, which was recently unsuccessfully marketed by Lapeyre under the trade name of Wood Protect®.

INRA, INPT and ENSIACET academic institutions worked on wood preservatives from ASMA (Anhydride succinite of methyl alkenoate), through a European project called SURFASAM. ASMA provides wood material with a Use-Class 3, and this product is now the subject of requests from industrials (Final report SURFASAM).

In addition to the protection to fungal and insects degradations, manufacturers are now developing more flame retardant solutions. Piveteau Bois® company developed Igni-B, in collaboration with Arch Protection®, consisting in a resin impregnation, in addition to active substances, in order to definitively fix them in the wood following the resin polymerization.

Finally, WoodHa® company had obtained a durability certificate with the preservative system BIME®1, combining flame retardant and non-film forming saturator in aqueous phase.

Table 14: Wood modification technologies, producers, companies and production volumes in France

Wood modification technology	Producer, process short description and website	Annual volumes n.a. = not available
Thermal modification	BOIS DURABLE DE BOURGOGNE® -. Part of the ThermoWood® Association., Jartek® www.boisdurablesdebourgogne.fr	3,000 m³/year, mainly used for siding, cladding, decking, joinery and furnitures
Thermal modification	HIGH TECH WOODS	n.a.
Thermal modification	ECOLWOOD - ThermoVacuum process, Maspell®	1,500 m³/year mainly used for cladding and decking
WTT process	THERMO COLOR BOIS, WTT Process www.thermo-color-bois.fr	1,500 m³/year, mainly used for siding, decking, parquet, garden furniture, pool surrounds and exterior joinery.
Thermal modification	BOIS DURABLE CENTRE FRANCE, ThermoVuelto® process www.parquet-chene-massif.com	n.a.
Thermal modification	DUMOULIN, BESSON® process, Commercializatiuon under Lunawood® trend (www.lunawood.fi) www.dumoulin-bois.fr	8,000 m³/year, mainly used for Cladding, flooring and plywood
ThermoWood	Silvalbp http://www.sivalbp.fr/	8,000 m³/year
ThermoWood	DUCERF Group https://en.ducerf.com/	n.a., A JARTEK thermally modification, mainly hardwood timber
Retification	SEFWOOD, Bois rétifié® process www.sefwood.com	n.a., mainly used for siding, decking, exterior furniure.
Thermostabilisation	SYLVABP, Baschild® process, Commercialization under Ecothermo® trend www.sivalbp.com	8,000 m³ mainly used for cladding and decking
Thermal modification	BMT PRODUCTION, BESSON® process www.bois-thermo.com/	n.a., mainly used for siding, decking, parquet, exterior furniture.
Thermal modification	LIGNIVALYS, Stillwood® process perfomed with a Maspell® vacuum oven www.lignivalys.fr	n.a., mainly used for siding, decking, exterior furniture.
Inductive heating	Laglasse www.laglasse.net/	n.a., used for coopers in wine industry
Retification	RETIWOOD, N.C	n.a.
Thermal modification	KIT FORET, N.C www.kit-foret.fr	4,000 m³/year, mainly used for siding, decking, exterior furniture.
Anhydrides mixtes traetement	LAPEYRE – Woodprotect®, Vacuum/pressure impregnation + heating 140°C-2H Developped in coopération with INP Toulouse Patent WO 03 084 723 [58]	n.a., mainly used for exterior joinery in pine wood
Fire retardant	PIVETEAU BOIS / ARCH PROTECTION, Igni-B Resin impregnation http://www.piveteaubois.com	n.a., mainly used for siding and wood building material.
Fire retardant	WOODHA®, BIME®1, flame retardant and non-film forming saturator in aqueous phase http://www.woodenha.com	n.a., mainly used for siding and wood building material.

Modification technologies and production volumes

There are a range of evolving modification processes being commercialized within France, and due to the relative newness to the market are still in the expansion phase. Table 13 gives a brief overview of these modification methods. In addition, France has a high demand for quality products, meaning that there is a strong import demand for modified wood.

Timber from different commercialised modification processes are mainly harvested in French and closed European forests, but they are also imported directly into France for use. The main wood species transformed by this different processes are mainly: pine, Douglas fir, beech, ash, poplar, etc. (Gérardin 2016).

Practical examples

Figure 23 show some examples of the uses of modified wood in France.

Figure 23: *The use of modified wood in France: siding of thermally modified poplar wood by Bois Durable de Bourgogne® company (left), thermal-modification kiln, Jartek®, 20 m^3, Bois Durable de Bourgogne® (middle), and WoodenHa® process, fire-retardant impregnation in an autoclave (right).*

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Wood modification in Germany

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Introduction

Within the past decades, wood modification technologies were developed in different European countries, with focus on countries of the northern hemisphere (e.g. Austria, Finland, Germany, Norway, The Netherlands). Motivated to create alternatives to new, innovative building materials, preservative treated wood as well as endangered tropical timber, intensive fundamental research made possibly the commercialization of some of these technologies. In Germany, production plants for thermally modified timber and various chemical modifications commenced operation towards the end of 20^{th} century. Initially focused on solid wood, predominantly chemical wood modification was over time successfully applied with wood-based composites.

Modification technologies and production volumes

Tables 15 and 16 illustrate wood modification technologies, for which production plants do exist in Germany. The production volumes are premised either on estimates by the Institute of Wood Technology Dresden (IHD) in case of thermally modified timber (Scheiding 2018) or taken from manufacturer´s websites. Production volumes may differ to the precise and actual production of the respective company.

Table 15: *Wood modification technologies, producers and production volumes – thermally modified wood. n.a. = not available; * currently insolvent; production continues; ** production plant shall be sold; production stopped.*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Thermal modification at approx. 180-220°C	BES Bad Essener Sägewerk GmbH & Co. KG; open process; http://www.bad-essener-saegewerk.de*	4,000-6,000 m³
	Timura Holzmanufaktur GmbH; closed vacuum process; www.timura.de	1,500-2,000 m³
	Holzbodenwerk Krottenthaler GmbH & Co. KG; closed pressure process; www.holzbodenwerk.de	1,500-2,000 m³
	JEP Hardwood Flooring GmbH; open process; www.jep-parkett.de	n.a.
	Holzindustrie Templin GmbH; open process (presumed); www.hitemplin.de	n.a.
	Firstwood (Golden Mile GmbH); open process; www.firstwood.de**	n.a.

In comparison with thermal modification plants, a similar amount of companies operates chemical modification mainly with phenolic resins or treatment with hot-melting waxes (Table 16). Contrary to heat treatment applied to solid wood, phenolic resins are used to merge and finish veneers to plywood, laminated veneer lumber or synthetic resin densified wood. Such wood-based composites enable to meet a range of specific customer needs. Supplemented by specific additives (e.g. flame retardants), very individual customer requirements (mechanical strength, insulating properties, noise absorption, corrosion resistance, flame protection etc.) can be met with such technologies. Thus, since respective products are usually made to customized demands and some production plants are still in the start-up phase (e.g. BauBuche®), precise annual volumes produced are not available or disclosed (Table 16). Besides existing production plants using reactive modifying resins, a production plant for acetylated wood (Accoya®) is planned near Freiburg (Germany). However, the actual implementation was postponed up till now (EUWID 2015).

Table 16: *Wood modification technologies, producers, companies and products – Chemical and wax treatment*

Wood modification technology	Producer, process short description and website	Products (brand names)
Chemical modification with phenolic resins	Delignit AG/ Blomberger Holzindustrie GmbH; wood-based panels; synthetic resin densified wood; additional refining steps; www.delignit.de	Delignit®, Delignit®, Feinholz®, carbonwood®, obo-Festholz®, Panzerholz®, VANyCARE®
	Pollmeier Massivholz GmbH & Co. KG; laminated veneer lumber: parallel oriented veneers; https://www.pollmeier.com/en/	BauBuche®
	Röchling SE & Co. KG; synthetic resin densified wood; https://www.roechling.com/de/	Lignostone®
	Deutsche Holzveredelung Schmeing GmbH & Co. KG; synthetic resin densified wood; http://www.dehonit.de/page/en/homepage.php	Dehonit®
Wax treatment	Dauerholz AG; impregnation of solid wood with a hot-melting wax under temperature supply; http://www.dauerholz.de/	Dauerholz®

Practical examples

Figure 24 illustrates products made out of modified wood for practical application. Besides several applications outdoors (decking (a), facades, garden furniture), thermally modified wood is used and favoured for interior flooring and furniture due to its changed optical appearance. Innovative laminated materials as mentioned in Table 15, enable the use for wooden constructions (BauBuche® (b)), interior floors and walls inside transport vehicles (e.g. Delignit®) and many other customized solutions (c).

Figure 24: *Densified resin-impregnated and laminated beech veneer from Deutsche Holzveredelung Schmeing GmbH & Co. KG (left), and Baubuche from Pollmeier Massivholz GmbH & Co. KG in a fram construction under construction at Neue Holzbau AG Lungern (right)*

Future perspectives and processes ready to industrialize

Since the early 2000s, intensive research activities on chemical wood modification technologies were conducted by the University of Göttingen, closely linked to the wood-working industry. Focus was on wood modification with DMDHEU (formerly: Belmadur®) and a 'combi-treatment' of thermal treatment followed by an impregnation with melamine resins, in order to replace teak wood in the boat building industry. For both technologies, processes were developed up to pilot scale and ready to industrialize. Currently, several activities ongoing between the University of Göttingen, chemicals producer and wood-working industry show promising prospects for both modification technologies, pushed by an increasing demand for environmentally benign technologies to establish innovative bio-based materials.

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Thermally modified wood,
Hudiksvall, Sweden

Wood modification in Greece

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Research and industrialization of wood modification in Greece

Industrial applications of wood modification processes such as thermal modification, acetylation and furfurylation in Greece are very rare and to date have no industrial implementation.

Research in the field of wood modification exist at two institutes: Forest Research Institute "Demeter" and University of Thessaly (TEI of Thessaly) / WFDT Dept.

Demeter

In the field of wood modification, the Laboratory of Wood Anatomy and Technology of FRI is equipped with a custom made 1L stainless steel reactor capable of carrying out impregnations (capacity for vacuum = -0.8bar (gauge), capacity for pressure = 12bar), hydrothermal (steam), thermo-hydro-mechanical treatment at temperatures up to 230°C. The process is almost fully automated using labview software and has a large degree of adaptability to special needs. There is also a precision mini-heated press with plate dimensions of 100x100mm with precision controlled temperature that can be mounted onto universal testing machines for accurate pressure/thickness control. Data acquisition is carried out with Labview virtual instruments.

The current research activity related to wood modification is mainly focused on

- thermo-hydro-mechanical treatment of wood
- Densified/melamine formaldehyde modified wood.
- Hydrothermal modification of wood
- Enhancement of wood properties by impregnation with nano-metal dispersions

TEI of Theessaly

In cooperation with the FRI Athens, WST lab at TEI of Thessaly carries out two separate research projects:

a) the resistance of European beech (*Fagus sylvatica* L.) wood impregnated at high pressure with two nano-dispersions of zinc oxide (nano-ZnO) and zinc borate (nano-ZnB) is presently examined against several termite species; and,
b) beech and black pine wood is examined for oil-retention, adsorption, swelling and tensile strength properties, following a steel vessel treatment using the empty cell process (Lowry method). The effect of surface treatment with turpentine is investigated.

In another technical project, the weathering and biological resistance of industrially produced furfurylated wood, of three wood species, exposed outdoors, has been examined under the climatic conditions of central Greece.

Shou Sugi Ban or Yakisugi (charred) wood,
Higashiyama district, Kyoto, Japan

Wood modification in Hungary

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Introduction

Wood modification technologies date back several decades at the University of Sopron. Among the first investigations were high pressure and temperature steaming, and ammonia treatment of black locust. The demand for modified wood material has increased Europe-wide, due to the commercialisation of different wood modification processes during the last few decades. Wood modification accounts for much of the research objectives in our institute. Wood modification processes indicate continuously new challenges. During the last years, special attention has been given to heat treatment processes in vegetable oils and paraffin, acetylation and some impregnation processes. As in the last years, nanotechnology came to the front, with investigations into the application possibility of nano-scale materials in wood industry. Unfortunately, the wide-spread research activity in the field of wood modification is not coupled with active industrial applications in Hungary. However, there were some trials with thermal modification technologies.

Modification technologies and production volumes

Compression parallel to the grain, to improve the bendability of wood (accordionisation), Table 17. The purpose of the longitudinal compression of wood is to make it more bendable. Several factors influence the outcome of compression (wood species and quality, moisture content, temperature, compression rate, etc.). Most hardwood species with initial moisture content above 20% can be compressed. The wood is normally softened by steaming, and during the process, kept at temperatures above 80°C. While compressed in fibre direction it needs to be restricted within the compression chamber to prevent the wood from suckling. Frictional forces need to be minimized so that the transformation is performed at even rate. The middle lamellae, mostly consisting of lignin and hemicelluloses, are softened by thermo-hydro modification, allowing of the wood fibres with high cellulose content to slip during compression, and the longitudinal cell walls crinkle. Consequently, the elasticity of the wood decreases, thus it will be much easier to bend, even when dry and at room temperature.

Table 17: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Compressed wood parallel to the grain (accordionisation)	Compwood Products Kft. Thermo-Hygro-Mechanical treatment. www.compwood-products.com	~20 m³ (2016) 50 m³ (Production capacity)

Practical examples

There is a wide range of utilization fields for the wood material produced by the Compwood technology. One of the most interesting utilization is the production of wooden springs. With the use of these springs, it is possible to produce upholstered furniture based only on biomaterials. Another common field of utilization is the production of bent furniture and parts. Special applications are design elements (Figure 25) in interior design, or music instruments, sport instruments, ship building, toys, medical aid equipment, etc.

Figure 25: *Examples of modified wood in the form of bent components*

Wood modification in Ireland

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A summary of wood modification activities

Whilst there are no research groups directly active in areas of wood modification in Ireland, there is considerable interest from architects, specifiers and home-owners to use commercially available modified wood. Much of the issues surrounding the development of wood modification in Europe has been the timber resources available, which have been predominantly Sitka spruce. Indeed in 1998, a technical review of the potential of wood modification in Ireland (Birkinshaw 1998) assessed the scientific and economic viability of commercialisation in Ireland, within which it was stated:

"Timber utilisation patterns in Ireland differ from those in other European countries, but many of the same environmental and economic pressures apply. Before getting involved in modification, Irish mills and joinery manufacturers will require detailed cost information. Costs are going to be considerable, as the nature of the processes, involving corrosion-resistant pressure vessels, ovens and chemical handling, recovery and storage facilities, indicates a large investment compared with a CCA plant. It is therefore important to realise that acety1ated timber is not simply a new method of preservation which will compete with use of CCA or borates, but is a way of upgrading the material to allow it to be used for higher value applications.

A significant cost benefit may arise through savings in waste wood disposal. European and national regulations are making handling, and in particular, disposal, of CCA treated materials problematic and potentially expensive. Acetylated wood can be dealt with and disposed of without any special precautions, and no environmental hazards are presented.

The investment required is within the capability of the large wood composite companies, but would be more of a challenge for the smaller units involved in solid wood processing. Economies of scale make it very difficult to envisage more than a very small number of modification plants in Ireland, but decisions about how these will be owned and operated rest with the industry and State bodies."

With the development of greater commercialisation across Europe, supplies of modified materials have become more commonplace and are commonly stocked by timber suppliers across the country. However, the interest in acetylation explored by Birkinshaw (1998) led to ongoing activities by Medite, a large-scale MDF manufacturer in Ireland, which has led to the launch of Tricoya®, with joint investment in a new acetylation plant in Hull, UK, Figure 15.

As indicated above, the availability of modified wood via timber merchants has allowed the marketing of thermally modified, acetylated, furfurylated and silicon treated wood. Whilst there has been no confirmed direct production by these merchants, activities of some may lead to future commercial activities.

As an example, Correll Timber advertise supplies of Accoya and ThermoWood, as well as a modified hardwood sold under the brand name THERMA wood cladding, where it advertises a moisture content reduced down to 16% compared to the untreated 27%, Figure 26. Another company, Erin Trading, have exclusive sales rights for Thermory in both the UK and Ireland.

Figure 26: *Example of Accoya board (left), and ThermoWood cladding on St Andrews College, Dublin (right)*

References

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Wood modification in Italy

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Introduction

With the development of thermal modification technologies in northern countries, Italy has also developed its own processes and technologies starting since 2000. In the country the industries active in the wood drying process, starting from their technologies, have developed different treatment processes. As regards the physical modification of wood intended as densification processes, the sector has been active in Italy for over 50 years. Products and plants for the chemical modification of wood are also very rare apart impregnation with salts with different purposes such as durability or fire-retardant. Mild processes, such as treatment with water, at temperature below 100°C in alkaline medium and vaporization, are often used in Italy.

Modification technologies and production volumes

As shown in Table 18, in the field of thermal modification technologies plants, four industries are actually active in Italy.

Thermally modified timber is at present produced in Italy for different purposes such as durability in external applications, aesthetics in internal applications. Practical uses are furniture, boat flooring, cladding, decking, and fences. Ranprex is used in different contexts where a stable, light and resilient material is needed. Some examples are shown in Figures 27 and 28.

Figure 27: *Certified window in thermally modified beech (left), [b] decking in thermally modified ash (middle), furniture in thermally modified ash (left)*

Figure 28: *Decking in thermally modified ash (left), cladding in thermally modified ash (middle), gears made of Ranprex (right)*

Table 18: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Thermal modification	Baschild - http://www.baschild.com – produces plants for thermal modification since 2002. The ovens operate in superheated stem under very small overpressure conditions. Ovens vary between 10-12m³ to 80-100m³. Treatment temperatures can be up to 230°C. A complete cycle is 2 or 3 days.	Baschield has installed about 60 plants. One in Italy of 60 m³ - http://www.pozzialbino.it – the others in Croatia, Germany, Latvia, Romania. The Croatian company Evolen is directly owned by Baschild - http://evolen.hr
Thermal modification	BIGonDRY - http://www.bigondry.com – The ovens operates under superheated steam conditions in controlled overpressure and controlled conditions of oxygen. Samples conditions moisture content is also monitored during cycle and used as an input of the process. Ovens vary between 9 and 30 m³.	BIGonDRY has installed 18 plants. Three plants in Italy for a total volume of 56 m³. http://www.segheriavallesacra.it https://www.cpparquet.it http://www.fabianolegnami.it Other plans in Serbia, Russia, Romania, Poland, Turkey, Mexico.
Thermal modification	ISVE - http://www.isve.com – produce small plans working under vacuum (0.2 bar) conditions where the heat transfer is done by contact using electrically heated plates. Ovens vary between 2 and 4 m³. Treatment temperatures can be up to 230°C. A complete cycle can be 3-5 days.	ISVE has installed a total number of 10 plans for thermal modification of wood. The main business of ISVE is the production of plans for double vacuum impregnation.
Thermal modification	WDE Maspel – TermoVuoto - http://www.wde- maspell.it – produce plans working under vacuum (0.2 bar) where heat is transferred by a high efficiency air ventilation system. Wood is dried under vacuum condition and treated at temperature varying between 150 and 230°C. Ovens vary between 6 and 30 m³ but ovens up to 80 m³ are under development. The complete cycle can be 1 or 2 days. Patented process and hardware. Vacwood registered trademark.	WDE Maspell has installed a total number of 21 plans whom one of 6 m³ in Italy. Alac –Recanati (MC). Alac produce between 500 and 600 m³ year of Vacwood. The other plans are installed Belgium, Brazil, Chile, France, Korea, Norway, Poland Portugal Sri Lanka and USA.
Densification	Rancan – Ranprex - http://www.rancan.com – produces technological laminates by impregnation of beech wood with thermosetting resins and by densification.	Rancan offers 5 types of product made with parallel sheets, crossed, crossed at 90 and 45°, crossed in more than four directions.
Chemical modification	Renner – PAA – New consolidating and preservative products based on Polyamidoamines (PAAs) functionalized with siloxanes.	Patent WO2015004590 A1, Renner Italia SpA, 2015.

Wood modification in Latvia

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Introduction

Latvia is the fourth country in Europe (after the Finland, Sweden and Slovenia) in terms of largest proportion of land area covered by forests and other wooded lands (FAO). Forests and overgrown agricultural lands occupy 3.22 million ha or 50% of the country's territory (Latvian National Forest Inventory). The forests of Latvia are dominated by three tree species – Scots pine, Norway spruce and birch species (silver and downy birch); together they constitute 73.8% of the total forest area (according to NFI data). The proportion of pine stands is 28.9%, but the proportion of spruce and birch stands – 17.0% and 27.9%. The remaining forest areas are occupied by stands of black alder (5.1%), grey alder (9.8%), aspen (7.7%), ash and oak (1.5 %), and other tree species (2%). The coniferous stands in general occupy 46% of the total forest area, but stands of deciduous trees – 54%.

Wood modification in Latvia

Thermally modified timber (TMT) is the only modified wood products that is commercialized in Latvia, and SOTRA ENSO is dominating the production with an annual volume of 10,000 m³ TMT in Stora Enso's treatment facility in Launkalne, Latvia. Launkalne sawmill is located in the parish of Krogzemji, Valkas district in close proximity to main roads and also the forestry region of Latvia. The sawmill produces sawn spruce and pine with new machinery and a new saw line. During its two years of operation, the sawing capacity has grown to 215,000 m³.

There is additionally 3-5 small companies producing TMT in Latvia, with a total annual production of about 2,000 m³, Table 19.

Table 19: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Thermal modification (ThermoWood)	AS Stora Enso Latvija, Thermal modified timber for constructive use and flooring. Thermo-S and Thermo D products; KOMO certificated for thermally modified timber	10,000 m³
Thermal modification	3-5 small companys producing thermally modified timber	2,000 m³ (all together)

Wood modification research in Latvia

Research in the field of wood modification is ongoing at Latvian State institute of Wood Chemistry in Riga, and at Latvia University of Life Sciences and Technologies in Jelgava.

Latvian State institute of Wood Chemistry has ongoing research in wood modification. Thermal modification related to the WTT process is frequently studied. The main task of the research is to acquire knowledge about the synergy between wood protection processes and comprehension of the properties of the new material. The aim of the activity is to obtain wood material with improved service properties, by exploring the interaction of thermo-hydro treatment (THT) and impregnation, taking into account the impact on the environment through life cycle assessment (LCA). Thermally modified veneer for the use in plywood is a product that has been extensively studied. The institute also perform research on treatment of birch veneer with commercial phenol-formaldehyde (PF) resin water solutions.

Latvia University of Life Sciences and Technologies is a higher education and science establishment of the Republic of Latvia, where scientific research as well as academic and professional study programmes are carried out. A Study programme in Wood Materials and Technology on Masters level The university has some research projects concerning wood modification with furfuryl alcohol to improve durability in water.

References

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Latvia University of Life Sciences and Technologies: https://www.llu.lv/en/

Wood modification in Lithuania

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Research and industrialization of wood modification in Lithuania

At this moment there are no modified wood industry, local or foreign companies in Lithuania. Most of the wood working industries deal with particleboard and furniture production. However, there are several small or medium companies using wood modification technology for facing material (parquet, flooring, decking etc.), e.g. ThermoWood producer - JSC Volunta, Donteks. Only a small amount of modified wood is currently being produced, because there is little demand of such products in Lithuania and of course big competition with producers of modified wood from Scandinavia.

Our Institute of Forestry, LAMMC are working on huge project together witch company „JSC Grigo". The aim of the project is to create a new, eco-friendly wood modification method, which will be created and tested, changing the wood's appearance and providing the wood characteristics of different tree species wood, similar to the 'swamp' oak and ensuring the rational use of ligno-cellulosic material and giving higher added value to the products.

The JSC "Grigo" are working with a newly-patented technology on Bog oak veneer, bog oak lamella, bog oak flooring. Potential yearly production could be only about 120 m³, but real quantities sufficient lower.

Traditional Japanese bent wood, Koshoji Temple,
Nagoya, Japan

Wood modification in the Netherlands

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Introduction

The Netherlands were involved in the pioneering stage of industrialized wood modification. Working under one roof in Wageningen since 1994, the separated R&D activities, led by Cr&Do (earlier: SHELL) and SHR wood research, have respectively culminated in the early offspring production companies Plato and TitanWood. Other innovations include new pro-cesses for vacuum-heat treatment, pressurized superheated steam heat treatment and a pre-polymer furfuryl alcohol resin treatment, as summarized in Table 20. The Dutch company in Lignostone produce phenolic resin densified beech plywood since 1917.

The demand for modified wood in The Netherlands is steadily increasing. In the early days, mainly serving as a substitute for tropical hardwoods and chemical impregnated wood in ground and waterworks, and western red cedar in the building industry. Today, as the solution in high-end façade elements: window frames, doors and cladding applications; in combination with prefabrication, latest building regulations (fire retardants) and public perception (Circular Economy and the use of sustainable and local products). There are also good modified wood market opportunities in niche products and with limited series of customized products.

Modification technologies and production volumes

Table 20: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes
Resin-densification Lignostone (since 1917)	Vacuum impregnation of beech veneers with thermosetting phenolic resin, curing and densification (170°C, 20 MPa). www.lignostone.com	Lignostone no data on production volumes
2-stage thermal modification PLATO (since 2001)	Heat treatment of air-dried wood in subsequent hydrothermal (165°C, 6 bar) and dry heating stages (180°C), with intermediate kiln drying (<6%MC) www.platowood.nl	Platowood 3,500 m³
Thermal modification Smartheat (since 2002)	Vacuum heat treatment of kiln dried wood between heating plates (<245°C). www.lignius.nl	Lignius 1,200 m³
Acetylation Accoya (since 2007)	Autoclave acetic anhydride impregnation in kiln- dried (<6%) radiata pine with adjacent heat-curing and acetic acid removal. www.accoya.com	Accsys Technologies 39,000 m³
Hygrothermolytic modification FirmoLin (since 2009)	Heat treatment of kiln dried wood (12%MC) under moisture-controlled conditions in pressurized superheated steam (<7 bar, <180°C). www.firmolin.eu	FirmoLin Technologies 6,500 m³
Furfurylation Nobelwood (since 2010)	Autoclave impregnation of pre-polymerized furfuryl alcohol in air-dried radiata pine. Subsequent drying and heat-curing in high-temperature kilns. www.foreco.nl	Foreco Dalfsen 1,000 m³

Some examples of remarkable achievements with modified wood in the Netherlands are shown in Figures 29 and 30.

Figure 29: *Accoya sunken pedestrian "Moses" bridge (left), and FirmoLin extreme dimensioned TM Douglas fir (right)*

Figure 30: *Plato thermally modified wood cladding (left), and fitting of densified resin-impregnated and laminated beech veneer (Dehonit®) from Deutsche Holzveredelung Schmeing GmbH & Co. KG (right)*

Wood modification in North Macedonia

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Introduction

The territory of North Macedonia that is under forests is 988,835 ha, of which 82% are deciduous, 12% are coniferous and 6% are mixed forests. The total wooden mass is 74,343,000 m³, and the annual growth is 1,830,000 m³, with an average growth of 2 m³ per hectare. The planned harvest volume is around 1,300,000 m³, and 70% of it is used. Around 80-85% of the mass is used as firewood. Although the country has a large forestry potential, the downsides are the low quality of the wooden mass because of which is used as firewood and not as technical wood, lack of modern equipment and automatization systems. Manufacture of wood and of products of wood and cork, except furniture is around 70,000 m³ annually in 2014. Wood waste during the production in 2014 is 1,153 ton, of which, non-hazardous is 1,137 ton and hazardous is 16 ton. The wood products being produced are: parquet, wood flooring, inside and outside wall leaf, doors, buildings and similar.

Modification technologies and production volumes

The modification of the wood products is mainly oriented on thermal modification, such as: drying and steaming the wood products, Table 21.

Table 21: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process, short description and website	Annual volumes produced
Total production	Companies in Macedonia	70,000 m³
Thermal modification, drying and steaming	Ela-Mak, GamaDizajn etc.	1,500 m³ (only Ela- Mak)

The most common thermal modification process is as follows. At first a steaming of the wood is made, which usually takes 2-3 days. The steaming is conducted on a temperature of around 100-130°C with a high humidity in the steaming chamber. Afterwards, the wooden product is taken into drying chamber. Depending on the wood the drying process can be: 14-17 days for firewood, 24-25 days for beech, 30-33 days for oak, up to 60 days for birch. The drying process is computerized and there are 17 steps in the process in which the temperature inside the chamber is gradually increased starting from 30°C until 70°C, while the humidity is declining.

The company Ela-Mak from North Macedonia, works with beech and fir wood to produce sawn timber, (boards, planks, beams), slats, parquet and wooden floors as well as briquettes. The production capacity is 1,500 m³. During the production, the beech wood is dried to 10% humidity and steamed to protect it from insects and afterwards is used in production of furniture. The fir wood is usually 40% humidity and is used for construction works of roofs and walls.

In the country there is certain number of companies that produce laminated wood, among which is Bulart, Table 22.

Table 22: Wood products

Wood products	Producer, process, short description and website	Annual volumes produced and
Total production	Companies in Macedonia	70,000 m³
Wooden boards	Elkotehna	/
Wooden houses	MDC Architectonica, HotHot, Pijana Plackovica, Geoing	/
Laminated wood	Bulart (www.bulartconstruction.com) - mechanical pressing, glues type - D3, D4	

Practical examples

There are several companies in Macedonia that produce and construct wooden houses such as: MDC Architectonica, Hot i Hot etc, Figure 31.

Figure 31: *Wooden constructions: laminated wood (Bulart) (left), and timber buildings under construction (middle and right)*

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Wood modification in Norway

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Introduction

In Norway, there is one large manufacturer (Kebony ASA) of chemically modified wood known also to the international market and at the moment one small manufacturer of thermally modified wood for the domestic market.

The end-use of modified wood is mainly claddings and decking, where some large prestige multi-story buildings have been built the last years with facades of modified wood. Most of the modified wood, except furfurylated wood, for these projects are however imported from other European countries. There is an increase in demand for "maintenance free" wooden cladding and decking for the consumers.

The demand for environmental product declarations (EPD) is relatively high in Norway and several of manufacturers have therefor prepared EPDs. In construction projects, there are also sometimes demands for an LCA for the whole building with a focus on carbon footprint.

Modification technologies and production volumes

In Table 23, the producers of modified wood in Norway have been listed together with process description and production volume.

Table 23: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Furfurylated wood	Kebony ASA Impregnation with furfuryl alcohol which give locked- in furan polymers in the wood cell walls. www.kebony.com	Approx. 22,000 m³ produced by Kebony
Thermally modified wood	Marnar bruk AS. Has installed thermal modification equipment and have had some production, but has had a large increase in demand for their main product (royal impregnated pine) and hence have postponed the thermal treated pine production.	Zero production at the moment.
Thermally modified wood	Sæteråsen Sag & Høvleri. Thermally modified at 210˚C., www.saeteraasensag.no	Approx. 350 m³ produced by Sæteråsen.

Kebony ASA has performed life cycle assessment (EPD) for their products and documented the results in environmental product declarations (EPD). Marnar Bruk AS has EPD for their main product, royal impregnated pine, but not yet for the modified wood products. Sæteråsen Sag & Høvleri has not performed any known LCA work.

There are several large importers of modified wood products. Moelven Prosjekt AS is importing thermally modified spruce, pine and ash from Thermory in Estonia and has developed EPD for these products. Accoya are imported and sold by Fritsøe Engros, and Accoya has also developed an EPD which is registered at EPD-Norway.

Practical examples

In Stavanger municipality, a building program for using more wood in multi-story residential and non- residential buildings was activated in 2012. One of building project was Vannkanten which have used a high degree of wood, and the cladding material is thermally modified pine (Figure 32).

Figure 32: *Vannkanten, Stavanger, Norge. Built 2014. Thermally treated pine (Delivered by Moelven). Photo: NIBIO, Ona Flindall*

The building project Lislebyhallen Flerbrukshall (multi use sports arena) was a lighthouse project for Fredrikstad municipality and the use of chemically modified wood as cladding is shown in Figure 33. The building project had several innovative feutures, including first passiv house standard applied in Norway for a sport arena, cross laminated timber construction, low carbon footprint concrete in foundation, minimalistic material use and the carbon footprint was calculated for the materials, energy use and transport of users during the reference service life of the building. Lislebyhallen was also rewarded as the sport facility of the year in 2016 and the users are highly satisfied (Tellnes & Rønning 2018).

Figure 33: *Chemically modified radiata pine cladding (Accoya). Lislebyhallen, Fredrikstad, Norway. Photo: Ostfold Research/Lars Tellnes*

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Wood modification in Poland

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Introduction

Traditionally changes of surface properties were obtained in aging treatment, nowadays due to wood modifications. The most popular aged wood species are those that age in the nicest way, at the same time preserving their durability, such as oak, larch, pine, robinia (black locust) or ash. As a result of treatment, wood changes occurring (depending on the modification conditions) such as: improvement in dimensional stability and resistance to biodegradation, unfortunately often followed by reduced MOE, MOR, abrasion resistance and tendency for cracks and splits, reduced hygroscopicity.

Modification technologies

In order to improve wood properties, it is densified (mechanically), thermally and thermo-mechanically modified. Another way to change initial properties of wood is modification with thermo-chemical components, treatment with superheated vapour, modification in smoke and fumes, etc. There are also combinations of modification methods, such as: thermal modification in vapour together with superheated vapour and surface densification with the use of single impulse and pulse densification (gradual densification causes less stress). The problem of densified wood is maintaining the effect of compression (set-recovery), especially at variable humidity, hence also studies related to the use of oil as a stabilizing agent. T-M densification may apply to natural wood or wood T-M before. Stages of T-MD are: heating wood over temperature of lignin softening, and wood mechanically, pulsating pressing.

Applications and practical examples

Modifications in Poland are carried out in industrial and laboratory conditions. Research is conducted in two major scientific centres: in Warsaw University of Life Sciences – SGGW and Poznan University of Life Sciences, related with colour stability of wood modified for example with isocyanates, water vapour sorption in different artificial climates, influence of treatment on polysaccharides composition, influence of modification on cutting resistance during drilling and specific cutting resistance. Another field of interest is a use of modified timber in construction as well as acoustic emissions from densified wood useful for musical instruments. The densification of wood with hot rolls is a combination of the thermochemical method and surface densification. Such modification is performed on solid wood, as well as veneers and face veneers. SGGW in collaboration with business partnership developed a new wood product based on the SGGW patent on wood modification through heating and subsequent pressing. The project was organized as part of MSODI by UMWM and International Development Norway AS. Another field of interest is thermal modification of panel products (MDF) and thermal modification of veneers. Densification provides for a greater homogeneity and water tightness of MDF. Modified wood chips could be used to manufacture chipboards. Another research direction is secondary HDF densification, which provides an extra-high density of boards.

Veneers could be also chemically modified and then subjected to secondary TM treatment. Veneers are modified in order to obtain better aesthetical and mechanical properties to produce plywood, bent-glued elements or carpentry panels. SGGW analysed also possibility of plywood with higher water resistance technology production. Usually, modified wood is used as parquet material: as solid wood (oak, ash, elm, beech) as the top layer in laminated parquets. Densified wood in Poland is produced by 4 companies (Jablonski, Drewspan, Versal, Gajewski), TM wood by a several dozen of facilities, chemically by only two (Drymar and Dreweko). Modified wood could be also applied in reconstruction of antique parquets. Oak wood modified chemically with ammonia and thermally, however these methods lead to less durable colours in comparison with natural black oak.

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http://www.thermo-drewno.pl/en

Wood modification in Portugal

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Introduction

The majority of wood protection in Portugal has focused on conventional wood preservation, with a study in 1985 (Reimão & Cockcroft 1985) showing there were fourteen companies, with 26 cylinders installed in 17 locations, including four companies of prefabricated houses. These companies used mostly mixtures of salts, such as the CCA. In Portugal, as in most industrialized countries, a large proportion of these preservatives have been withdrawn from the market. The CCA, which was the most widely used preservative since the 60s in Portugal, was withdrawn in 2004, being replaced by chromium and copper borate CCB, which is generally viewed as less efficient due to leaching issues. Recently, the formulations with chromium were also withdrawn, and the CCB is no longer used, leading to its replacement by other formulations whose main active ingredient is still copper.

Modification technologies and production volumes

In Europe and to some extent North America wood protection has been gradually changing from traditional preservation methods by impregnation with toxic biocides to more environmentally friendly methods, such as wood modification processes. Wood modification improves wood properties, producing a new material, which, at the end of its life cycle, does not present an environmental hazard higher than untreated wood. In addition to the increased durability, these processes also improve dimensional stability, among other properties. The best known processes are thermal modification, acetylation and furfurylation (Nunes *et al*. 2016).

Despite the acceptance of modified wood by architects and consumers, in Portugal there are two companies producing thermal modified wood, Table 24. The wood modification plants are located in the central region of Portugal. The first company to produce thermally modified wood in Portugal was Santos & Santos, located in Febres-Cantanhede that started the production in 2012. The supply of material for thermal modification was originally from Estonia, but more recently they have focused on home-grown materials (Esteves *et al*. 2014), branded under the name Atlantic Wood®. The second company, Palser from Sertã, started recently in 2015.

Other companies focus on the import and sales of material. For example, the company Banema started the marketing of thermally modified wood (Thermowood®) imported from the company Lunawood in Finland (Esteves *et al*. 2014) and Jular also started selling Thermowood imported directly from Finland (undisclosed provenience). The company Multiplacas started to sell Thermowood® a little later, around 2004. Carmo Industries joined this group when it started selling thermally modified wood from Plato in 2009.

Table 24: *Wood modification technologies, producers, companies and production volumes*

Wood modification process	Producer, process short description and website	Annual volumes produced
ThermoWood	Palser Bioenergia e Paletes Lda. Production of Thermo D (212ºC) for decks and cladding as part of the International ThermoWood Association. www.palser.pt	340 m^3 (2016), (4,500 m^3 Production capacity)
Thermal modification	Santos & Santos. Range of treatment temperatures, between 160 and 230ºC. Products mainly used for decks and cladding. http://www.atlanticwood.pt/	3,000 m^3

Practical examples

The wood species commercialised with ThermoWood treatment imported from Finland are mostly Scots pine, Norway spruce and birch. Santos & Santos is treating mainly maritime pine; the most common species in Portugal, and also some ash but tests are being made to allow the treatment of blue gum wood which is considerably cheaper. Wood species commercialised with Kebony® are Scots pine, acer, birch and SYP (southern yellow pine), Figure 34.

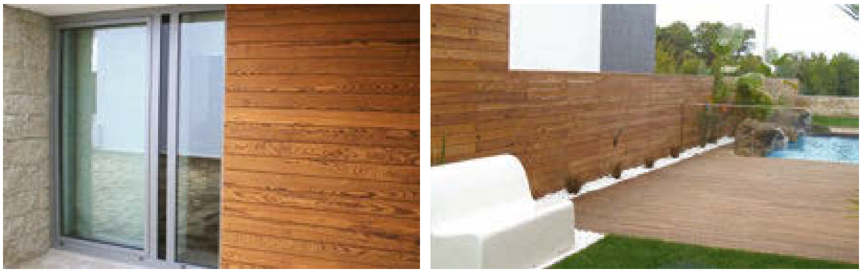

Figure 34: *Cladding and decking products from Santos and Santos (Esteves et al. 2014)*

Figure 35 show examples of imported modified wood in use in Portugal (Esteves *et al*. 2014).

Figure 35: *Examples of imported modified wood in use in Portugal. From left: Treehouse in Duoro (ThermoWood), Decking at Buçaquinho (Plato), and Cladding in Penafiel (Kebony)*

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Wood modification in Romania

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Introduction

Romania is situated in eight position in EU in terms of the biggest forest area, this being of 6.5 milion hectares. At the same time, comparing to other European countries, Romania has a total forest coverage area of about 27.3% from its total surface, lower than the European media with about 5.1%. From the total surface of 6.5 milion ha, 3.3 milion ha (51%) belong to the National Forestry Agency, the rest belonging to the private sector.

The most common wood species found in Romanian forests are: beech (about 30%), resinous conifers (30%), and oak (19%), while the rest of about 21% is composed by other hard and softwood species.

In the last years, it was recorded an accentuated exploitation of wood. In a report published by the NIS (National Institute of Statistics) (Nutescu 2017) it is mentioned that from the total volume exploited in 2016: 36% was softwood (spruce, fir, Douglas fir, larch, pine), 34.2% beech, 11.1% different hardwoods (hornbeam, acacia, sycamore, birch, ash, chestnut, cherry), 10.1% oak and 8.6% other low-density hardwood species like: poplar, willow, lime, and alder.

Considering the wood industry, in Romania most of the processing is stopped after cutting the logs and kiln drying them. Further, the processed wood is used as it is in different applications from construction to furniture or domestic uses or it is prepared for export.

Modification technologies and production volumes

Even Romania has a wide coverage of forest and the production of wood mass it quite high, the modification industry is not so developed. In Romania, we identified only three companies producing ThermoWood: J.F. Furnir SRL, S.C. INCO INDUSTRY S.R.L, and S.C. ECOLEMN S.R.L. and many other companies selling the treated wood for different applications, Table 25.

Table 25: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
ThermoWood technology	J.F.Furnir SRL Thermal treatment of ash at 208°C, in an oven of 14-15 m³. http://www.jffurnir.com/ro/produse/lemn_termotratat	J.F.Furnir SRL Volume 2016: 1,600 m³ Volume 2017: 1,450 m³
ThermoWood technology	S.C. INCO INDUSTRY S.R.L The process consist in three steps: drying phase at 140°C; treatment phase at 220-250°C for 3-4 h, and cooling and conditioning phase – the temperature is reduce with a constant rate in the presence of steam. One cycle takes about 4 days for a quantity of 25-30 m³/chamber. Maximum capacity is of 120 m³ /cycle. http://lemntermotratat.ro/en/index.php/thermo- layered-wood/	S.C. INCO INDUSTRY S.R.L Maximum capacity: 5,000 m³ (depending on the costumers request)
ThermoWood technology	S.C. ECOLEMN S.R.L. Heating the wood in low oxygen atmosphere at temperatures between 165 and 240°C. www.ecolemn.ro/content/ro/noutati/lemn-termotratat	S.C. ECOLEMN S.R.L.

Practical examples

The thermal modified wood provided from the Romanian companies or imported from Europe or Russia is widely used in different applications, such as: thermal treated pine and ash mostly used for cladding, decking and flooring, laminated beams made with polyurethane glued thermally treated timber, banisters made from thermally treated ash wood, and indoor and outdoor furniture (Figure 36).

Figure 36. *Thermally modified pine for decking from http://www.pardoseli-lemn.ro/deck/autohton/pin- termotratat/ (left), and thermally modified ash for decking and flooring from https://decolandia.ro/terase-din-lemn-si- pardoseli-exterioare/podele-terasa-decking--frasin-thermo (right)*

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Lookout tower Pompejus in acetylated radiata pine (detail),
Fort De Roovere, Halsteren, The Netherlands

The Wasa student Village,
Amsterdam, The Netherlands

Wood modification in Russia

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Introduction

Russia has a long history of timber construction and furnishing. Spruce, pine, fir and larch have been used in structural applications, whereas oak, maple, ash and exotic hardwoods have been adopted in high-value floorings, cabinetry and decorative uses.

As one of the European Union's most important trade partners, Russia represents an area of great interest and opportunities. Domestic manufacture of products with high added value increases relatively slowly in Russia, since the economic structure is mainly based on the production of energy and raw materials, while the share of the forest sector in the gross domestic product (GDP) is low, for example, in 2010 only 1.3% (FAO 2012). After the collapse of the Soviet Union, domestic production of forest industries fell by 40% (Simeone 2013).

Modification technologies and production volumes

The Russian standardisation organisation (GOST) defines modified wood as wood with improved physical, mechanical, thermophysical, tribotechnical (metal ion implantation) or biochemical features, acquired during the process of its modification (State Standard of USSR 1980). Wood modification is a process which aims at changing these characteristics of wood. The modification methods included in the standard are presented in Table 26.

Table 26: *Wood modification methods according to the State Standard of USSR (1980)*

Modification approach	Explanation
Thermomechanical	Pressure modification of pre-heated, steamed, dried or impregnated wood with further high temperature drying and thermal modification
Chemo-mechanical	Pressure modification with preliminary or simultaneous wood plastification by ammonia or urine or impregnation with resins or lubricants and further thermal modification
Thermochemical	Impregnation with monomers, oligomers, or resins with further thermal modification in order to polymerise or polycondensate the impregnated compound in the wood structure
Chemical	Impregnation with ammonia or acetyl oxide in order to change the chemical composition of the wood
Radiation chemical	Impregnation of wood with monomers, oligomers or resins with further polymerisation of those under the influence of ionising radiation

Despite considerable interest in acetylation in the 1960s and 1970s, the process never achieved successful commercialisation, mainly due to the focus on using ketene as the acetylating agent. This gas was found to be highly corrosive and dangerous to work with, making scale-up processes difficult to achieve.

Production of thermally modified wood in Russia is based mainly on foreign technologies. However, some Russian producers have further developed the imported technologies and created brands of their own to better meet the needs of potential Russian adopters. As reported in 2015 (Kiseleva *et al*. 2017), the Russian wood modification technology providers include West Wood Ltd., Heat Wood Ltd., Bikos Ltd., TMD Ltd., Vacuum Plus Ltd. and Press Ltd. (producing the brand names Adaptika and Termoteh).

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Wood modification in Serbia

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Introduction

Serbia is classified as a mid-forested country, with 26% of the country covered by trees (2.06 Mha, 2010 figures) with each hectare estimated to have an average standing volume of 101.6 m^3/ha. The following five regions having the highest listed forest coverage: Raški (43%), Moravički (42%), Toplički (41%), Zlatiborski (40%) and Jablanički (39%). Broad leaved stands account for 86.4% of the national inventory, coniferous stands 9.8% and mixed stands 6.8% respectively. Of the dominant hardwood species, the most significant is beech with approximately 47%, followed by oak at 25%, other hardwood species at 16%, and poplar at about 1%. For the softwood species, the most significant is pine (black and white) with a share of 2%, followed by spruce 5%, and fir 3%. Other softwood and some hardwood species account for a mere 1%.

Practical Examples

Figure 37: *Thermal modified ash wood flooring (top layer), and maple wood, treated and untreated (right)*

Colour of thermal-modified wood - different species modified at a temperature of 185°C or 200°C

Modification technologies and production volumes

Only thermal modification is done in Serbian wood industry. Table 27 gives a brief overview of companies and modification methods. A small amount of thermal modification timber is produced in Bosnia for Serbian companies (but not more than 400 m³/year).

Table 27: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Thermal modification	Tarkett. Treatments according the ThermoWood processes, exclusively on ash wood. 1 chamber 25 m³. (www.tarkett.rs)	800 m³/year, used for top layer of floors
	Chabros. Treatment in steam atmosphere reached by using spraying of water (producer BigonDry), 3 chambers per 25 m³. (www.chabros.com)	1,000 m³/year mainly for cladding and decking; species: ash, maple, hornbeam
	Orago Termo-T. Treatment in nitrogen atmosphere, 1 chamber 25 m³	600 m³/year mainly for cladding and decking

Wood modification in Slovakia

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Introduction

As has been the case in most European countries, the wood-based industries in Slovakia have also implemented modification processes, with processing undertaken at temperatures of 100-260°C. The most used modification technologies of solid wood are thermo-hydro processes, which involve the combined use of temperature and moisture. According to Sandberg and Kutnar (2016) it can distinctly different purposes: 1) controlled changes in wood structure at temperatures between 150°C and 260°C with the purpose of improving its shape stability and decay resistance or 2) softening the wood in steam or water to release internal stresses and make the wood easier to further process.

Modification technologies and production volumes

In Table 28, the producers of modified wood in Slovakia have been listed together with process description and production volume.

Table 28: *Wood modification technologies, producers, companies and production volumes in Slovakia*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Thermally modified wood "Thermowood"	TECHNI-PAL, Banská Bystrica Production of thermally modified ash, oak, beech and pine wood. Adress: Malachovská cesta 92, 974 05 Banská Bystrica. Production: Polkanova, 3183, 976 02 Staré Hory	400 m³
Thermo-hydro modified wood "steamed logs"	SLOVINCOM, spol. s r. o., Hurbanovo Production of flat poplar plywood and blockboard cores. http://www.slovincom.sk/	26,000 m³
	DYHA TIROLA, spol. s r. o., Moldava nad Bodvou Production of beech structural veneer. http://www.dyhatirola.sk/	10,000 m³
	A-Z LOKOMAT, spol. s r. o., Kraľová Lehota Production of beech structural veneer and flat beech plywood. http://www.lokomat.sk/	12,000 m³
	FIBRA, spol. s r. o., Šahy Production of beech structural veneer and molded beech plywood. http://www.fibrasro.sk/	6,000 m³
	MS TECHNOLOGY, spol. s r. o., Bardejov - production of beech structural veneer. http://www.mstechnology.sk/	4,000 m³

Thermal treatments of sawn timber are representing a small proportion. In Slovakia, there are few small producers: TECHNI-PAL (Banská Bystrica) and others with annual produced volume less than 500 m³ per year. The actual import of thermally treated wood (cladding and decking boards, structural building profiles and other) from other European countries to Slovakia is *app.* 1 000 m³ per year (trade companies *e.g.* RM drevo s.r.o., JAF HOLZ Slovakia s.r.o., PMP stav s.r.o.).

Thermo-hydro processing is specially applied for the plasticization and conditioning of logs prior to cutting veneer (in following producers of veneer and plywood in Slovakia: SLOVINCOM (Hurbanovo), DYHA TIROLA (Moldava and Bodvou), A-Z LOKOMAT (Kraľová Lehota), FIBRA (Šahy), and MS TECHNOLOGY (Bardejov). Their annual logs processed volume is about 58,000 m³ per year (Tab. 1). Other new processing companies: BIO ENERGO (Žarnovica) and EUROPLAC (Topoľčany) are actually under construction.

Practical examples

Especially thermally modified wood (imported or produced) is a widely used material for both exterior and interior applications. Here are some uses from Slovakia, Figure 38.

Figure 38: *Thermally modified pine wood facade (a), gate and hence (b), bridge (c), terrace by the pool (d), garden furniture (f), flowerpots and stairs (g), washbasin (h). Thermally modified ash or beech wood terrace (e), bathing or cooling off tub (i). Thermally modified quercus parquet floors (k). (Foto: references from companies RM drevo s.r.o., TECHNI-PAL and Rostaco Slovakia s.r.o.)*

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Wood modification in Slovenia

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Introduction

As of early 2018, Slovenia has two main providers of thermally modified wood. One company developed its own process while the other firm provides treatment. In addition to Slovenia's wood modification industry, researchers in the country are deeply involved in various aspects of wood modification, including gather user perspective and investigating case studies of the use of modified wood. Researchers at the InnoRenew CoE, the University of Primorska, and the University of Ljubljana pursue technological advancements in wood modification, study its environmental impact, and investigate material properties of modified wood, Table 29.

Table 29: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Silvapro wood	Silvaprodukt d.o.o. Chamber capacity of approximately 4 m³, cycle duration between 18 and 36 hours, temperatures dependent on desired outcome and material thickness (approximately 170 to 230°C). https://en.silvaprodukt.si	~1,200 m³
I-Les, "Wood Treatment Technology"	I-les Iskra d.o.o. Chamber capacity of approximately 4 m³, treatment temperatures between 160 to 180°C. http://www.i-les.si/en-index.html	~1,000 m³; WTT A/S (DK) licenses the technology (http://www.wtt.dk/products/thermo-treatment).

Practical example - The Tango House, Ljubljana, Slovenia

An instructive example of the use of thermally modified wood in Slovenia is in the Tango House in the country's capital, Ljubljana, Figure 39. The house is a small house with modern elements and a nod to the historic construction methods of the region. The building uses cross laminated timber for the structure on a piling foundation. The facade uses thermally modified spruce cladding, which will silver with age but offers resistance to the effects of the local climate and improved dimensional stability.

Figure 39: *Tango house exterior with thermally treated spruce (material by Silvaprodukt d.o.o.) with interior and exterior drawings (Kitek Kuzman 2015)*

Architect's perceptions of modified wood in Slovenia

Slovenian architects were surveyed to assess their perceptions of engineered wood products, including modified wood (Kitek Kuzman *et al*. 2017). There was a total of 557 respondents to the questionnaire phase of the survey. Approximately 80% of respondents reported that they would use modified wood in architectural design, while only 70% reported familiarity with the advantages of modified wood. Their primary interest in learning about modified wood products and processes were through technical specifications; however, visits to building sites and objects were highly ranked as well. Currently, the most common way respondents get information about products is from the internet. Manufacturers and building companies are another common way for Slovenian architects to receive information about construction products. Respondents reported a desire to receive more information about engineered wood products, in general.

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Wood modification in Spain

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Introduction

According to the data of the last Spanish forest inventory in 2015, Spain has the second largest forest area within the EU-28 (27.6 million ha), which means that half of the Spanish land area is wooden land. However, the growing stock of timber available for wood supply in Spain was 943,980 m^3, well below of the volumes of countries such as Germany, France and Sweden, which present the largest growing stocks of the EU-28 (Eurostat 2016). In Spain, coniferous species are mainly used as solid industrial wood in the following order: *Pinus pinaster* (40%), *Pinus radiata* (23%), *and Pinus sylvestris* (15%). In contrast, hardwood species are most commonly used in the pulp and paper industry (principally *Eucalyptus* sp.), with reduced volumes of *Quercus robur* (1.5%), *Fagus sylvatica* (1.3%) and *Castanea sativa* (1.1%) used as raw material for wood processing (Anuario de Estadisitca Forestal 2015). The wood sector in Spain has been delimited between first transformation companies, which provide semi-finished products, and second processing companies, which provide final products. This delimitation is equivalent to that of the statistical classification of economic activities in the European Community (NACE). Figure 40 show some examples of the use of modified wood in Spain.

Figure 40: *Examples of the use of modified wood: a) Façade of thermally modified Radiata pine, Madrid, b) façade of thermally modified Eucalyptus, Segovia, c) Accoya interior panels, Google office Madrid, and d) Accoya façade, congress palace Vitoria*

Concerning the state of the art of the wood modification technologies (Table 30), the first transformation sector produces in Spain themally modified products at medium industrial scale under the patent Termogenik (Maderas Torresar, Orozko, Spain), using a Mahild chamber (Mahild Drying Technologies, GmbH) with steam as heating medium, and modifying wood at temperatures between 192 and 212°C. In the second processing sector, MH Parquets (Sigüenza, Spain) thermally modifies Eucalyptus and Ash wood at small scale for outdoor applications, and their products are presented as raw or coated with oils. Some practical examples are provided in Figure 40. Products from chemical modification processes (acetylation, furfurylation) are commercialized in Spain, but at the present time there are no industrial facilities located in Spain. In addition, the use of new technologies such as nanotechnology or surface modification are only studied at academic research level.

Table 30: *Wood modification technologies, producers, companies and production volumes in Spain*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
Thermal modification	Maderas Torresar: Termogenik. *Pinus radiata and Fraxinus excelsior* wood (mainly) between 192-212°C at saturated steam atmosphere. http://www.termogenik.com MH Parquets: Thermal modification of *Eucaliptus globulus* and *Fraxinus excelsior* wood between 180- 220°C (process not provided by company). http://mhparquets.com/en/outdoor Gabarró: Marketer in Spain of Lunawood TMT, which uses *Pinus sylvestris* and *Picea abies*, ranging from 190-212°C at saturaded steam atmosphere. http://www.gabarro.com/es/	Annual volume: Not provided by companies. Termogenik process belongs to Torresar and Torrebaso companies. MH Parquets belong to Mariano Hervás S.A. Gabarró is marketer of Lunawood products that belong to the International Thermowood Association.
Acetylation	Elaborados y Fabricados Gámiz: marketer in Spain of Accoya Wood (wood acetylation process) from *Pinus radiata* wood. http://www.grupo-gamiz.com/	Annual volume: Sales of approximated 300 m^3 of Accoya products, according to Elaborados y Fabricados Gámiz
Furfurylation	Euro Covering S.L: marketer in Spain of Kebony wood (wood furfurylation treatment) from softwood species. Company without website	Annual volume: not provided.

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Wood modification in Sweden

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Introduction

The concept of modified wood in Sweden has attracted considerable interest over the years both with industry and academia, with activities in several modification methods. Activities in acetylation were led initially by Chalmers University and later by SP (now RISE). For fibre acetylation, this led to a collaboration between British Petroleum, A-Cell acetyl cellulosics AB ("A-Cell"), and the BioComposites Centre (Sheen 1992). A detailed review of this collaboration has been recently published (Hill 2006), through which several key factors were identified:

- Feed fibres needed to have a moisture content around 5%
- Residual acetic acid inhibited the reaction at elevated levels (above 30%)
- Fibre damage occurred at temperatures above 130°C
- Removal of residual acetic acid could be carried out by drying at around 50°C

Despite the production of several batches of acetylated fibres, and their subsequent assessment, British Petroleum withdrew their interest in acetylation in the mid-1990s, leading to a temporary halt in the commercial development by the group as a whole, though A-Cell continued their activities, in association with Chalmers University (Sweden) and Forest Products Laboratory, Madison (USA). SP (RISE) also have a microwave reactor for the acetylation of larger timber samples.

Work into the furfurylation of wood was partly developed in Sweden, through the work of Mats Westin (Lande *et al*. 2004) in Association with Kebony in Norway (formerly WPT). Experiences gained with impregnation treatments and polymerization have allowed for the uptake of new treatments based on silicon.

The thermal modification of wood in Sweden was developed in the intercommunion with wood drying research at Luleå University of Technology in Skellefteå. Improvements of existing processes and material studies were in focus in this research. The thermal modification is now well established in Scandinavia with several commercial groups involved in the ThermoWood Association, including Heatwood from Sweden.

Modification technologies and production volumes

There are a range of evolving modification processes being commercialized within Sweden, and due to the relative newness to the market are still in the expansion phase. Table 31 below gives a brief overview of these modification methods. In addition, Sweden has a high demand for quality products, meaning that there is a strong import demand for modified wood. Whilst acetylation processes are not commercialized at present, the expertise and facilities within groups such as RISE allow for good collaboration with industry.

Table 31: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced
Thermal modification	HeatWood AB. Part of the ThermoWood Association. Treatments according the the ThermoWood S and ThermoWood D processes (www.heatwood.se/en)	6,000 m^3, mainly used for cladding, decking and saunas
WTT process	Uteträ AB. Treatment accordin the WTT process, with improvements in treatment possible with the WTT2.0 process	2,000 m^3 mainly for cladding and decking
Acetylation	A-Cell was the commercial development for the acetylation of wood fibres	No longer in operation
Silicate treatment	Organowood. Silicon polymers are bonded to the wood fibers creation a physical barrier against wood destroying organisms (www.organowood.com/en)	8,000 m^3 for 2017
Silicate treatment	Sioo:x. Treatment with a range of silicon treatments (www.sioox.se/en)	No figures obtained. Mainly aimed towards self treatment markets with sales of 7,000 m^3 of low concentrated silicate fluid.

Wood from different commercialised modification processes (e.g. ThermoWood, Kebony, Accoya) are imported directly into Sweden for use.

Practical examples

Figure 41 some examples of the uses of modified wood in Sweden.

Figure 41: *Some examples of uses of modified wood in Sweden: wooden façade of ThermoWood (left), decking of thermallly modified spruce - WTT process (middle), and hydrophobic properties of OrganoWood (right)*

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Wood modification in Switzerland

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Introduction

In Switzerland there exist traditional wood modification production such as wood bending as well as newer processing technologies, as shown in Table 32. Thermal modification is applied by two companies mainly focusing at processes at lower temperatures to achieve a so-called aged wood for interior use.

Table 32: *Wood modification technologies, producers, companies and production volumes*

Company	Trademark	Capacity	Products	Process	Webpage
Balz Holz AG	Baladur-Antikholz	3,000 m³/year	Aged timber for Interior joinery	HPS-Wood[1)]	www.balz-holz.ch www.hps-wood.ch
Corbat AG (Röthlisberger)	THERMO VAPO	3,000 m³/year	Thermally modified timber for outdoor above ground products, Aged timber for Interior joinery, and the new "Swiss Wood" pencils by Caran d'Ache.	WTT and a steaming process for production of aged wood (HPS-Wood process)	https://www.corbat-holding.ch/Outdoor-Timber/Know-How/Heat-Treatment
Swiss Wood Solutions AG	Sonowood	No information	Resin impregnated and densified wood	Densification	https://swisswoodsolutions.ch/en/
K. Winkler AG	WINKLER Holzbiegewerk	No information	Moulded veneer and solid wood products	Wood bending, moulding	www.holzbiegen.ch

[1)] A closed system with at a high pressure and with nitrogen as process medium. The process is based on work by Giebler E. (1983). Dimensionsstabilisierung von Holz durch eine Feuchte/Wärme/Drück-Behandlung. Holz als Roh- und Werkstoff, 41(1):87-94.

The company Balz Holz AG is a sawmill company specializing on noise barriers, wood treatments from vacuum pressure impregnation with metal salts, and thermal modification manly for interior use. With the product line Baladur-Antikholz (oak and spruce, they provide an alternative to old wood (artificial aged wood) for the construction of chalets.

The company Corbat AG apply two types of thermal modification processes:

1) THERMO-treatment is a conventional WTT thermal modification process used for both hardwood and softwood (150 to 200°C).
2) VAPO-treatment is steaming process were the timber is exposed to saturated steam at temperature of 110-130°C (the HPS-Wood process). This corresponds to a high pressure steaming (HPS) and insure the perpetuation of structural properties of timber. It gives to the wood a very nice, rustically and antique appearance that can be combined with brushing.

Swiss Wood Solutions was founded in 2016 as a spin-off from ETH Zürich and EMPA. Their main product is impregnated and densified wood for advanced use in for example music instruments (Sonowood) instead of the use of tropical species such as ebony. Some examples of properties for Sonowood is given in Table 33.

Table 33: *Properties of Sonowood*

Property	Maple	Norway spruce
Density (kg/m³)	1,200 – 1,400	1,300 – 1,400
Brinell Hardness) [N/mm²]	> 80	> 100
Colour	Mocha	Caramel
Dimensional Stability (Diff. swelling, % per % moisture content change)	Height ~ 0.7 Width ~ 0.3	Height ~ 0.75 Width ~ 0.33
Sound Velocityb) (m/s)	> 4,400	> 5,500
Damping (Log. decrement)	~ 0.053	~ 0.04
Elastic Modulusc) (N/mm²)	> 23,000	> 39,000

Figure 42 some examples of the uses of modified wood in Switzerland.

Figure 42: *Traditional bended wood product from Winkler Holzbiegewerk (left); steam modified spruce from (Baladur-Antikholz) Balz Holz AG (middle), and guitar headstock in impregnated and densified wood from Swiss Wood Solutions AG (right)*

Wood modification in Turkey

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Introduction

The total land area of Turkey is about 80 million hectares while the forested area of the country is 28.6% (22.3 million ha) of the country land area (URL 1). Turkey has a rich and diverse range of herbaceous and woody plant species (endemism of almost 34%). The main tree species used for roundwood production are pine species (*Pinus* sp), beech (*Fagus orientalis*), fir (*Abies bornmülleriana/alba/nordmaniana*), spruce (*Picea orientalis*), cedar (*Cedrus libani*), and oak (*Quercus*) (URL 2).

Roundwood production in Turkey is about 13 million m³ annually (Tolunay & Turkoglu 2014). The forest products industries in Turkey have increased their capacity over the last decade. 70% of timber produced in Turkey is used in construction, 20% is used in furniture production and 10% is used in packaging and other industries (URL 2).

Pressure and heat treated wood materials in Turkey are commonly found in the market as well as in practical examples but acetylated wood products have not gained enough attention yet. Acetylated wood products are not produced in Turkey; however, because of the demand on acetlayed wood products such as in decking, cladding, sidings and flooring, a Turkish Accoya distributer has started to sell Accoya products in Turkey (URL 3).

Modification technologies and production volumes

There are three producers, namely Novawood, Naswood and ARIN in Turkey dealing with thermal modification. All three producers use Thermowood techonology developed by VTT in Finland, Figure 43. The heat-treatment process used by these companies is summarized in Table 34. Novawood is the first company to introduce the thermal modification technology "Thermowood" in Turkey. The plant is located in the Bolu Gerede Industrial Area. The Novawood plant produces 18,000 m³ of heat-treated timber and 600,000 m² of heat-treated finished goods annually.

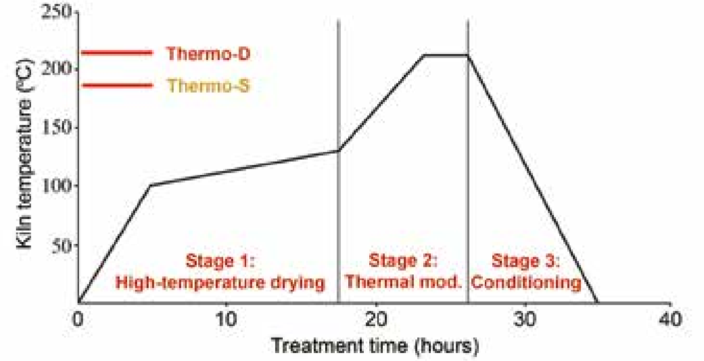

Figure 43: *The ThermoWood process*

The main range of ThermoWood products by Novawood include Exterior Cladding, Panel Cladding, Decking, Decking Tiles, novathermowood Door and Window Profiles, novathermowood Pergolas and Fences (URL 4).

Nas-thermowood plant is located in Muğla and produces about 5,500 m³ of thermal-modified timber. The softwoods of the Siberian and North European Taiga forests, hardwoods of the Black Sea Region and tropical trees of African and South Asian forests are used as source materials, Naswood pays attention to work with FSC certified suppliers of raw material. The main range of ThermoWood products by Naswood includes decking, flooring and siding (URL 5).

ARIN forest products plant is located in Düzce and produces about 4,200 m³ of heat-treated lumber. Pine species, ash, iroko and other tropical species are used. The main range of ThermoWood products by ARIN includes decking, flooring and siding (URL 6).

Table 34: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved in the process
ThermoWood	Novawood The producers websites; http://novawood.com	The Novawood plant produces 18,000 m³ of thermal modified timber and 600,000 m² of thermal modified finished goods annually.
ThermoWood	Naswood http://www.nasreddingroup.com	Naswood produces about 5,500 m³ of thermal modified timber.
ThermoWood	ARIN http://www.arin.com.tr	ARIN forest products plant produces about 4,200 m³ of thermal modified timber.

Figure 44 some examples of the uses of modified wood in Turkey.

Figure 44: *Examples of the use of modified wood: thermally modified wood decking (left), and thermally modified iroko wood cladding (right)*

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URL 4: http://novawood.com

URL 5: http://www.nasreddingroup.com

URL 6: http://www.arin.com.tr

Wood modification in Ukraine

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Introduction

Forest occupies 17% of the territory of Ukraine, being an important component of the Ukrainian economy. However, until recently, most of the timber was exported as a round timber. After the introduction of the moratorium on the export of round timber, the main wood product is sawn softwood, sleepers, billets for euro pallets and hardwood billets.

Furniture companies use mainly Ukrainian wood, but furniture made of natural wood is too expensive and it is much cheaper to purchase furniture from chipboard.

Disadvantages of traditionally used organic binders are hazardous working conditions for workers at wood-processing/woodwork and living conditions of building occupants experienced acute health problems because of emissions of hazardous substances, so-called "sick building syndrome" (SBS). One of such solutions to improve indoor air quality is to replace organic binders by inorganic ones and the use of the alkaline aluminosilicate binders of the system R_2O-Al_2O_3-SiO_2-H_2O is a highly advantageous solution due to simple manufacturing process and no need to preliminary treatment of wood.

The alkaline aluminosilicate binders of the following structural formula: R_2O-Al_2O_3-SiO_2-H_2O can be a vital alternative to traditionally used inorganic adhesives for the production of wood board materials. These binders are successfully used in anticorrosive and fire resistant coatings, decorative finishing materials, including wood-based materials. The increased rigidity of these binders did not allow to use the resulted wood-based materials in high humidity environment.

In order to remove this disadvantage the studies were held dedicated at optimization of the binder composition to produce health safety and ecologically friendly wood-based materials with required physico-technical characteristics.

As it follows from Table 35, internal bond of the particle board in which the alkaline aluminosilicate binder of the reference composition (without modifiers) (binder content 40% by mass) was 11.5 MPa, which did not meet the requirements of EN 312. Vinapass and Agocel make it possible to increase the internal bond of the particleboard to 14.5-14.8 MPa, which meets the requirements of EN 312 for particleboard of this thickness, for which the internal bond should be ≤ 14 MPa.

The formulated alkaline aluminosilicate binders were tested in pilot production of the adhesive-bonded plywood (Table 36). The plywood produced using the reference composition of the alkaline aluminosilicate binder (without additives) did not met the requirements of EN636 – 1 for plywood used in dry conditions. The addition of Vinapass slightly reduced internal bond to 68 MPa, tensile shear strength of the lap joint and modulus elasticity in bending, but increased water resistance of the plywood.

Table 35: Characteristics of the adhesive (alkaline aluminosilicate binder)-bonded particle boards (pressure – 3.0 N/mm²; pressing time– 10 min)

		Design of boards, % by mass		Characteristics of boards			
No.	Modifier	Binder	Wood chips	Thickness, mm	Density, kg/m³	Internal bond, MPa	Swelling in thickness, 24 h, %
1	Reference	40	60	10	809	11.5	30
2	Agocel	40	60	10	808	14.8	22
3	Vinnapas	45	55	10	815	16.1	19

Table 36: Characteristics of the adhesive (alkaline aluminosilicate binder)-bonded plywood (pressure – 1.65 N/mm², pressing time – 12 min)

			Characteristics of plywood				
No.	Modifier	Consumption of binder, g/m²	Thickness, mm	Tensile shear strength of lap joint, MPa	Internal bond, MPa	Modulus elasticity in bending, GPa	Immersion for 24 h in water
1	–	190	12	1.81	80.5	12.8	-
2	Vinnapas	190	12	2.73	68.2	10.7	+

Practical examples

Figure 45: Photos of the samples of the adhesive (alkaline aluminosilicate binder) bonded wood-based materials: particle boards and (left) plywood after testing for internal bond (right)

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Wood modification in United Kingdom

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Introduction

The concept of modified wood in the UK is one that has been considered for many years, with work undertaken by several groups, in particular Bangor University (Hill & Jones 1996 , Hill *et al*. 1998), The Building Research Establishment (Suttie *et al*. 1999, 2000), Imperial College and the Biocomposites Centre (Ormondroyd *et al*. 2015) as far back as the 1980s. Most of the work has focused on the lab scale development of treatments, usually with imported timbers (e.g. radiata pine) or with clear specimens (sapwood only) of selected UK species (e.g. Scots pine, Corsican pine, Sitka spruce, beech).

Modification technologies and production volumes

Whilst there have been laboratory and field study trials into modified wood for some time in the UK, the commercial development within the country has been very small. Instead, the UK depends on imported materials from the main commercial producers in Europe (e.g. Accoya, Kebony, ThermoWood). For thermally modified wood, it is estimated that the UK currently imports between 12,000 and 15,000 m³, whilst for Accoya the estimate volume is around 9,000 m³ and for Kebony it is approximately 600 m³. There are a variety of ongoing activities, as listed in Table 37, which either do not produce significant amounts of modified wood at present or are still in production.

Table 37: *Wood modification technologies, producers, companies and production volumes*

Wood modification technology	Producer, process short description and website	Annual volumes produced and companies involved
Thermal modification	Coed Cymru. Small scale ovens for treatment of regional timber supplies at temperatures lower than ThermoWood process	< 250 m³, typically for supply to joinery manufacturers
Thermal modification	Brimstone. Thermal modification of UK hardwood species such as ash and sycamore	Estimated at < 1000 m³ based on sales of distributors
Acetylation	Tricoya Ventures UK Limited (TVUK). Production due to start in 2019. Will involve the acetylation of wood chips for use in manufacture of Tricoya	30,000 tonnes of acetylated chips
Resin impregnation/ polymerisation	Lignia. Production starting in 2019. (www.lignia.com)	Expected to produce 15,000 m³ initially
Silicate treatment	Sioo:x. Whilst treatments are mainly provided for direct application, impregnation can be undertaken (in association with Russwood Timber). (www.sioox.org.uk)	Treatments to order through services provided by Russwood timber.

Of these, the most interesting is the development of an acetylation plant for wood chips by Tricoya Ventures UK Limited (TVUK) – a consortium comprising BP (British Petroleum), Accsys Technologies through its subsidiary Tricoya Technologies Limited (TTL) and Medite Europe at the BP site in Hull. Whilst this is still under development – with production due to start in 2019, the ground preparation for the plant has already begun. There are also initiatives with other countries – e.g. Sioo:x has a UK base, an expansion of the Swedish company. Other commercialised modification processes (e.g. ThermoWood, Kebony, Accoya) are imported directly into the UK for use.

Figure 46 show some examples of the uses of modified wood in the UK.

Figure 46: *Accoya cladding at Pipers High School London (left), and the joinery company Richard James in Northumberland, UK*

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