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Innovative Approaches to Increase Service Life of Poplar Lightweight Hardwood Construction Products

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Abstract. *During the second half of last century the forestry-wood chain has evolved and today ecosystem services in a sustainability framework are important. Forests are intended to provide services for the bio-economy, human health, biodiversity and climate control. An increased need for more renewable resources both for material and energy use has initiated extra interest for the potential to produce more lignocellulosic biomass, in short to increase wood production. One option is to provide in complementary production in planted forests. Both forestry and agriculture can take part in this. The cultivation of poplar hybrids in the temperate regions is a key option for the current and future bio-economy. These fast-growing trees are producing lightweight hardwood with a low natural durability, but with an important potential as construction material especially as engineered wood products. All wood protection methods are of interest to be evaluated for this wood resource, making it suitable even for high quality applications. Poplar, for many reasons, has been nominated as hardwood with the best potential to perform similarly as softwoods for applications in wood construction. Benchmarking with wood species like spruce is relevant for several engineered wood products like plywood, LVL and even CLT. Wood treatments to increase durability have evolved from traditional wood preservation towards modification techniques such as thermally modified timber. Innovative poplar based products have been assessed on their performance and are designed to fit for purpose in relation to a specific combination of use class and service life. Introducing innovative poplar based construction product for green building requires adequate testing tools. Performance based assessment should allow to integrate different protective measures. Related to moisture dynamics and the linked fungal decay risk, opportunities to extend service life are manifold. Treatment can be differentiated e.g. for cladding (building envelope) and loadbearing construction components. Simple or sophisticated modification processes can alter the equilibrium moisture content. The use of wood based panels and new engineered wood products allow for better moisture control impacting fungal decay risk, but also alter the probability of insect damage. This paper intends to present several innovative poplar based construction products and show some cases of benchmarking in relation to an integrated service life approach.*

Keywords: *Poplar, Engineered Wood Products, Wood Protection, Wood Modification.*

1 Introduction

In recent decades, the interest for building taller all-timber structures using engineered timber materials such as cross-laminated timber (CLT) has increased substantially, especially in the framework of sustainable use of resources and the positive carbon footprint of wood materials. The specific structure of CLT panels improves the dimensional stability, bending strength and other mechanical properties, thus enabling its use as load-bearing elements in various constructions. Especially in Europe, mainly spruce (*Picea abies*) is used for this purpose, while other wood species have been largely overlooked. Poplar, for example, is considered a potential species to be used in CLT as a substitute of spruce. Poplar is of interest as fast-growing tree species providing lightweight material. It is a majorly important tree species in planted forests and agroforestry worldwide.

However, since poplar in general has a very low natural durability, we need to acquire sufficient knowledge on its behavior when incorporated in CLT. Therefore there is a need to focus on moisture dynamics (Van Acker 2017), which are in direct relation to the fungal susceptibility and thus decay resistance and service life of the product. Hence investigations should deal with moisture sorption properties (including *e.g.*, equilibrium moisture content, fiber saturation point and thermodynamic analysis) of unmodified and modified poplar products, and test the fungal susceptibility as well, aiming at incorporation in CLT products.

2 Durability Challenges for CLT (Cross Laminated Timber)

Wood, as a renewable and environmentally friendly material, has been widely exploited and used in the construction industry. However, sawn wood, timber and lumber have limited dimensions related to the tree's dimensions. This can be overcome by producing engineered wood products and especially mass timber. In recent decades, the interest for building taller all-timber structures using such EWPs has increased substantially. Engineered wood, also called composite wood, man-made wood or manufactured board, includes a range of derivative wood products which are manufactured by binding or fixing the strands, particles, fibers, or veneers or boards of wood, together with adhesives, or other methods of fixation to form composite materials. Mass timber construction uses large prefabricated engineered wood members for wall, floor and roof construction that replace steel and reinforced concrete in many building projects. These products include for example glued-laminated timber (glulam or GLT), nail laminated timber (NLT) and cross-laminated timber (CLT). While GLT is considered a 1D element (bar/trusses), CLT is mainly used as 2D element (plate/slab) as shown in Figure 1.

Figure 1. GLT ('1D' elements at the left hand side) vs CLT('2D' element at the right hand side). (Canada Wood, 2018)

GLT exists since long and more recently also CLT has become popular. The production of CLT is about 0.8 million m³ worldwide, with 90% of the CLT production in Europe. An increase of 10% on an annual basis of CLT as a building product shows potential for not only softwood species, but also hardwood species. Within the next decade, therefore, CLT could become as important as glue-laminated timber, and it is likely to extend the limits of tall wooden buildings upwards. At present, most central European producers are using spruce (*Picea abies*) as main wood species in CLT. New studies began to focus on hybrid CLT, where the hybrid build-up can be designed as a rigid composite with small error on exact analysis. The novel investigations reveal the potential to overcome low rolling shear properties in cross layers of mixed softwood-hardwood (*e.g.* beech and spruce) CLT build-ups for structural elements in the building sector (Aicher *et al.* 2016). These approaches show potential to use also other species than spruce. New technologies such as CLT (cross laminated timber) have accelerated the construction of multi-story wooden buildings and weather protection during construction has not always been used but moisture safety remains important (Mjörnell and Olsson, 2019).

Although CLT is clearly an engineered wood products with great potential and by many considered adequate for high rise buildings in relation to mechanical and structural properties as well fire safety (Brandner *et al.* 2016, Barber 2018) the topic of sensitivity to wood rotting fungi might be underestimated. Several authors have already indicated that increased moisture in the framework of building physics, both condensation and leakage cannot be fully avoided and some preventive protection or monitoring might be required. Treatment options for mass timber products, particularly cross laminated timber (CLT) remain however to be addressed (Mankowski *et al.* 2018). Since wood species currently used to fabricate CLT are non-durable, and current design standards do not properly address incorporation of preservative treatments into these systems some experiments using a ground proximity test were proposed. Using mass timber such as CLT, but also GLT (glulam) and related engineered wood products require special attention when used in exterior applications (Morris 2015). Already some recommendations on feasible treatments of CLT have been compiled to increase awareness of decay risk and possible preventive measures (Wang *et al.* 2018). For tropical regions this could even be extra underpinned (Oliveira *et al.* 2018).

3 Assessing the Potential of Poplar

With the increasing demand of wood materials, plantations or planted forest consisting of fast-growing tree species increasingly contribute in providing a complementary wood resource and as such lower the pressure on natural forests. The cultivation of hybrid poplar is an eminent fast-growing species. As a fast-growing tree species in China (8.5 million ha) and Europe (close to 1 million ha), the major poplar hybrid plantations are now mainly focusing on plywood production. For traditional products like plywood, but also constructional timber, poplar or aspen are readily available. Aspen-OSB is an established product since decades in North-America. Specific strength and stiffness are interesting characteristics, but the ability to select quality trees with a major impact on production yield are an asset as well. Today researchers are reassessing the potential of solid timber products using poplar wood. Dimensional stability and biological durability are improved using modern wood modification methods besides traditional treatments. In this respect both glulam and CLT (cross laminated timber) show major potential eventually in combination with *e.g.* thermal modification.

In literature, it has been assessed that poplar and poplar products like plywood are considered non-durable (De Boever *et al.* 2008), thus protection can be necessary to comply with service life expectations in harsh environments (Zannutini *et al.* 2003; De Smet and Van Acker 2006; Van Acker 2008). When considering moisture dynamics some plywood products can perform quite well in outdoor conditions without ground contact (Van den Bulcke *et al.* 2011, Li *et al.* 2016). The potential of poplar is worth exploring. In some studies, poplar has been assessed as alternative for softwood to produce glulam, and combinations with other hardwoods are investigated. One study revealed that the beams composed using a specific eucalyptus clone, by its own or in combination with poplar, showed outstanding mechanical performance and the best structural efficiency. Additionally, the bonding quality, at the interface between the two species, proved to be excellent (Castro and Paganini 2003). Clearly, poplar is a promising wood species to obtain enhanced quality in very good products based on both thermal and chemical wood modification, as well as by several other treating processes used adequately (Fraanje 1998). As such wood protection and modification can increase the potential use of poplar and poplar products considerably. Some Garnica plywood products developed recently are good examples (Sufrategui *et al.* 2016) and prove that they can be used to produce building products in a fit-for-purpose concept.

4 Innovation and Treatments to Enhance Service Life

Plywood has been the model material to investigate the impact of moisture dynamics on service life prediction. Plywood outperforms in practical circumstances what can be expected from fungal testing (Van den Bulcke *et al.* 2011, De Windt *et al.* 2018). Although in many cases low durability wood species are used and the impact on fungal growth of the glue is only temporarily, many plywood products last quite long in outdoor out of ground contact applications. The fact that such wood products under use class 3 (EN 335) circumstances can exhibit limited moisture uptake in combination with ease to dry, is not yet fully considered as an extra resistance to decay. These moisture dynamics can be assessed as time of wetness (ToW) and simulated using exterior continuous moisture measurements (CMM) as well as soaking – drying lab methods as defined in the standard CEN/TS 16818 (Van Acker *et al.* 2017b). The service life approach combining performance in relation to end use based on biocidal components, structural properties and moisture dynamics allows anyhow to provide more info than the simple material resistance only based on natural durability as in EN 350. This will provide a tool towards better integration of wood protection in the forestry wood industry chain (Van Acker 2019).

Although poplar CLT based on a range of poplar hybrid timber resources is providing important parameters for design, a second focus is to select treatments with focus on low level biocidal treatments, and on low impact thermal and chemical modification that improves moisture dynamics up to levels suitable for overall or specific conditions in a timber construction based on poplar CLT. Such treatments need to be explicitly selected based on minimal requirements and can relate to less than perfect wood protection but fit for purpose (Van Acker *et al.* 2017a). Recently Singh *et al*. (2019) showed that untreated OSB and CLT based on radiate pine were very susceptible to decay, while LVL was less susceptible. Simple boron surface treatments are suggested as potential option to lower the risk for decay. Furthermore this research indicated that moisture sorption behavior is important for experimental work especially when products treated by selected protection or modification methods. Such experiments under different experimental conditions (by changing the temperature and relative humidity) allow to provide equilibrium moisture content (EMC) modeling based on statistical analysis linked to identified significant effects from the modification. Empirical models can be compared and selected to fit the data (Jiang 2019) providing moisture sorption isotherms (MSI). Based on these data hysteresis will be analyzed and a thermodynamic analysis will be carried out.

To face the durability performance, fit for purpose and environmental challenges, the concept of introducing innovative engineered wood products is to focus on lightweight poplar, being at one hand strategically important in European forestry, while at the other hand the technology can be transferred to other lightweight hardwoods, as well as softwoods. To achieve the performance requirements with increased cost-effectiveness, an integrated approach is applied combining wood modification (wood engineering), protection (preservation and coating) and fire resistance, the latter governing for many high-end building applications such as multi-story buildings. This leads into a specific new generation of products which are emerging: engineered and multi-level treated wood in the form of LVL, CLT, LSL and I-beam or I-joists made thereof.

Wood modification technologies like acetylation, furfurylation and different thermal modifications are intended anyhow to alter chemical and physical properties. When carried out to a sufficient level throughout the wood, these processes protect it from rot by making it "inedible" to most micro-organisms and fungi, without requiring biocides. It greatly reduces the wood's tendency to swell and shrink, making it less prone to cracking and ensuring that, when painted, it requires dramatically reduced maintenance. The innovation potential of engineered wood products from modified poplar wood is huge. TMT (thermally modified timber) poplar is already considered a SoA product. However it is always critical on lower mechanical strength, and therefore a load bearing application can be hard to achieve. Specific research on THM (thermo-hydro-mechanical) densification treatments on trembling aspen and hybrid poplar can alter some mechanical properties in a positive sense (Fang *et al.* 2019) and is considered an opportunity for future environmentally friendly wood products (Sandberg *et al.* 2013). This type of treatments are often considered of interest for low density hardwoods (Bao *et al.* 2017). Some treatments even do not focus on fungal decay resistance but are intended to improve delamination resistance (Han *et al.* 2017).

Contrary to thermal modification, chemical modification of poplar is not yet fully established. Treatability of poplar can be considered rather straightforward but still requires some technicalities due to difficult to impregnate transition zones. Chemical impregnation processes, *e.g.* with self-polymerizing and crosslinking agents can furthermore imply that the mechanical strength will be preserved (or even increased) and thus giving the innovative potential of creating renewable structural building materials from European poplar. Similarly, the use of low molecular resins can be applied on solid wood but is also valuable for *e.g.* stand based products like OSB (Wan and Kim 2004). Chemical modifications and in particular the curing step when resin treatments are applied, can lead to some embrittlement (Xie *et al.* 2013).

Building with poplar can be considered a forgotten reality that is picked up recently in an attempt to use lightweight hardwoods in construction (Kesteloot and Hudel 2016). Poplar CLT has been explored alongside GLT by several researchers (Kramer *et al.* 2014, Wang *et al.* 2014) and several companies in Europe have recently started producing this product at pilot scale. For poplar we can integrate all these trends by combining a fast growing wood resource from specific poplar cultivation, introducing this for construction and applying fit-for-purpose treatments to enhance material resistance. An example being explored in this context is poplar CLT, optionally thermally treated when decay could be a risk. Thermal treatment of poplar wood has been identified as having good potential (De Boever *et al.* 2016), being however only one of the options to increase service life under different use classes.

In Table 1 an overview is provided on how the service life of different engineered wood products could be increased. The different engineered wood products are subdivided in categories depending on the components constituting the product: strands, veneer and timber. For each category a wood based panel product as well as a beam like product is used as example.

The use of durable wood species is clearly related to the use of primarily heartwood which is often difficult to achieve in full. Vacuum pressure based wood preservation of the final product is often limited by the treatability. Glue-line additives are mainly useful when thin veneers or strands need to be protected. A third option related to wood preservation technology is spraying a diffusible component based product (*e.g.* borates) on the surface. Modification technologies might have some impact on mechanical properties and hence not fully adequate for loadbearing applications, but thermal modification for full panel products and chemical modification of strands prior to incorporation in a panel is potential technology. Finally resin treatments have similar or even better potential than glue-line additives and could also be applied as modification methods for timber based products. Applying coatings to control moisture dynamics is mainly useful for veneer and timber based products.

Table 1. Options to increase service life of Engineered Wood Products (EWP).

Component	EWP	Durable wood	Vacuum pressure[1]	Glue-line additive	Surface spray[2]	Thermal modification	Chemical modification	Resin[3]	Coatings
Strand	OSB	-	-	±	+	+	+	+	-
	LSL	-	-	±	±	-	-	+	-
Veneer	Plywood	+	+	+	+	+	±	+	+
	LVL	±	±	+	±	±	±	+	+
Timber	CLT	+	+	-	+	+	±	±	+
	GLT	+	+	-	±	±	±	±	+

Legend: +: existing option, ±: feasible option, -: less probable option

[1]: deep impregnation with biocides; [2]: surface biocide application with potential diffusion, *e.g.* borates, [3]: analogue to glue used for production or a hydrophobing agent; Abbreviations: EWP = engineered wood product; OSB = oriented strand board; LSL = laminated strand lumber; LVL = laminated veneer lumber; CLT = cross laminated timber; GLT = glue laminated timber or glulam.

5 Conclusions and Future Perspectives

The overall concept of introducing innovative engineered wood products based on fast growing plantation trees like hybrid poplars to achieve results, relate to the following objectives: (1) to link methodology (service life prediction) and product development (poplar EWP's – glulam & CLT; plywood & LVL; OSB and LSL); (2) to focus on European hardwood species; and (3) to integrate options for untreated and protected products through both biocidal and non-biocidal treatment. A holistic approach is needed to combine resistance to fungal decay, insect attack, fire, dimensional stability; in due consideration of different applications: construction (both loadbearing and not) from damp up to marine environments, interior and exterior applications (cladding, garden furniture,…), transport (caravans, containers, automotive,…) and their requirements in terms of time of wetness, aesthetics, weathering, maintenance, long-term mechanical properties (creep, mechano-sorptive behaviour, impact of treatment), as well as in terms of life cycle assessment and life cycle costing performance. All wood protection and modification methods are of interest to be evaluated for this plantation wood resource, making it suitable even for high quality applications. Poplar, for many reasons, has been nominated as hardwood with the best potential to perform similarly as softwoods for applications in wood construction. Benchmarking with wood species like spruce is relevant for several engineered wood products like plywood, LVL and even CLT. Wood treatments to increase durability have evolved from traditional wood preservation towards modification techniques such as thermally modified timber depending on the performance required or fit-for-purpose in relation to a specific combination of use class and service life.

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