WCTE 2016
World Conference on
Timber Engineering
August 22-25, 2016 | Vienna, Austria

INTERDISCIPLINARY APPROACHES TO DEVELOPING WOOD MODIFICATION PROCESSES FOR SUSTAINABLE BUILDING AND BEYOND – INNORENEW COE

Michael David Burnard[1], Matthew John Schwarzkopf[2], Andreja Kutnar[3]

ABSTRACT: This publication provides a discussion on interdisciplinary research needs in wood modification and presents the research, development, and innovation plan of a new centre of excellence, "Renewable Materials and Healthy Environments Research and Innovation Centre of Excellence (InnoRenew CoE)", under development in Slovenia that will focus on restorative environmental and ergonomic design and wood modification.

KEYWORDS: wood modification, restorative environmental design, ergonomics, built environment

1 INTRODUCTION [123]

Wood modification is a critical area of research for the forest and construction sector as its purpose is to improve the resource efficiency and functionality of renewable resources for a variety of applications. Wood modification can ensure and improve performance, meet and exceed building and product sustainability requirements, and is a significant value-added process for the forest sector. Wood modification treatments include chemical, thermal, impregnation, and polymerization. These modification processes are at various stages of development, and there are many challenges that must be overcome to scale them up for industrial applications. Given that any additional processing will have associated environmental burdens, the environmental impacts of modification processes need to be balanced against benefits such as: service life extension, functionalisation, reduced maintenance, suitability for upcycling, reuse, material cascading, and final disposal with recovery of the intrinsic solar energy stored in the material. While fundamental research into wood modification processes and modified wood properties remains necessary, modification processes must target specific property changes to meet the demands of market ready products. This requires an interdisciplinary approach and innovation in the wood modification field.

In this paper wood modification is discussed while emphasizing further research needs that will be pursued at the new centre of excellence, "Renewable Materials and Healthy Environments Research and Innovation Centre of Excellence (InnoRenew CoE)".

2 WOOD MODIFICATION

Sandberg [1], delivers a systematic overview of wood modification treatments in a book covering present and future developments in wood additives. The resulting modified wood products range from impregnated wood with improved resistance against biological attack to improved fire performance. Acetylated wood, resulting from esterification of accessible hydroxyl groups in the cell wall, has been widely use on the market. Another commercialized wood modification process is furfurylation which involves impregnation of wood with furfuryl alcohol under pressure. The alcohol is then polymerized and reacted within the cell wall at elevated temperatures.

Thermal treatment processes have undergone considerable developments in recent decades. CEN [2] defines defines thermally modified timber as wood in which the composition of the cell wall material and its physical properties have been modified by exposure to a temperature higher than 160°C under conditions of low oxygen availability. Thermal treatment is wood

[1] Michael David Burnard, University of Primorska, michael.burnard@iam.upr.si

[2] Matthew John Schwarzkopf, University of Primorska, matthew.schwarzkopf@iam.upr.si

[3] Andreja Kutnar, University of Primorska, andreja.kutnar@upr.si

modification in a strict sense, because the material undergoes chemical changes. The process essentially involves a controlled degradation of the wood primarily resulting in the destruction of hemicelluloses. The thermal treatment process is in most cases performed in a vacuum or with an inert gas such as nitrogen. Preheated oil can also be used, in which case, the oil acts as a heat-transfer medium and also excludes oxygen from the wood. The underlying motivation for applying thermal treatments is the increasing demand for environmentally friendly high-durability wood. This process achieves this by increasing the service life of wood materials without the use of toxic chemicals. Kutnar et al. [3] provides an overview of recent developments of thermo-hydro-mechanical treated wood ranging from surface densification, compressed wood, and shaped wood.

Thermo-hydro-mechanical processing 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. These processes can be divided into two major categories; Thermo-Hydro treatments (TH) and Thermo-Hydro-Mechanical (THM) treatments. There are some differences between TH and THM treatments concerning what can be achieved during the process (Table 1). Some TH/THM processes include other materials such as adhesives or thermoplastics, but the shaping of the wood takes place by TH/THM action. Examples of such products are laminated veneer products, wood plastic composites (WPC), and various board materials. The main purpose of the adhesives or thermoplastics is to increase the bonding strength between the wood components and to prevent spring-back.

In Figure 1 a cross section of hybrid poplar that was densified with a THM process at 160°C under saturated steam environment is shown. The THM treatment causes deformations, which are largely the result of the viscous buckling of cell walls without any fracture taking place. The strength and stiffness of the wood material are therefore increased approximately in proportion to the increase in density [4]. The density profile of the THM wood varies with the degree of densification [5]. Different density profiles are the consequence of temperature and moisture gradients, and their relationship to the glass transition of the wood cell wall at the time the compression stress is applied. A density distribution is also visible on the cross-section of THM specimens. Lower and higher density layers can be distinguished by the different quantities of void areas across the thickness.

Table 1: *Results from the TH and THM processes [3].*

TH processes	**THM processes**
Dissipate internal stresses	Shaping wood • Moulding • Bending
Dry and soften the wood	Joining the wood • Self-bonding veneer • Wood welding
Improve wood properties • Shape/dimensional stability • Durability (biological)	Improve wood properties • Strength • Hardness • Abrasion resistance
Change properties • Colour	Change properties • Colour

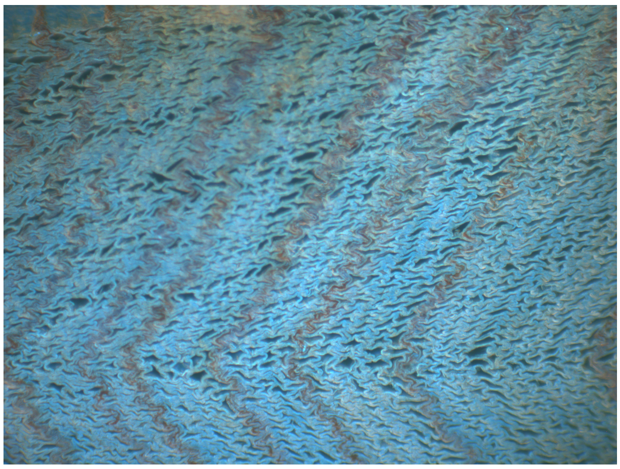

Figure 1: *Cross section of hybrid poplar densified with THM treatment at 160°C under a saturated steam environment.*

Surface densification can be especially advantageous in applications where it is desirable to maintain the low bulk density of wood, yet improve the surface properties [6]. In surface densification only the first few millimetres beneath the surface of the wood are compressed. In surface densification, a modified density profile is developed in the compressed wood. The density profile depends on factors such as the initial moisture content of the wood, fibre orientation, wood species, press temperature, and the press closing and holding time [7]. In Figure 2, a cross section of pine wood that was surface densified at 150°C is shown.

Figure 2: Cross section of surface densified pine wood.

TH and THM processes have been used for many years [8]. Familiarity with these processes, however, should not detract from the fact that they are very complex and demand a high degree of knowledge. Researchers from a variety of disciplines have currently been working to increase the knowledge of mechano-chemical transformations, optimize TH/THM processing parameters, and achieve better material properties of modified wood products. However, further research delivering better understanding of mechanisms taking place during the treatment is needed. Only with a focused research agenda will success be found in industrial scale up, process improvement, understanding material property enhancement in existing products, and the development of new products.

Sandberg and Kutnar [8] delivered state of the art developments in thermally modified timber and discussed the role of thermal wood processing as it relates to resource utilization and sustainability. They found that more research is needed in the field of thermally modified timber if it is to substantially contribute to the low-carbon economy.

To optimize wood modification processing and 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.). The review of Sandberg and Kutnar [8] clearly shows that such data are missing or at least are not documented in a systematic and transparent way. They concluded that research in the future should investigate and characterize the relationships among thermal modification processing, product properties, and the associated environmental impacts. This will require analysis of the entire value chain from the forest, through processing, installation, in-service use, end of life, second and third life (cascading), and ultimately incineration with energy recovery.

The standard Life Cycle Assessment (LCA) methodology is defined in ISO 14040 (ISO 1997) and ISO 14044 (ISO 2006). Since the 1980s, when LCA analysis was first developed, numerous methodologies to classify, characterize, and normalize environmental effects have been developed. The most common are focused on the following environmental impact indicators: acidification, eutrophication, ozone layer thinning, various types of ecotoxicity, air contaminants, resource usage and green-house gas emissions.

For a product, the life cycle starts with procuring the raw material, primary processing, secondary processing or manufacturing, packaging, shipping and handling, installation, in-use energy consumption, maintenance, and end-of-life strategies. LCA is performed for various stages of a products life. For example, cradle-to-gate refers to life cycle assessment from raw material stage to the point it is shipped from the manufacturer. Similarly, cradle-to-grave involves LCA of all stages of the product or the material, starting from raw material procurement to end-of-life strategies. For wood products, the life cycle generally starts with extraction of raw resources from the natural environment or recovery of materials from a previous use. The raw resources are then manufactured into useable products. The finished products are shipped to a site, consuming energy in the process. During the service life of the product, it may consume energy based on its use (e.g., energy used to maintain the product). Over time, renovations or retrofitting may be performed on the products, which may require additional materials and energy. Finally, the product is removed/demolished and its materials disposed of either as construction waste or recycled for reuse. Each of these steps consumes energy and materials and produces waste. The purpose of LCA is to quantify how a product or system affects the environment during each phase of its life. Examples of parameters that may be quantified include: energy consumption, resource use, greenhouse gas production, solid waste generation, and pollution generation. Another option is to perform LCA from cradle-to-cradle, which means that the analysis includes efficient product reuse, recycling and end-of-life scenarios.

Studies related to wood modification and LCA in the field of wood research have become more frequent over the last decades. Search results from the Scopus database of peer-reviewed scientific literature using keywords "wood modification", "wood", and "LCA" reveal a growing trend of publication quantities. In 1990 there were 17 articles published that were found with the keyword "wood modification", while in 2015 this number increased to 223. On the other hand, publications related to LCA and wood are still in the developing phase. The the first peer-reviewed article dates to 1992 (in the selected timeframe of the search). Until 2008, a slow increase in number of publications can be seen, while after 2008 a sharp increase in number of publications with keywords "LCA" and "wood" began. Increased involvement of LCA in scientific studies has been a result of requirements and guidelines for life cycle assessments becoming standardised in 2006 (ISO, 2016).

2.1 COST Action FP1407

The COST Action FP1407 "Understanding wood modification through an integrated scientific and environmental impact approach" was started in March 2015 and will continue through April 2019. This Action is characterizing the relationship between modification processing, product properties, and the associated environmental impacts. This includes the development and optimization of wood modification processing, quantifying the impacts of emerging treatment technologies, and identifying alternative materials to maximize sustainability and minimize environmental impacts. By focusing European-wide knowledge of these subjects, the Action provides the critical mass needed to achieve developments in wood modification processing, the integrated assessment of processing parameters, development of improved product properties, and environmental impacts.

The Action has members from 96 institutions (R&D and industry) coming from 24 European countries, 3 COST Near Neighbour Countries (Ukraine, Albania, and Tunisia), and 5 COST international partner countries (USA, Canada, New Zealand, South Africa, and Chile).

The specific objective of this Action is to advance research in the field of wood modification to allow significant contributions to the goals of European and global resource efficiency and a low carbon economy. This is being achieved by implementing excellent research in the area of wood modification, properties of modified wood, and environmental impacts. The interactive assessment of process parameters, product properties, and environmental impacts performed in this Action brings together the current knowledge, expertise, and infrastructure to achieve the Action’s objective.

The goals of sustainable development to increase economic efficiency, protect and restore ecological systems, and improve human well-being are expected to lead to new concepts, products, and processes optimizing the multiple utilization/recycling of forest-based resources. Life cycle analysis, industrial ecology, and cradle-to-cradle concepts are being developed as tools to be used in economic development, leading to new business opportunities involving innovative products with optimized physical properties and environmental impact properties. It must be emphasized that this work is also extended to unmodified timber products, since baseline comparisons have to be made. This greatly extends the range and impact of the Action beyond wood modification industries alone.

The Action FP1407 has four Working Groups (WG) that address the key areas of the Action:

Working group 1 - Wood Modification & Product Category Rules: Development of product category rules for modified wood based on the scientific and industrial state-of-the-art of commercialized and developing modified wood products and technologies.

Working group 2 - Environmental Impact Assessment & Life Cycle Assessments: Objective environmental impact assessments of commercial modification processes and incorporation of environmental impact assessments into wood modification processing and product development, including recycling and upgrading at the end of service life.

Working group 3 - Environmental Products Declarations: Development of environmental product declarations of modified wood and harmonization of various national EPDs in the field of wood modification.

Working group 4 - Communication & Knowledge Transfer: Dissemination, evaluation, and exploitation of the Action’s results together with establishing a strong network with the relevant industrial stakeholders.

Networking activities within COST Action FP1407 include scientific and administrative meetings, short-term scientific missions and organization of training schools and workshops. These activities help achieve the goals and objectives of the Action FP1407 by:

- Making connections, facilitating collaboration and building enduring, mutually beneficial inter and intra disciplinary relationships between individuals, institutions and companies;

- Creating transnational, innovative, and interdisciplinary excellence to enhance the research and innovation performance of the sector;

- Facilitating collaboration between industry, SMEs, stakeholder associations, research organizations, leading-edge scientists from a wider range of disciplines covering wood materials, chemistry, construction, biology, polymer science, environments, and other relevant fields who bring their broad expertise to this Action;

- Collaborative scientific excellence, interdisciplinary research, and development leading to innovative and higher-value uses of renewable materials for technical applications;

- Training and development for professionals as well as under- and post-graduate students in COST countries, where special emphasis is given to exchange knowledge, especially between COST countries that traditionally have high levels of participation to those who do not, like COST Inclusiveness countries and COST Near Neighboring countries.

These activities of COST Action FP1407 are enabled through Working Group meetings, Short Term Scientific Missions (STSMs), Interaction with and visits to innovative companies, Training Schools for Early Stage Researchers, International seminars, and Workshops. For example, in the first year of the Action FP1407 there were 13 STSMs dealing with wood modification, Life Cycle Assessment (LCA) of wood products, environmental products declarations, etc. Another example is the training school in LCA studies, which was held in Finland. Fifteen Early Career Investigators gained knowledge on how to perform LCA studies and most of them performed their first LCA calculations.

3 INNORENEW COE

The University of Primorska is coordinating a nine partner consortium dedicated to developing the new Renewable Materials and Healthy Environments Research and Innovation Centre of Excellence (InnoRenew CoE) using the Horizon 2020 Teaming grant instrument. The instrument supports and encourages the increase in innovation excellence throughout Europe, especially in member states categorized as underperforming in innovation. This is achieved by an underperforming country partnering with a leader in innovation, called an advanced partner. This partner serves as a mentor for the centre's development, and provides best practices and knowledge gained in the development of their organisation. The InnoRenew CoE advanced partner is the Fraunhofer Institute for Wood Research – Wilhelm-Klauditz-Institut (WKI) located in Braunschweig, Germany. The other consortium partners are all institutions from Slovenia: the University of Maribor, the Institute for the Protection of Cultural Heritage of Slovenia, the Slovenian National Building and Civil Engineering Institute, the Pulp and Paper Institute, EuroCloud Slovenia, the National Institute of Public Health, and the Regional Development Agency of the Ljubljana Urban Region. By design, this partnership brings together expertise from a wide variety of disciplines including health, information technology and computing, engineering, construction, urban development, cultural heritage, renewable material use and management, material science, and sustainability.

The key distinguishing technologies and activities of the InnoRenew CoE are the development of new wood modification treatments and optimization of existing treatments to create new, efficient materials and products for applications in buildings and products designed within the restorative environmental and ergonomic (REED) paradigm. The modification portion of this is focused on TH and THM treated wood. To move this area of research forward the CoE must deliver a better understanding of TH and THM processes. These specific modification methods were chosen because they have not received the directed institutional focus necessary to explore their scientific promise and overcome the challenges being faced in scaling-up exiting research findings elsewhere. The CoE must improve existing processes and enhance the understanding of modified wood properties, material properties, and new products.

Figure 3 illustrates how the CoE's research, development, and innovation plan relies on deeply interdependent research into sustainable building, renewable materials, ICT, and business support which are focused through the core research themes (Health, Design and Cultural Heritage, and Policy) to produce new, advanced knowledge related to REED and modified wood. Topical research activity groups like buildings and materials are placed on the left side of the illustration and their relative relationship with the InnoRenew COE's core research themes is indicated by the weight of their connecting arm. The health, design and cultural heritage, and policy core research themes are further focused through the lens of the REED paradigm and modified wood technologies.

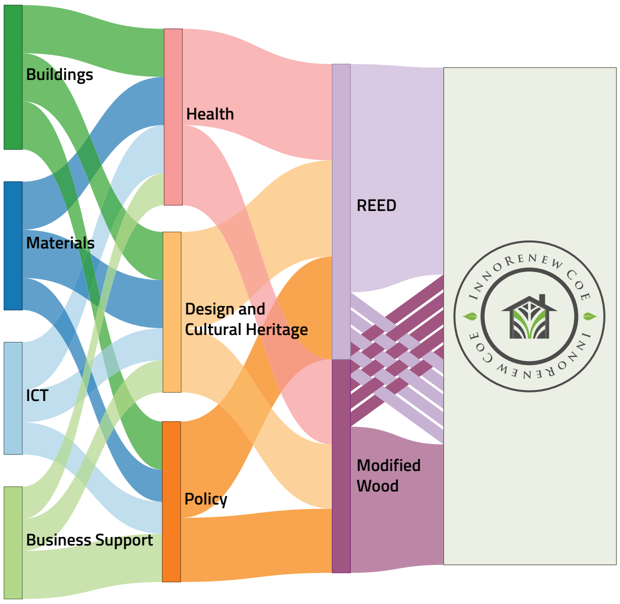

Figure 3: *Depiction of the interdependence between the main research areas of the CoE and how they will contribute to the overall development of the CoE.*

3.1 InnoRenew Living Lab

In order to develop a transparent, well-supported, and effective centre, the consortium has established a living laboratory, the Innovative Renewable Material Uses Living Laboratory (LL InnoRenew).

A living lab is an ecosystem for experimentation and co-creation with real users in real life environments. End users together with researchers, industrial firms, and public institutions jointly explore, design, and validate new and innovative products, services, solutions, and business models with the support and usage of ICT. It is a user-centered, open-innovation ecosystem often operating in a territorial context (e.g. city, region), integrating current research and systemic innovation processes within a public-private-people partnership.

The objective of the LL InnoRenew is to create an environment to discuss the InnoRenew CoE project, develop creative and innovative new ideas, provide critical feedback, and ensure stakeholder involvement in the development of the business plan of the new CoE. The LL InnoRenew incorporates a wide range of fields related to renewable materials (e.g. wood, hemp, grasses) including: construction, biology, chemistry, polymers, social sciences, cultural heritage, computing, mathematics, psychology, kinesiology, modelling, simulation, design, logistics, deployment, risk-assessment, decision making, and management.

Consortium partners of the InnoRenew CoE project are all members of the LL InnoRenew as well as 57 stakeholders from 16 countries. The LL InnoRenew has already met to participate in lively and engaging workshops focusing on understanding and innovation in the wood products sector.

4 RESTORATIVE ENVIRONMENTAL AND ERGONOMIC DESIGN (REED)

REED is a building design paradigm expanded from restorative environmental design (RED) and regenerative design to include aspects of ergonomics and kinesiology, as well as scientific support framework. The relationship between nature and the built environment are critically important to both RED and regenerative design (and, by extension, REED) [9,10,11]. Integrating nature into the built environment, through views of nature, by using natural materials (especially local materials), and by reflecting local ecology in building design and use, is thought to improve building user's perception of the natural environment and therefore motivate them to care for it (Figure 4) [10,11]. It is hoped that the long term effect of this exposure to nature, will be reduced environmental harm and eventually environmental regeneration [10,11]. Other research on integrating nature into the built environment has demonstrated positive human health impacts of building occupants, especially in terms of reduced stress, and improved recovery from it [9]. REED augments these concepts with integrated frameworks for improving occupant and user health, increased safety, and improved building management. This represents a shift in building design (and neighbourhood/community design) from minimising environmental harm towards creating positive impacts for the natural environment, building users, and society in general.

To achieve these goals an array of disciplines must come together to participate in a wide variety of research, development, and innovation activities as methods for creating the desired effects are not well understood. For example, design concepts such as biophilic design encourage bringing life, and life-like processes in to the built environment, but offer little scientific evidence to support the effect or identify the cause of any perceived effects [12]. However, studies into the restorative effects of nature have clearly identified significant increases in the ones' ability to recover from stress more effectively in natural environments as opposed to urban environments [13]. Restorative effects have also been identified in indoor environments with wooden elements [14]. To extend the current level of knowledge and research, the InnoRenew CoE and its partners will investigate these key areas of research to further develop REED:

- determining the psychophysiological and neurological mechanisms at play in restoration triggered by natural environments and materials
- determining how materials (visual recognition, haptic response, scent, etc.) – and which of their attributes (grain pattern, colour, texture, etc.) – trigger restorative effects
- functionalising renewable materials for enhanced effects such as heat and energy storage (e.g., developing phase change materials from renewable sources), air cleaning, etc.
- identifying and testing methodologies for including ergonomic interventions in buildings
- designing buildings for deconstruction to maximise the quantity of reclaimable and reusable materials
- identifying and testing methodologies for improving adaptability and safety measures in buildings (including fire safety, reduced toxicity in materials, accessibility, etc.)
- improved integration of ICT components into the built environment to monitor the health and behaviour of materials, to manage environmental controls, and improve the existing knowledge about building behaviour in use
- expanding application of REED principles from buildings to communities of buildings and cities.

Figure 4: *Sibilius Hall, Lahti, Finland. Natural, local materials, views of nature, and structural elements designed to imitate nature link building occupants to the natural environment.*

In addition to the extensive research tasks ahead in this area, several other challenges remain. Locality and place are critical aspects of both the restorative and social aspects of the REED paradigm (and others). Development of REED must consider these aspects and produce data and research outcomes that can be applied in many locations. Supporting designers in creating restorative environments by including aspects of the local ecology of the building in its design, will enhance acceptance and utilisation of REED. Using local materials is one way to achieve this, but material attributes need to be exposed in a way to elicit the greatest restorative effect.

Recent and ongoing research specific to REED being conducted in conjunction with the InnoRenew CoE project includes understanding and determining user perceptions of building material naturalness [15], perceptions of office environments related to the bio-based and natural materials present, and human stress response and recovery experiments in offices with different types of wood furniture. The study of building material naturalness revealed that both stone and solid wood materials were identified as being more natural than composite or synthetic materials. Similarly, materials that appear more heavily processed such as particleboards, despite being predominantly made from wood, were considered much less natural [15]. The connection between nature and the built environment is likely to be increased by utilising materials considered to be more natural such as solid wood (Figure 5), the study suggests.

Figure 5: Building material sample (Ash heartwood) used in the building material naturalness study [14].

There are many aspects of REED being researched and many fields of research that will inform REED. The scope of the research tasks ahead requires some alignment of research activities, and critical input from design and building practitioners, industry members, and users. All of these groups are present in the LL InnoRenew, and the network will expand as the project continues. Many other researchers currently investigate issues related to sustainable and healthy buildings, communities, and cities as well. Their collective and specific work is a strong contribution to the development of REED, which is intended to become a unifying factor to align and merge the research activities of scientists exploring this area of research.

5 CONCLUSIONS

The InnoRenew CoE partnership brings together expertise in a wide variety of disciplines including health, information technology and computing, engineering, construction, urban development, cultural heritage, renewable material use and management, material science, and sustainability. The emphasised renewable material is wood, its products and derivatives in all forms, ranging from solid timber and wood fibre to "green" chemicals and energy. The new institution was developed with the understanding that a new approach to research, development, and innovation that brings a wider array of expertise from different fields and places is necessary to reshape and revitalise the forest sector in Slovenia and elsewhere. To implement this change, the InnoRenew CoE will build upon the group's diverse expertise to bring Slovenia to the forefront of the European construction and renewable materials sectors by developing new, smart, sustainable, and modern built environments for all generations. The new InnoRenew CoE will pursue original research as well as provide research, development, and innovation support to the industry and undertake an extensive outreach project to promote the use of renewable materials in sustainable development.

ACKNOWLEDGEMENT

The authors acknowledge COST Action FP1407 and the support of WoodWisdom-Net and the Slovenian Ministry of Education, Science, and Sport of the Republic of Slovenia for their support of the What We Wood Believe and Cascading Recovered Wood projects; European Commission for funding the project InnoRenew CoE (#Grant Agreement 664331) under the Horizon2020 Widespread-2015 program, and infrastructure program IP-0035.

REFERENCES

[1] Sandberg D.: Additives in wood products – today and future development. In: Environmental Impacts of Traditional and Innovative Forest-based Bioproducts. Kutnar A., Muthu S.S. (Eds.). Springer Singapore: 105-172, 2016.

[2] CEN (2007) CEN/TS 15679, Thermal modified timber - Definitions and characteristics. European Community for Standardization (CEN), Brussels, Belgium

[3] Kutnar A., Sandberg D., Haller P.: Compressed and moulded wood from processing to products - A review. Holzforschung 69(7):885-897, 2015.

[4] Kutnar A., Kamke F.A., Sernek M.: The mechanical properties of densified VTC wood relevant for structural composites. Holz als Roh- und Werkstoff 66,6: 439–446, 2008.

[5] Kutnar A., Kamke F.A., Sernek M.: Density profile and morphology of viscoelastic thermal compressed wood. Wood Science and Technology 43,1: 57–68, 2009.

[6] Rautkari L., Properzi M., Pichelin F., Hughes M. Properties and set-recovery of surface densified Norway spruce and European beech. Wood Science and Technology, 44: 679–691, 2010.

[7] Rautkari L., Laine K., Laflin N., Hughes M. Surface modification of Scots pine: the effect of process parameters on the through thickness density profile. Journal of Material Science, 46:4780-4786, 2011.

[8] Sandberg D., Kutnar A.: Thermally modified timber: Recent developments in Europe and North America. Wood and Fiber Science, 48(SWST 2015 Convention Special Issue): 28-39, 2016.

[9] Burnard M.D., Kutnar A.: Wood and human stress in the built indoor environment: a review. Wood Science and Technology, 49(5): 969–986, 2015.

[10] Derr V., Kellert S.R.: Making children's environments ''R.E.D.'': restorative environmental design and its relationship to sustainable design. In: Pavlides E, Wells J (eds) Proceedings of the 44th