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Review of new and emerging international wood modification technologies

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Review of new and emerging international wood modification technologies

Prepared for

Forest & Wood Products Australia

By

By Elizabeth Dunningham and Rosie Sargent

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Executive Summary

The specific objectives of this review were to:

- Summarise current technical literature on wood modification technologies, their likely future direction and market opportunities.
- Consider the fit of the modifications to the Australian Building Code.
- Deliver a webinar based on the review to mill managers and business analysts in Australia.

The intended outcome of this review was to rank commercial (and emerging) wood modification technologies with respect to their potential to positively impact timber constructions, and to identify the technologies that offer the greatest benefits and have the highest potential for application in the Australian context. Successful modified wood products to date have targeted high-value niche products, so this review also focusses on high value applications within the construction sector such as window and door joinery, flooring, specialist decking, cladding and interior fit-out.

Immediate opportunity

One technology is identified as having potential to provide high-value products for the built environment in the shorter term. This is **thermally modified wood** (such as ThermoWood®) utilising **Australian-grown radiata pine**. The main reason that this technology is considered the best option in the short term is its prior implementation in New Zealand and relatively low cost of implementation. This option would require investigation into:

- The **quality and continuity of supply** of the required timber resource (i.e. clear radiata sapwood).
- Distance to **suitable manufacturing operations** that could implement the technology and distance of Australian markets. Vertical integration of supply chain and manufacturing should also be considered here.
- **Price point and degree of competition** with other Australian and imported products. This would include the **level of market demand and fit of performance** to specific product requirements
- **Compliance with Building Code Australia** in each state, including **durability to H3 standard**.

Longer term opportunities

One longer term option is the application of **thermal modification to other Australian-grown plantation species**. Thermal modification of these species looks promising but requires further evaluation to determine the performance and scope for commercialisation of the modified timber. Another longer term option is thermal modification plus an additive to improve fire performance or termite resistance. **Technical investigations would be required** for these longer term options, as there is very little or no data available on Australian-grown wood species other than pine. For each species or additive investigated, this would include:

- Lab-scale thermal modifications to give performance data for different treatment intensities, or additive loadings.
- Pilot scale modification of processes showing promise at the lab scale to further refine processing conditions and to gather further property data.
- Feasibility studies, including data gathered on the lab and pilot scale would be required to confirm commercial viability.

Other modification technologies (Accoya® and HartHolz™) were evaluated as having potential for application into Australia. However it was deemed to be too early in their commercial cycles for the building of Australian-based production facilities. It would be worthwhile to reassess their potential once uncertainties around sustained market growth and plans around expansion of production facilities have reduced.

1.0 Introduction

The aim of this review is to identify wood modification technologies that show promise for commercialisation in Australia. Wood modification is an increasingly popular way to turn lower-value, sustainably grown wood species into high-value products. Wood modification technologies include processes that modify wood to gain property improvements, are non-toxic in use and non-biocidal in approach. Therefore traditional preservative wood treatments are excluded in this definition.

The scope covers a summary of wood modification technologies from technical literature and includes information on the commercialisation and current status of the commercial technologies. Aspects important to the successful implementation of wood modification technologies are also covered and include wood species, structure and the ability to process effectively, along with the quality of the local resource. While wood, both conventionally-treated and naturally durable, has been used effectively in buildings to date, wood modification seeks to respond to increasing consumer expectations for performance and sustainability, by lifting the performance of sustainably grown wood species which currently cannot compete with the properties and appearance of old-growth, or tropical hardwoods.

Wood is a renewable natural resource that has been used in a wide range of applications for millennia. For certain uses, the natural wood properties of many wood species do not give adequate performance and it is necessary to treat or modify wood. Over the years, a range of processes based on chemical, physical and heat treatments have been developed and applied to enhance material properties of wood, such as dimensional stability, stiffness, hardness and durability. Traditional wood preservation is based on chemicals toxic to wood-degrading microorganisms and insects, and has been widely used in the past to extend in-service durability of wood. More recently, the treatment of wood with suitable (sometimes more benign) chemicals can also enhance other desirable properties, such as dimensional stability, hardness and resistance to weathering (Hill 2006).

There has been a huge increase in research, and commercial wood modification operations in recent years. Key drivers for this include the uncertainty around supply and sustainability of naturally durable wood species, a desire to move away from traditional heavy-metal based preservatives to lower toxicity alternatives and the need to address dimensional instability of many plantation species. Many wood modification technologies offer protection in above-ground applications, improved dimensional stability so that coating performance is improved and distortion in-service reduced, and some also offer desirable darker colours for softwoods, similar to highly valued hardwoods.

When considering wood modification technologies, it is important to take account of how wood structure and chemistry can be effectively leveraged and manipulated during the modification process, and to consider what limits are presented by anatomical differences between wood species. The wood resource and species mix are considered as these are most important inputs into any modification process. These aspects are briefly considered at the start of this review.

Applying wood modification technologies to Australia

This review considers the different types of wood modification technologies in literature. Each main modification type (thermal modification, chemical reactions with wood, impregnation/polymerisation modifications) is considered separately, giving the changes each modification makes to the wood and the performance gained in general terms, some history of each, along with their applicability to different wood species. The focus is on the major modification technologies, particularly those that have become commercial, given that the overall objective is to rank modification technologies for application in Australia. A brief history and the current status of commercial wood modification technologies are summarised, along with any information on production volumes, plant capacities and costs where available. Finally, market segments and future opportunities are briefly considered for modification technologies generally.

The second half of the review is focused on the application and development of these modification technologies in Australia, in particular the prospect of building production facilities in Australia and applying the technologies to Australian-grown species. As modified wood products are targeted at high-value applications, the quality and consistency of the wood going into the process is of key importance. For radiata pine, this means a supply of pruned logs. For other pine species, and for plantation hardwoods, the supply of quality wood is unknown.

A key aspect to consider is the market opportunities for modified wood materials and products. Therefore market drivers, potential product segments, and consumer preferences are outlined, although hard data for Australia have been difficult to obtain. A range of advantages and disadvantages for wood modification production being located in Australia are covered, including environmental benefits, potential cultural issues, regulatory structures and other possible barriers to adoption. Modification options for application in the Australian context are then ranked, with the potential of these wood modification technologies for targeted research and development to improve the applicability to Australia.

2.0 Wood species, structure and processing

Trees are subdivided into conifers (softwoods), and broadleaved plants (hardwoods). Wood is composed of elongated fibre cells, which are oriented in the longitudinal direction (i.e. the grain direction) of the stem. They are connected with each other through openings, referred to as pits. These cells vary in their shape and according to their function, provide the necessary mechanical strength to support the crown and branches, and also perform the function of liquid transport as well as the storage of reserve food supplies. The xylem (or wood) is usually organised in concentric growth rings, consisting of alternate bands of dense thick-walled latewood cells, and thin-walled earlywood cells, although these can be indistinct or absent in some tropical and subtropical species. Wood also contains rays in horizontal files extending from the pith to the bark. This three dimensional structure means that wood is anisotropic - its properties vary relative to the grain direction and between different parts of the tree.

The inner part of a tree usually consists of dark-coloured heartwood, which is no longer used by the tree for sap transport, and an outer layer of lighter coloured sapwood which is used to transport water and nutrients from the roots of the tree to the foliage. Because of this difference in function, heartwood tends to be less permeable than sapwood, so does not take up water (or modification chemicals) as readily as sapwood. The innermost growth rings (corewood) of many trees tend to have a lower density, and lower strength compared to the rest of the tree, making the wood unsuitable for high-value applications.

As well as the obvious differences in the foliage of softwoods and hardwoods – softwoods have needles, and hardwoods have broad leaves, there are some notable differences between their timber structures. Softwoods are composed of two different cell types, tracheids (90-95% of the wood) and ray cells (5-10% of the wood). Tracheids make up the bulk of the wood 'grain' and give the wood mechanical strength and transport water up the tree. Ray cells provide water transport radially (from the pith to the bark) between tracheids. Hardwoods contain several cell types, specialised for different functions. Hardwood fibres provide strength and support for the tree, but unlike softwoods tracheids, do not provide water transport in the tree – this is provided by large tube-like cells called vessels, which run vertically through the stem. The distribution and number of vessels vary between tree species, which leads to very large differences in wood porosity. Hardwood species can be classified as being ring-porous, or diffuse-porous from the distribution of their vessels. Ring-porous species have vessels concentrated in bands in the earlywood, giving them very distinct growth rings. Diffuse-porous species have vessels distributed evenly throughout the wood, giving less distinct growth rings. Like softwoods, hardwoods also have ray cells, and these can comprise 5-30% of the wood volume, further leading to variations in wood behaviour between species (text adapted from Sjöström 1981). There are substantial differences in structure among hardwood species, whereas softwoods have more structural similarity. Such anatomical differences impact the suitability of different wood species for modification processes, especially modifications that involve impregnation.

During drying, some species of softwoods and hardwoods can be prone to collapse and checking, where the hollow earlywood tracheids collapse as a result of water tension, drastically reducing the wood dimensions in a localised area, leading to cracks (checking), or to collapse, where the earlywood shrinks across the entire thickness of the board to give a wavy 'washboard' surface.

For trees which produce large branches, pruning is required to give clear defect-free wood with consistent properties and a consistent appearance, as knots can produce a weak point in a board, or can sometimes fall out and create a hole. Some tree species are self-pruning, where branches tend to be small and are shed naturally from the lower section of the tree as it grows. These species can have numerous small knots which do not affect the board properties and are not considered to mar the appearance of the board.

Wood resource in Australia

Currently there are approximately 2 million ha of plantation forests in Australia (Pink 2012), with a 50:50 mix between softwoods and hardwoods. The softwood plantations are over 75% radiata pine (*Pinus radiata*), and the hardwood plantations are dominated by eucalypts (*Eucalyptus globulus:* 50%, *E. nitens:* 25%; Pink 2012). Softwood plantation area has remained relatively static over the last two decades at about 1M ha, with the hardwood plantation area growing rapidly over this same time span more than tripling in size. While the hardwood resource is still young, this increasing supply of plantation hardwoods represents an opportunity to lift value beyond log, veneer and pulp & paper applications.

The supply of eucalypt sawlogs is a small proportion of the overall hardwood supply, and this supply appears volatile, having grown in 2010-2012, but having declined since (Australian Government, 2012, 2014). It is not known whether this volatility is driven by a lack of supply of suitable sawlogs, or a lack of demand for sawn timber from common plantation species. The majority of the plantation forest is *E. globulus*, with a smaller volume of *E. nitens*. *Globulus* is considered the superior species and is used extensively for pulp and woodchip production, as well as very small quantities for sawn timber (Australian Bluegum Plantations; Wardlaw 2011). Despite having inferior pulping and sawing properties, nitens is grown widely in Tasmania and parts of Victoria due to its cold tolerance (Wardlaw 2011). Both species can produce acceptable quality timber, but present processing challenges, due to growth stresses and the propensity to check and collapse. Australian plantations have smaller volumes of other eucalypt species, primarily *E. saligna, E. dunnii, E. piluaris, E. cloeziana* and *Corymbia* species (Washusen 2013), as well as African mahogany (*Khaya senegalensis*). The volume of these species that are grown in plantations and used for sawn timber production is not known, but it is likely to be small. Some species are likely to have greater application to high value appearance products than others. For example, *saligna* and *piluaris* are less susceptible to checking and collapse during drying compared to *E. nitens* (Haslett 1986a,b), and are both considered desirable sawn timber species (McMahon et al 2010a,b). *Eucalyptus dunnii* is a desirable species for pulp and veneer (McMahon et al 2010c), so is not expected to have a large application to sawn timber.

The heartwood of eucalypts tends to not be treatable by pressure impregnation, so is unlikely to be suitable for chemical and impregnation modifications. Many eucalypts have sapwood that is considered to be moderately treatable (i.e. able to be impregnated with preservatives fairly evenly through the cross section) (Haslett 1986a, D. Page, Scion, personal communication, 24 April 2015), so these may have potential for chemical or impregnation modifications. Some eucalypt species (e.g. *E. saligna, Corymbia spp., E. pilularis*) are currently CCA treated for uses such as electricity transmission poles. Eucalypt species which have treatable sapwood, and produce sufficient sapwood to allow sapwood-only sawn timber (e.g. *E. nitens*) could be considered for chemical or impregnation modifications. Thermal modifications do not have the same requirements for wood permeability, so may be suitable for eucalyptus heartwood. Ongoing research at Scion indicates that within-ring checking and collapse are not exacerbated by thermal modification, so even for species such as nitens that are very collapse-prone, wood that has been dried without degrade could be thermally modified without any further collapse occurring.

Whilst the majority of Australia's softwood resource is radiata pine (*Pinus radiata*), a significant proportion (~25%, Australian Government 2012) consists of other pine species such as maritime pine (*P. pinaster*), hoop pine (*Araucaria cunninghamii*), and southern pines such as slash pine (*P. elliottii*) and its hybrids. These species all have sapwood that is able to be pressure impregnated, showing that they may be suitable for chemical and impregnation modifications. Some of these modifications have been successfully undertaken on Southern Yellow Pine (species unspecified). Slash pine is included in the Southern Yellow Pine (SYP) grouping, so is very likely to be suitable for these modifications. Slash pine has a high resin content, which may make it especially suitable for thermal modification, as this dramatically reduces the resin content of the wood.

Most modifications require long clear lengths of sapwood so use pruned logs from species such as radiata. This is both because of concerns about variation in wood properties around knots after modification, and because knots are considered a visual defect in appearance-grade radiata. For thermal modifications, there are indications that strength and stiffness losses may be disproportionately high around knots in radiata pine. Some modifications (such as ThemoWood and Kebony®) can use wood from self-pruning trees such as spruce, which have numerous small knots. Slash pine and hoop pine are similarly self-pruning, so may be suitable for modifications which currently use spruce. Like radiata, maritime pine is likely to need to be pruned to be suitable for modification. The radiata pine resource is mostly not pruned, so long clear lengths are in more limited supply (Mead 2013). This could be a constraint when looking to supply high quality wood feedstock to modification operations that require consistently good wood properties. There is increasing government support for the establishment of plantations to ensure the continuity of supply, but this will have more impact on wood supply in the longer term. An alternative strategy to avoid knots would be to use engineered products such as lamination or fingerjointing. The suitability of wood modifications for these engineered products is unknown. However, as most modified wood materials are able to be machined, and glued with particular classes of adhesives, it is likely that such processing options would be viable, but would require further research targeting high-value, niche applications for these engineered wood products.

As Australia only grows a small volume of Douglas fir, this species has not been given much consideration in this review. Douglas fir is already well utilised in structural applications, and is not able to be pressure treated, which makes it unsuitable for chemical and impregnation modifications. It should be possible to thermally modify Douglas fir to give improved stability (Li et al, 2011), and if it also had sufficient durability this could be used in applications such as decking, if there was a suitable market.

Australia also has large areas of native forests (147 m ha total) with a wide range of wood species, including eucalypts (700 native species, comprising 80% of all forests, Pink 2012), acacias (common name wattle, 1000 species, website 2015a), tea trees (*melaleuca*), she-oaks (*casurinas*), cypress pine (*callitris*), mangroves, and rainforests. Some of these species especially the eucalypts and acacias have been utilised in commercial wood processing operations, but increasingly access to this resource is becoming more restricted.

Therefore the feedstocks for possible future modification operations will be considered to be coming from plantation resources (both softwoods and hardwoods). The assumption has been made that local timber resources will be used for any Australian wood modification operation, although if supply is limited in the shorter term, importing high quality kiln-dried timber from New Zealand would probably be a viable option.

3.0 Wood modification technologies

For the purposes of this review, wood modification technologies have been defined as chemical, biological or physical processes that produce desired property improvements for the service life of the modified wood. The modified wood should be non-toxic and not release toxic substances during use, recycling or disposal. For durability, the mode of action should be non-biocidal (Hill 2006).

Due to the latter requirement, conventional wood preservatives are excluded from the wood modification definitions. However, traditional wood preservation treatments are starting to target improvements to other properties of the treated wood material such as colour and water repellency, in response to consumer demands and desires (as presented at the recent Wood Innovations conference, 2014). Therefore there is overlap in some of the product applications such as decking and cladding. There is also potential for some of these recent additives to be applied to modified wood to further enhance these properties, e.g. colour.

The rise of wood modification technologies both in research and commercially, indicate the strength of the environmental and sustainability drivers, as well as consumer desires for high performance and low maintenance products. Another factor is the legislation restrictions on some conventional preservative treatments such as CCA in Europe. Modified wood seeks to address a wider scope of performance than durability alone, with dimensional stability performance in service conditions a key focus.

This review considers how wood modification technologies could be produced in Australia and applied to Australian-grown wood species, addressing performance challenges such as fire and termites in addition to decay resistance and improved stability. The fit of such modifications with Australian codes, standards and regulations is briefly considered.

Three main types of modification; thermal modification, chemical reactions and impregnation/polymerisation modifications, have been considered separately due to the major differences between their modification approach, applicability to various species and the property gains achieved. Then examples of current global operation for each type of modification are covered.

There have been small commercial operations producing modified wood products for niche markets since the 1930s (Hill 2006). However, since the mid 1990s, there has been an increase in interest and development of commercial wood modification technologies. There have been commercial thermal modification operations in Finland, France, Austria and The Netherlands, up to 23 years, and this has been extending more recently throughout Europe (Hill 2006). Impregnation-based modifications such as acetylated wood are starting to take off commercially, with the current Accoya® production plant estimated to now be at capacity, after about ten years of operation. The Kebony® technology (furfurylation) in Norway started commercial production more recently in 2009.

The total volume of modified wood being produced globally is still very low (estimated around 190,000 m^3 pa, calculations given in Appendix 1) compared to worldwide volumes of conventionally treated wood. Therefore, wood modification technologies must be considered embryonic as a global industry, even after a decade or two of commercial operation. However, there is evidence (Mayes 2014, Pratt 2014) that in the last 2-3 years, consumer demand and subsequent sales are growing rapidly, with at least two modified wood materials (Accoya® and ThermoWood®) being exported widely in more significant volumes.

3.1 Thermally Modified Timber (TMT)

Thermal modification is a process where wood is heated to high temperatures (170°C and above) in the absence of oxygen to prevent the wood from catching fire. There are various processes to do this, most differ according to the way they exclude air/oxygen from the system (Navi & Sandberg 2012): a steam or nitrogen atmosphere can be used in the kiln, or the wood can be immersed in hot oil.

Thermal modification processes can be applied to a wide range of wood species, but need to be optimised for each species (Navi & Sandberg 2012). The property improvements gained are highly dependent on process conditions, treatment intensity (temperature, duration), wood species and thickness of samples. In general softwoods and hardwoods require different treatment parameters.

<u>Changes to the wood</u>
The thermal modification process breaks down the hemicelluloses (wood carbohydrates, (Hakkou et al 2006), which lose some of their hydroxyl (OH) groups so water is less able to attach to the wood. There is also a reduction of the chain lengths of the cellulose microfibrils (Militz, n.d.).

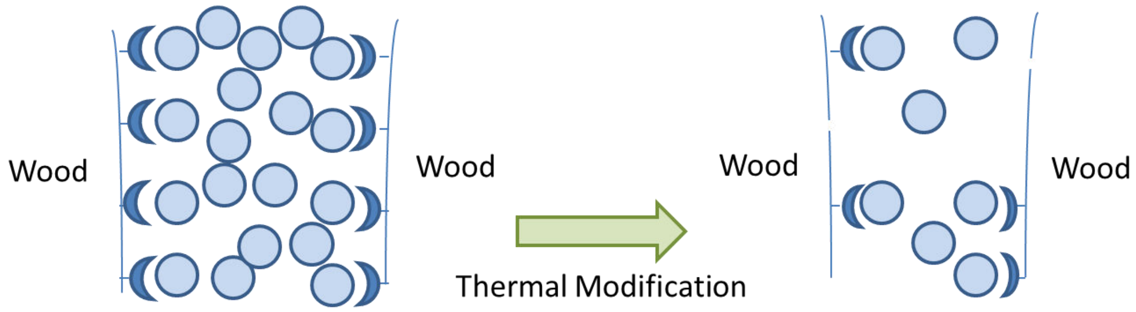

Figure 1: Changes of Wood OH and wood cell walls on thermal modification

Figure 1 is a simple representation of the wood material, with dark blue crescents representing OH groups that attract water and water is shown as the light blue circles that fill and bulk out the wood cell walls when it is green (never dried). When the wood is dried, much of this water is removed, so the wood shrinks. On thermal modification, OH groups in wood are reduced. With fewer OH groups to attract water, the moisture content of the wood is lower after modification and the wood is less responsive to moisture change, giving improved stability and durability (Christmas et al. 2005). This process also breaks down some of these hemicelluloses, so the wood becomes darker in colour, there is some mass loss (so density will be slightly lower), and there is some loss of strength and stiffness (Xie et al. 2013). All these effects increase with increasing thermal modification temperature, or with increasing duration of the thermal modification.

In general, thermal modification processes are relatively low-cost wood modification technologies as there are usually no chemicals added and they use similar processing facilities to existing wood processing operations (i.e. special high temperature drying kilns). Because thermal modifications use heat extensively, the cost of processing is highly dependent on the price of energy. Durability performance is highly dependent on the wood species and the level of thermal treatment (time, temperature, atmosphere), but most softwoods can be modified so they are suitable for above ground exterior applications in Northern Europe. However, decay hazards found in Northern Europe are likely to be less challenging than in temperate and tropical parts of Australia.

The small amount of literature available on the thermal modifications of eucalyptus species has targeted colour change and improved dimensional stability. The main eucalyptus species that have been investigated are *E. grandis* and *E. globulus,* although other eucalypts have been included in at least one article (e.g. *pellita, camaldulensis, urophylla, saligna* and *cloeziana*). Studies tend to focus on plantation-grown eucalypts, from plantations outside Australia. Esteves (2007) found that *E. grandis* could achieve similar stability improvements to Scots pine with a similar mass loss (a measure of thermal modification severity), but strength and stiffness were reduced more than in the Scots pine. Most studies concentrate on colour changes of eucalypts. Pincelli (2012) suggested that thermal modification of *E. saligna* could add value by giving the wood similar colours to tropical hardwoods. No studies on the durability of thermally modified eucalypts could be found. De Cademartori (2014) thermally modified the naturally durable *E. cloeziana* to improve the dimensional stability of fast-grown wood from Brazil.

Results for termite resistance are variable and appear to depend on the wood species, as well as the termite species. For example, thermally modified Grevillea gave good resistance to Kenyan *Macrotermes natalensis* (Mburu, et al., 2007), but thermally modified European Ash gave no improvement in resistance to Mediterranean *Reticulitermes banyulensis* (Oliver-Villanueva, et al., 2013). Thermally modified radiata pine is not expected to give any resistance to Australian termite species, so this area would need further Australian-specific research before considering commercialising TMT. While there is only limited data relating termite resistance to modification schedules, there appear to only be modest improvements from more severe modification schedules, so this is unlikely to be a path to improving termite resistance in non-resistant wood species.

Stability improvements are moderate (for example, 50% reduction in swelling with soaking in water). Adjustments in product design or resource selection (e.g. starting with a stiffer grade of timber) may need to be made for loading-bearing applications (e.g. decking) due to significant reduction in some mechanical properties.

Testing by the Finnish ThermoWood Association found that Scots pine TMT had the same fire resistance properties as unmodified pine. TMT was classed as European Fire Class D. The ThermoWood Handbook (Finnish ThermoWood Association, 2003) includes preliminary results suggesting that TMT treats more readily with traditional fire retardant chemicals that unmodified wood.

Current commercial TMT operations

Thermal modifications are the most common commercial modification operations globally, and, with the exception of Compreg (a densified wood product, produced in very small volumes since the 1940's), the most long-standing, having started commercial operations in the early 1990s (Hill 2006). The most common commercial TMT, ThermoWood®, started in Finland and is licenced from there via the International ThermoWood Association, with many operations throughout Europe and a growing number outside Europe. For example, over the ten years from 2003 to 2013, ThermoWood® global production grew nearly 6 fold, from 21,631 m^3 in 2003 to 127,791 m^3 in 2013 (ThermoWood Association, 2013). In 2003, 32% of the market area was in Finland, with the majority in the rest of Europe (61%). By 2013, Finland was in the small minority (7%), with the rest of Europe being dominant (76%) and a small but growing portion outside Europe (now 17%). These volumes might appear low, but wood modification technologies fit more in value-added niche segments, rather than in commodity products that have minimal processing. Overall 12 years of operation (2001 to 2013), there has been sales growth of at least 18% per year (Mayes 2014).

The ThermoWood® process uses a steam atmosphere during the high temperature phase. It is done in a specially designed high-temperature wood drying kiln, as an additional drying step. The Plato® process uses liquid water in the first heating step (thermolysis) under pressure, and then there is a drying step before a second heating stage (curing) before final conditioning (Militz & Tjeerdsma 2000). The oil-heat-treatment (OHT) process uses oil to exclude oxygen. The OHT process operates in Germany and uses linseed or rapeseed oil with green wood with several steps, resulting in a weight gain (50-70%) and a lingering smell (Esteves & Pereira 2009). For TMTs that use oil to exclude air, the oil can also have a role as a water repellent agent, and the weight gains can provide some advantages compared to the weight losses obtained from TMTs not using oil (Dubey et al 2011).The ThermoWood® process remains dominant especially in the European market (Navi & Sandberg 2012), even though there are many other heat treatments operating commercially or have been trademarked.

Regarding the size of ThermoWood® kilns, there is a range available to buy commercially (mostly produced in Finland). These range in size from small (10-25 m^3 capacity) kilns, with annual production of 2000-3000 m^3. There are medium sized (40-60 m^3) kilns, producing 5,000-10,000 m^3 annually, and larger kilns (100 m^3), producing 10,000-15,000 m^3 available. There is also a continuous process available which has the capacity of 30,000-50,000 m^3 pa (Hill 2006). Because of their similar design, it is considered likely that a ThermoWood® kiln will cost in the same range of that of a new HT drying kiln (approximately $1m installed).

There are two TMT kilns currently operating commercially in New Zealand, with more being planned. The smaller operation has a charge volume of about 3.4m^3, with an estimated maximum capacity of 900 m^3/year of wood. The main product being marketed currently is radiata pine beehive boxes, with prices offered for a ThermoWood® product of NZ$16.52 per box (large orders, excluding GST and freight) compared to a TanE KD product of NZ$18.31, and an untreated KD product of NZ$13.04 (Tunnicliffes, 2014, prices as of June 2014). The more recent larger operation has a kiln volume of 80 m^3, with an estimated annual production of 9000 m^3/year (Pan Pacific Forest Products, 2013). There is also a local kiln supplier (Windsor Engineering) who claims to produce a TMT kiln (Windsor Engineering Group, n.d.).

We are aware of several companies importing thermally modified wood into Australia and of one company who is producing TMT from Australian-grown hardwood species, but information on sales volumes could not be obtained from these companies. Information on current prices of thermally modified timber imported and sold in Australia are similarly hard to obtain. However, a price was found for a solar batten 42 x 42 mm cross-section from Scots pine (*P. sylvestris)* under the brand of LunaWood which sells for AUS$5.85 per piece (length unspecified, excluding shipping and tax), (Wright Forest Products, n.d.). Hurford Hardwood in NSW (Hurford Hardwood, n.d.) import thermally modified American hardwoods and have recently purchased a TMT kiln from Mahild and are modifying Australian grown hardwoods (species unknown).

Key applications in Europe have been cladding, decking and window joinery (ThermoWood Association 2003). The darker colour obtained from TMT is usually considered an advantage as this mimics some tropical hardwoods that are desired in the market. However, during weathering outdoors, this darker colour does change over time to the typical grey colour due to weathering. ThermoWood can be discoloured by surface mould growth, but it is likely to be less susceptible to mould than unmodified wood (Frühwald, et al., 2008).

ThermoWood® has schedules for softwoods and hardwoods which can be tailored for stability or durability improvements. In general, softwoods tend to achieve greater property improvements than hardwoods (Finnish ThermoWood Association, 2003). ThermoWood® has been applied at least 9 species commercially and these include (Navi & Sandberg 2012):

- Pine (*Pinus sylvestris* L., *P. radiata* D.Don)
- Spruce (*Picea abies* (L.) Karst)
- Birch (*Betula pendula* L.)
- Aspen (*Populus tremula* L.)
- Ash (*Fraxinum excelsior* L.)
- Larch (*Larix sibirica* Ledeb.)
- Alder (*Alnus glutinosa* (L.) Gaertn.)
- Beech (*Fagus silvativa*)

Additionally, Southern Yellow Pine is thermally modified using a similar TMT process, as ‘EcoPrem’ in North America. Margin: Mininco have a thermal modification kiln in Mulchen, Chile which modifies *E. nitens*. They have done a lot of development work to reduce degrade during drying and modification. There has been a suggestion that another operation (VAP HolzSysteme®) which has been widely researched in Brazil (Calonego et al., 2012, de Moura et al., 2012) has been commercialised, but we have been unable to independently confirm this.

Platowood® has been produced in the Netherlands since 2000, according to its sales document on the website (Platowood, 2014a). It is difficult to get current production statistics, but Hill (2006) notes that at that time (circa 2005), Platowood® had one production facility in Arnhem, The Netherlands, with the capacity of dealing with 35,000 m^3 of wood per year, but was only producing 12,000 m^3 pa at that time. Hill (2006) notes that the production costs were about €150/m^3, with operational costs of €20/m^3 (2005 figures & values). A large commercial plant with an annual capacity of 75,000 m^3 would require a capital investment of approximately €10-15M. The Platowood® website focuses mainly on cladding applications but no prices are listed, although it is possible to order a sample or obtain a quote for the wood supply for a project (Platowood, 2014b). More recently, it was noted that companies in Portugal are importing Platowood® for use as decking and other exterior applications (Esteves et al 2014).

Competing products for thermally modified timber will come primarily from conventionally treated wood products and naturally durable timbers, as well as non-wood materials such as cementboard, plastic, brick, metal-based and concrete products in exterior applications such as cladding and decking.

<u>TMT with additives</u>

In research studies, there has been a recent trend of including various additives in combination with TMT, to further extend performance. For example, wood preservatives or biocides and water repellents have been investigated (Ahmed & Morén 2012; Salman, et al., 2014). Adding boron compounds, as in Salman et al, (2014) have the potential to improve both the termite resistance and fire performance of TMT, which would be of particular interest to some Australian markets. However, these boron-based compounds need to be fixed in the wood, and this can be challenging.

Stora Enso has launched a commercial TMT product, Q-Treat®, which is impregnated with sodium silicate prior to mild ThermoWood® modification (wood temperatures up to 170°C). This is claimed to have improved hardness with slightly improved fire performance (Stora Enso, n.d.). Despite these modification temperatures being within the capabilities of many existing high temperature kilns, it is likely that using such chemicals with a thermal modification would require a specially made TM kiln due to incompatibility of the sodium silicate with aluminium used in conventional kiln construction.

<u>Other heat treatments</u>

There are other heat treatments that include compression, making them thermo-hygro-mechanical modifications (THMs). The combination of heat, moisture and mechanical compression (with or without the addition of resins or other chemicals to fix the compression) use the plasticisation that occurs in wood at higher temperatures with sufficient water present to deform the wood structures but avoid damage. This approach has been well known for many decades with many research studies (Inoue et al 1993, Dwianto et al 1999, Navi & Girardet 2000) and commercial applications, with an early "Compreg" operation producing compressed wooden propeller blades for planes (impregnated with resin to fix the compression) during WWII (Rowell 1999). There are still small commercial operations that supply Compreg wood, mostly for electrical boards.

3.2 Chemical reactions with wood

Chemical reactions with wood involve the reaction of chemical groups on the wood polymers with the modification agent, such that new groups are formed and bonded directly to the wood polymers themselves. In the most part, these have focused on the reaction of the wood hydroxyl groups (Hill 2006), primarily on lignin and hemicelluloses in the cell wall, as these groups are involved in many of the undesirable behaviours of wood (decay, weathering, swelling on uptake of moisture) and are the most accessible to reaction agents. While cellulose in wood is also involved in aspects of wood behaviour such as strength, cellulose microfibrils are not very accessible to treatment chemicals mainly due to strong hydrogen bonding, and so have low reactivity to these treatment agents.

A wide range of chemical reactions of wood have been researched with the view to improving key properties. With the exception of acetylation, these reactions are unlikely to be suitable for commercial operation due to potentially toxic reagents, the need for solvents, limited or temporary property improvements, and/or the high cost of the reagent itself (Hill 2006). The range of reagents investigated include: other anhydrides (cyclic and non-cyclic), carboxylic acids, acid chlorides, isocyanates, epoxides, alkyl halides, aldehydes, acrylonitriles and others (Hill 2006, Rowell 1983). For these reasons, the following will only cover the acetylation process.

<u>Changes to the wood</u>
The acetylation reaction of wood is one of the most extensively studied chemical reactions, with many studies completed on a wide range of wood and plant species since the 1920s (Hill 2006; Rowell 1983). Acetylation involves the reaction of the wood hydroxyls (OH, blue crescents in Figure 2) with acetic anhydride. Once the wood is dried, acetylation replaces the OH groups with acetyl groups (-O-CH_3, orange triangles) that bulk out the space in the cell wall to near-green volume (at 20-25% weight gain). The reaction requires elevated temperature (100-140^{o}C) and some hours of time if no catalyst is used. While the chemistry of the modified wood is fundamentally changed, the main reason for the property improvements is the bulking of the cell wall (Hill and Jones 1996) with very little swelling and shrinkage occurring on water uptake/loss, and it appears that fungal enzymes are no longer able to recognise the wood as a food source (Rowell et al 2009). Tests with Japanese termites (*Reticulitermes speratus*) and Formosan subterranean termites (*Coptotermes formosanus*) found that they were able to chew the acetylated wood but will prefer untreated wood source as food, and ultimately starve to death if only offered acetylated wood, although mortality rates were higher than if no food source is offered (Hill 2006). Weight losses due to termite attack declined significantly in

many studies, but the results have been more mixed on marine borer tests (Hill 2006).

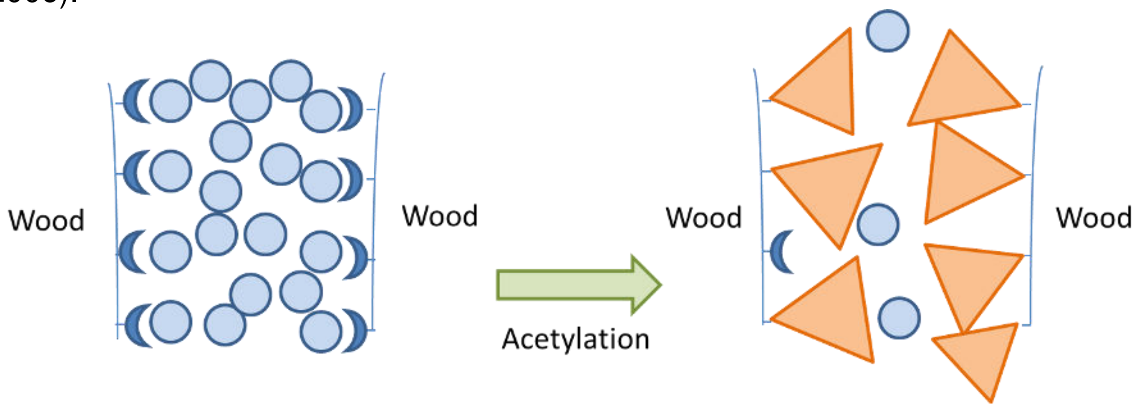

Figure 2: Changes of Wood OH and wood cell walls on acetylation (not to scale)

Acetylation of the wood to 25% weight gain gives very significant improvements in both dimensional stability and durability. For example, the commercial material Accoya®, has >75% reduction in swelling on water soak tests and long term in-ground protection (H4), equivalent to CCA treatments (Accoya, n.d. 1). There is also a fibre-based commercial product offered, Tricoya^{TM}, which can be used in outdoor applications.

As mentioned, there has been a wide range of wood and woody plant material (hemp, flax, bamboo) acetylated via a range of laboratory treatment methods over the last 50 years and more, with some species more easily able to achieve high loadings than others (Hill 2006). Radiata pine (*Pinus radiata*) is the major commercialised species globally due to its ease of treatment and the ability to have wood supplied in long clear lengths (from some New Zealand suppliers). Acetylation requires specific wood properties (permeability) to modify evenly throughout the sample, so will not work with some wood species. However, Perennial Wood in North America was producing acetylated Southern Yellow Pine, and the Accoya® website mentions a trial of a covered porch made of SYP. Accoya® are also developing a product using North American Alder, so there could be scope to use the Accoya® platform on other Australian plantation species, providing they have suitable properties. Some exploratory research acetylating a highly coloured NZ species (rimu) indicated that, while moderate uptakes were achieved in veneer, the colour was significantly degraded (E.A. Dunningham, Scion, personal communication, April 2015). Many wood species also require much longer reaction times or the use of catalysts to obtain sufficiently high uptakes for good property gains. For example Hill & Jones (1996) showed WPGs of up to 35% with Corsican pine when using a pyridine catalyst, in contrast to the maximum of 15% Ozmen (2007) obtained for poplar, willow and eucalypt (camaldulensis) – who also used the catalysed method with pyridine.

Acetylation does not alter the fire-resistance of the wood (Morozovs, et al., 2009). The colour of acetylation material is not much changed from untreated material, but in outdoor applications, mould and stain fungi change the colour of the wood surface to the typical grey weathered look (Wakeling 1991; Hill 2006, Gobakken & Westin 2008).

The combination of high performance in both stability and durability of acetylated wood has allowed extreme applications in demanding environments. One example is an exterior dance floor 16 m in diameter in Denmark that required very low tolerances, with little movement with water uptake/loss (1 mm, 0.5% of board width) and good elastic behaviour (Lankveld et al. 2014). Another example is canal lining in the Netherlands which would have otherwise used tropical hardwoods (Accoya, n.d. 2). Other speciality applications are structural and architectural items, and kitchenware. Acetylated wood is also used in more traditional applications such as window and other exterior joinery, commercial decking and board walks. Therefore the main competing wood products are from high-performing (and high priced) hardwoods.

The acetylation process is a relatively expensive one, as it requires the wood to have a low moisture content (<6%) and the modification plant must be specially built with high quality stainless steel, in addition to the cost of the modification chemicals. Therefore there is a significant investment in capital for commercial-scale acetylation plants, as well as the high operational costs which therefore require high performance applications to match cost/benefit. Various sources put the relative cost of acetylation between 2.5 and 3.5 times that of untreated wood (Tullo, 2012), but the fully installed costs are expected to be even higher due to the high specifications for fasteners and coatings required. The current Accoya® plant is estimated to be at capacity and plans are in place to build a second plant. This shows that there is a growing market for Accoya® material in a range of applications. Therefore customers must believe that the benefits of using Accoya® material (lower maintenance cycle, low toxicity and increased stability) are outweighed the sharp increase in cost,

The wood itself needs to be high quality sapwood, without heartwood (Hill 2006) or many defects such as knots, compression wood or spiral grain, otherwise uptake can be uneven through a sample, leading to distortion in the final treated product.

Commercial acetylation operations

There have been a number of attempts to commercialise acetylation over the decades, with attempts in USA, the former USSR, Japan and UK (Hill 2006). However, the cost always overcame the benefit until the regulatory and economic climates changed in Europe. A more recent example is Eastman's Perennial Wood which was launched in 2012 at a trade show but had closed its only production plant (pilot scale) in March 2014. This was a strategic decision based on the lack of economic sustainability of the small demonstration plant and the lack of market uptake of their product lines, mostly decking, outdoor furniture and outdoor porches (Wormer 2014). A bigger plant was deemed necessary to improved efficiency but sales did not support further expansion.

Titan Wood was formed in 2003 by Accys Chemicals PLC, a company based in the UK, and their acetylated wood is branded Accoya®. They acquired a pilot plant with a reactor capacity of 2.3 m^3 (0.83 m diameter, 4 m long) which was capable of acetylating 0.9 m^3 per charge (Hill 2006). In 2005, a full scale acetylation plant was built in Arnhem, The Netherlands which is now capable of producing 35,000 m^3/year of acetylated solid wood (costing an estimated €20-30M). In 2011, it was reported that they were producing around 12,000 m^3, and this has increased significantly over the last few years (Pratt 2014), so that it is estimated that by mid-2014 production volume (as measured by sales growth, Pratt 2014) had doubled from 2011 figures to over 31,000 m^3/year. With the reported increases continuing in sales volumes, it appears that this first commercial plant is near capacity. Accoya's main marketing strategy includes promotion for exterior applications in four main areas: window frames, doors and shutters; siding and facades; decking; and outdoor furniture and equipment (Accoya, n.d. 2).

In 2012, Accys Technologies PLC announced a licence agreement with Solvay Rhodia for the "production and sale of Accoya across Europe" (Accoya, 2012). This licence grants Solvay Rhodia "the exclusive rights for a 15 year period for Rhodia to produce and sell Accoya to over 40 European countries except the UK, Ireland and Benelux [Belgium, the Netherlands, Luxemburg]. The agreement also allows the construction of multiple Accoya production plants in various locations over a period of 25 years."

The first full-scale production plant under this agreement is still in planning process, despite the initial aim of having it operational by end 2014. It has recently been confirmed that Solvay will build a larger plant (63,000 m^3/year) in Germany and plan to have it operational by mid 2016 (Solvay 2014). It is also believed that Accys Technologies are scouting options for building production plants outside Europe.

Accoya® list three Australian distributors that are importing a range of products into Australia currently (Accoya, n.d. 3). These were Agora Timbers, Britton Timbers Australia and Mathews Timbers. However, it was not possible to obtain prices for any of these.

3.3 Impregnation /Polymerisation modifications

These are processes where small modification agents (i.e. monomers) are impregnated using standard vacuum-pressure cycles into the kiln-dried wood, then the monomers are polymerised together (usually with themselves only) to form the polymers *in situ*, around and in the wood itself. There are a wide range of impregnation/polymerisation modifications both in the market and as the focus of research studies (Hill 2006).

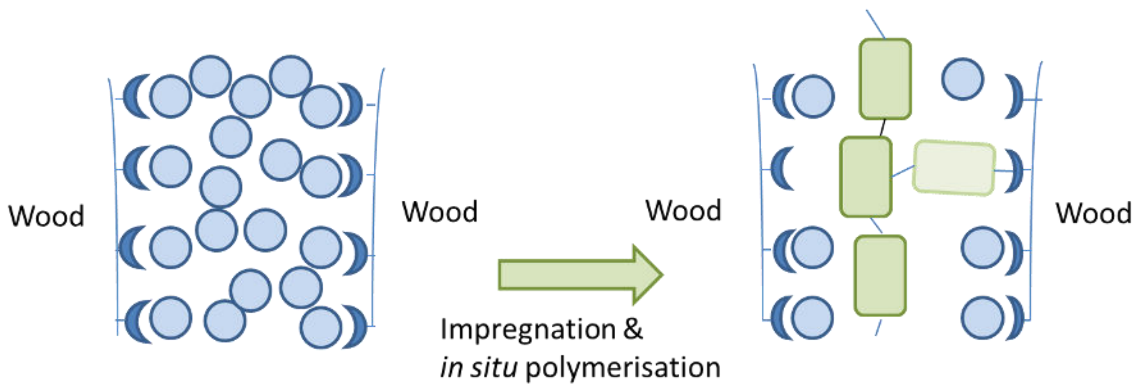

Figure 3: Formation of polymers within cell wall

Changes in the wood

Figure 3 shows a picture of how the monomers (dark green oblongs) link to form the polymer chains in the wood cell wall. Some polymers are able to form bonds with the wood polymers, called cross-linking (light green oblongs in Figure 3), and this fixes the polymers to the wood, thus improving leach resistance.

Depending on polymer loading, this type of modification also bulks the cell wall, taking up much of the space held by water in the green wood, meaning the cell wall does not shrink when the wood dries. Some of the monomers do not diffuse into the cell wall but remain in the lumen (the open space in the centre of the hollow wood fibres), especially at higher loadings when the cell wall spaces are full. Polymer formation in the lumen provides reinforcement of the wood material which is thought to contribute to the improved mechanical properties. For the success of these modifications, suitable wood species need to be amenable to impregnation throughout the wood structure. This will exclude many hardwood species and the heartwood of many softwood species.

One example of an impregnation modification is the furfurylation reaction achieved by impregnating the monomer, furfuryl alcohol (FA), into dry wood along with a cross-linker and other additives. This modification also requires heat to start the curing or polymerisation reaction. It is thought that most of the FA monomers react with themselves to form a chain within the cell wall spaces. It is possible that a branch from the polymer chain forms a connection to the wood polymers via the wood lignin hydroxyls (Thygesen et al. 2010).

The properties achieved with furfurylation depend on the loading, as it is possible to target a wide range of loadings (Lande et al 2004). At the low end, a loading of <20% weight gain would provide some improvement in dimensional stability (20-30%), and small improvements in stiffness also. Higher loadings (30-50%) give moderate improvements in stability and stiffness (60-70% gains) with a small to moderate gain in hardness (15-30%). At very high loadings (>100%), extremely high performance of hardness (100% improved) and stability (75% improved) is achieved. However, dynamic strength properties are reduced with furfurylation (Brischke et al 2012). Durability is greatly improved with outdoor mini-stake tests performing similarly to CCA treated to the equivalent of HCA4 (fresh-water contact, similar to our H5) (Lande et al 2004).

It appears that furfurylation provides improved resistance to termite attack above an uptake of around 30% (Lande 20004, Hadi 2005). However one study showed good performance before leaching in water but poor performance with Mediterranean termites after leaching the wood (Gascon-Garrido 2013).

Current commercial impregnation/polymerisation operations

The furfurylation modification has been commercialised under the Kebony® brand, and they primarily use Scots pine (*P. sylvestris*), although it is possible to order a limited range of other wood species – radiata pine, maple and Southern Yellow Pine (Kebony, n.d. 1).

Kebony® is a relative new-comer in the commercial space, with full-scale production starting in Norway in 2009 (Kebony, n.d. 2, Lande and Brynildsen 2014). It is estimated that this first full-scale plant cost €8-14M, which would have been specially designed and built for the furfurylation process. They now have subsidiaries also in Denmark and Sweden (2013), with sales reps in Germany, France, UK and the US (2014), with a global distribution network, according to its website (Kebony, n.d. 2). Currently a second production facility is being planned for 2015. As of last year (2014), Kebony® was sold into 22 countries, and has estimated sales volumes of about 12,000 m^3/year. Orders can be placed, with a batch of Kebony® radiata decking (22 x 145 x 1200 mm) costing in the vicinity of NZ$7500/$m^3$ retail (2014, 0.252 m^3 order size, including tax, excluding freight).

Applications of Kebony® range from decking and cladding to the more specialised marine applications and kitchenware (Lande et al 2014). Furfurylation is also a relatively expensive modification in comparison to TMT, mainly due to the cost of the modification chemicals.

There are a wide range of other small commercial impregnation/polymerisation operations globally, with many conventional wood treatment suppliers offering such an option. However, production volumes of these operations are very difficult to source as this information is often considered commercially sensitive. One can only assume the volumes produces are extremely low.

An example of a longstanding, but small operation is Lignia™ of Fibre7. This technology was started indirectly via Scion's Indurite development, and illustrates the timeframes often involved in taking a concept from the research lab to a commercial operation. An approach was made to Scion (formerly FRI) by the New Zealand Furniture Manufacturers Federation who were wanting a solution for radiata pine wood to improve its use in furniture applications. Research was conducted from 1985 to 1988, when a new chemistry strategy for wood modification was devised (Franich 2007). Patents were granted for the process (Franich & Anderson 1998), and the Indurite™ technology started the commercialisation process. The technology changed hands a number of times from 1994, and finally in 2004 to Fibre7 who then developed a similar technology independently to the original Indurite formulation (currently owned by Osmose UK). Fibre7 have production facilities in Tauranga, New Zealand and currently global sales continue to be small. These dates give an indication of the timeframes such technologies often require from research idea and development (1985 to 1988) to start of commercialisation (1994), patent filing (1998) to launch of the new technology (2004/5), around 20 years.

Lignia™ (Fibre7) uses resin monomers as the basis of a polymerisation modification which targets improved hardness in a range of colours for interior applications such as kitchen bench tops, furniture and stairs. Recently there has been an exterior version developed, LigniaXD™, which has a 35 year guarantee and used for above ground applications (Lignia, n.d.). One of the selling points is that the wood resource used is defect-free, available in clear, long lengths and in dimensions which may not be available from premium hardwoods. This high quality wood supply is currently sourced from New Zealand's pruned radiata resource, which is available in more limited quantities in Australia. Manufacturing for Lignia™ is in New Zealand with most or all the products exported to Europe and North America. While Lignia™ is currently only applied to radiata pine, it has been suggested that this modification is suitable for any wood species which can be pressure impregnated (Mater, 1999), which suggests potential for species such as slash pine, maritime pine and hoop pine, all of which have treatable sapwood. Hardwoods which produce sufficient treatable sapwood could also be suitable.

HartHolz[TM] is a newly branded modification offering from TimTechChem that has recently launched from a development in Europe (Belmadur) and utilises dimethylol urea chemistry, polymerised *in situ* after impregnation into the dried wood (Eddy 2014). It is a water-based formulation containing dimethylol dihydroxy ethylene urea (DMDHEU) and a proprietary catalyst, and cures at temperatures above 100 ^{o}C (Eddy 2014). It has shown a range of property improvements such as compression strength and hardness (Jiang et al., 2014b); creep resistance (Lopes & Mai 2014) as well as dimensional stability, weather resistance and durability (including some resistance to termites), with a 40-70% increase in density (Eddy 2014; Militz, et al., 2011). Further details on specific improvements are given in Appendix 2.

Field testing of DMDHEU-modified wood in Australia suggested that termite resistance varied with the species of wood, and the location and species of the termites, so further research into this would be required if commercialisation was planned. Militz and others (2011) modified slash pine and spotted gum samples, which have natural termite resistance, as well as Scots pine and beech, which do not. After modification, both these resistant species gave greater termite resistance compared to Scots pine, although the latter was substantially improved, compared to unmodified Scots pine. It was noted that penetration of the DMDHEU was incomplete with the spotted gum, however, no other information on the suitability of slash pine and spotted gum for modification could be found.

Other aspects are also promoted such as machinability (less wear on tools). Field durability testing around the world has been undertaken (or is in progress), including Europe, America, Australia and New Zealand. There is no improvement in fire resistance (Xie, et al., 2014), but there is the potential to couple the modification with fire retardants to achieve much greater fire resistance (Jiang, et al., 2014a). The applications include windows and high-end joinery, furniture (indoor and outdoor), decking flooring and marine piles (Eddy 2014, Münchinger, n.d.).

The commercial development of DMDHEU-modified wood started in Europe from about 2004 under the Belmadur brand, but a full-scale production plant was never built. More recently, development is underway in New Zealand (as HartHolz[TM]) with an Australian launch being planned for later in 2015. The cost is claimed to be less than some other modifications but no details are given (Eddy 2014).

The above range of impregnation modifications are only a selection of commercial technologies (due to lack of information, and assumed very small production volumes), and there are an even larger number of modification options that have been researched over the last few decades.

Depending on the modification agents themselves, these impregnation modifications mainly use existing conventional vacuum/pressure equipment, although they may need an additional curing step in a kiln or reconditioning chamber. However, if the modification formulation contains flammable solvents (such as ethanol), or toxic monomers (such as furfuryl alcohol), and thus has additional hazards to traditional wood preservative formulations, then a customised wood modification plant would need to be built to fit the additional regulatory requirements. These requirements have previously been overcome on a commercial scale by LOSP treatments (a traditional timber treatment delivered via a flammable solvent) showing the safety issues can be successfully managed in a cost-effective manner.

3.4 Other modifications

There are a wide range of other modifications that could fit into the wood modification space and some are being offered commercially around the world. These include other types of impregnation modifications where soluble modification agents are diffused into the wood, then modification occurs to cause them to become insoluble (e.g. precipitation). Examples of these that have been studied are inorganic silanes, silicates and silicones and many of these agents achieve some good property gains (Hill 2006), but in some cases, are not sufficiently fixed in the wood and can leached out over time. Due to their size, many of these agents do not enter the cell wall (Hill 2006).

The range of properties that can be improved using various Si-based modification agents are dimensional stability, water repellency, decay resistance, termite resistance and fire resistance (Hill 2006), although usually each agent only achieves some, but not all, of these property improvements. In the last few years, there appear to be a few commercial offerings based on Si treatment agents. However, these agents often have negative side-effects such as reduced mechanical properties, demanding treatment conditions, weight loss and uneven distribution within the wood (Hill 2006), which has limited their commercial development.

Another commercial example of a Si-based modification of wood is the TimberSIL® GlassWood Fusion process (TimberSIL, 2008). The company claims that through their ‘micro-manufacturing infusion process’, amorphous glass is formed in and around the wood fibres, resulting in a durable, fire retardant modified wood material (using SYP). They claim this material behaves as a Class A fire retardant. It is promoted for decking and window joinery and has other exterior and interior applications. The GlassWood product is claimed to be non-toxic, non-corrosive and non-carcinogenic. However, it appears that there have been significant durability performance issues in service (Daily Hampshire Gazette, 2013; New Orleans Advocate, 2015), with the distributors listed on the TimberSIL website no longer appearing to carry this product, so it is not known if this product is still commercially available.

This is not an exhaustive listing of all possible modification technologies but a selection of what are deemed to be the most relevant, i.e. most extensively tested with regards to property improvements and those with the best prospects commercially.

3.5 Market segments and future opportunities

Wood modification technologies are largely targeted at exterior applications such as decking, cladding, outdoor furniture, window joinery and other above-ground applications, with dimensional stability (and sometimes colour) adding to durability.

However, there are some modifications (e.g. Lignia™) that initially targeted high-value interior applications such as flooring, furniture and bench tops with improved hardness and colour options.

In recent years, the breadth of potential applications has increased, with more focus on specialist applications such as high performance window joinery (e.g. large sizes, double/tripled glazed), marine applications, applications in challenging climates (e.g. tropics), bridges, boats and kitchen utensils (Accoya, n.d. 2; Kebony, n.d. 2; ThermoWood Association n.d.).

Over the last 2-3 years, there has been a huge increase of sales and exports to a wider range of countries for most of the main modification technologies. An example is Accoya® who report rapidly increasing sales (Pratt 2014) with a second production plant in planning (Solvay 2014). Kebony® are reportedly exporting to 22 countries. As with many other step-changing processes, many wood modification technologies have relatively long lead times (5-10 years or longer) before they jump the "chasm of death" and become profitable.

Opportunities for modification technologies are generally considered to be very positive (Hill 2006, Hill 2011), as consumers are becoming increasingly demanding for the product performance in their homes and businesses, and local councils are required to consider environmental footprint, sustainability and long term performance of their buildings and infrastructure. Wood modification technologies are developed with these drivers in mind and are often focused on lifting local wood species that might be performing well at the commodity level into these high-value and high-performing applications. Another driver that will only increase in importance is the reduced supply of naturally durable hardwoods especially from developing countries as regulations and compliance requirements are tightened up. It is widely accepted that the supply of such timbers is rapidly declining and will continue to do so.

4.0 Application and development of modification technologies in Australia

The application of wood modification technologies into Australia will require the consideration of a number of important factors including market opportunities, perceived benefit in performance, economic and environmental, along with potential barriers for adoption, regulatory and cultural issues.

Modification options are ranked according to their perceived fit to the built environment in the construction sector, the benefits they bring and their application to the Australian context, including the locally grown wood resource. Then the potential to conduct research and development of these technologies is discussed, with the view that in some cases, there are gaps in required performance for some applications in Australia, for example, termite or fire performance.

4.1 Market opportunities

In the Asia-Pacific region, demand for timber is predicted to increase over the next decade or so. Modified wood targets high value niche applications which are largely part of the built environment sector.

A recent presentation (Makowski, 2014) illustrated the growth rates in the Asia-Pacific area for timber to be around 5%, with demand predicted in 2020 to exceed Western Europe's demand then and North America's current demand. Makowski (2014) outlined a clear view of the challenges, strengths and opportunities for Australian wood industry going forward:

- Challenges were listed as a relatively small domestic market and a current sector set-up that is not well-positioned to take advantage of value-added opportunities.
- Strengths were seen as location in the Asia-Pacific region which is a major growth area globally, good fibre & land availability, competitive wood costs (especially for softwoods), relatively strong Australian economy, and established industry players, with business models and concepts proven elsewhere already.
- Opportunities for Australia were summarised as the need to:
    - Export value-added products (not commodities for others to improve)
    - Operate with fully integrated processing that is competitive & efficient, using proven business models (implement new operating models to improve market reach)
    - Update processing facilities (to improve asset efficiency)
    - Provide customised export solutions which consider product, marketing and supply chain together.

Much of the focus for the above opportunities are dominated by the current commodity wood products, with high value applications that would be suited to modified wood products comprising a very small part. However, modified wood products would be used in the residential built environment in such applications as cladding, window joinery and other applications in the "outdoor room" spaces, as well commercial decking and other commercial applications (e.g. flooring and interior fit-out). In addition to these construction-focused applications, there would be other possible products such as furniture, kitchenware, utensils, catering and hospitality. Some modified wood companies promote applications in these areas, with wood bringing the advantage of anti-bacterial properties, scratch resistance and being easy to clean.

Solid wood products consumption in Australia has been relatively stable at 5-6M m^3/year over the last decade or so (Ajani 2011). Although there is no data available on the current market size for (imported) modified wood products in Australia, these products will be most suited (but not limited) to higher value applications in the built environment including interiors.

Some modified wood materials would be competing against naturally durable hardwoods such as kwila and teak, in addition to Australian-grown hardwoods, such as Jarrah, Blackbutt, Spotted Gum, and Ironbark (Narangba Timbers, n.d.).

One metric for the new residential builds are building approvals, with the trends for building approvals for private sector dwellings increasing steadily over the last 5 years (Kalisch 2015). There is a continued trend for non-house dwellings (i.e. apartments) increasing strongly, with the housing building approvals levelling out over the last year or so.

There are significant differences in the number of building approvals granted between states, with only NSW and Queensland increasing over the last year. Other states were static or negative in their growth. Overall for Australia, the trend was that building approvals were continuing to grow with a few dips over the last five years (Kalisch 2015). This gives confidence that the market for products that perform in housing and apartment applications will have increasing demand.

Not included in building approval figures are renovations. Over the last 6 years, these represented about 40% in value of housing construction (some AUS$27-32M pa, Anonymous 2014 b). Modified wood products could be utilised in residential renovation projects, such as replacement of decking or cladding, and in outdoor living spaces.

The actual uptake of modified wood products in Australia is unknown, although some material is being imported currently (quantities unavailable). There is a growing trend for increasing expectations from the consumer for the performance of residential products, including avoiding functional and appearance defects such as distortion, splitting, checking and colour changes.

There would be a need for research to match a particular product segment to a specific modified material with performance requirements and price point. TMTs tend to be more closely related in performance to current treated wood materials, due to their targeted properties of durability, stability and relative low cost. An opportunity could be for a combined TMT with an additive, e.g. a fire retardant agent but again this would need to be thoroughly researched. There is some recent commercial offerings of modified wood with enhanced fire performance (e.g. Q-Treat from Stora Enso, TimberSIL®), as already mentioned. It is unknown if adding these to modification processes give any advantages over combination with conventional wood treatments.

Modified wood materials tend to give benefits in the longer term for aspects such as increased length of maintenance cycles and increased life span, in addition to the key properties improvements of stability and durability. Other advantages are addressing the consumer and manufacturer pain points such as toxic treatments, material movement (instability) and customer call-backs (Campbell 2014).

4.2 Wood modifications: Advantages and disadvantages

One possible business benefit is targeting product segments that are performance-driven rather than price-driven. There is more potential for higher price points and higher margins on products that perform. There is the opportunity for modification operators to liaise directly with designers, architects and product specifiers to deliver bespoke wood products to the client that will command a premium.

Another potential business benefit is supplying clients in high profile projects such as the double glazed windows of high rise hospitals (in UK), or commercial board walks with local councils. There is an example of where a client (Auckland City Council) specified Accoya® wood to be used in boardwalk despite it being many times the price of conventionally treated wood (Accoya n.d. 2). These corporate clients are interested in the longer term maintenance schedules and life spans of products, as they are long term property and infrastructure owners.

To realise these possible business benefits, a change in approach would be required and this is a risk. However, these models have been used in wood modification operations overseas to good effect.

<u>Environmental benefits</u>

There are a number of environmental benefits for many wood modification technologies. These include reduced toxicity, increased product life, reduced maintenance cycles, reduced environmental impact and carbon footprint. In addition to these benefits, modified wood is sourced from sustainable plantation resources in contrast to many high-performing native hardwoods. If the modified wood is produced locally, from locally grown wood, transport distances can be greatly reduced compared to those of imported hardwoods.

One advantage of modified wood materials is their end of life disposal. Compared to traditional wood preservatives, there are no special disposal processes that modified wood need as they can be disposed of like untreated timber (Hill 2006). Modified wood products have lower maintenance requirements (Hill 2006) than conventionally treated wood products (such as re-painting and staining) and so make a positive environment impact (and reduction of cost for the consumer). However, actually quantifying a feature such as increased maintenance cycle would be a long term process.

One aspect when considering environmental impacts of modified wood products is the source of any chemicals required. Chemicals from non-renewable sources will have an associated negative impact, as will energy use when derived from non-renewable sources (Hill 2006).

Life Cycle Assessment (LCA) is one tool that is used to quantify the total environmental impact of a product. It includes all inputs such as raw materials, energy and chemicals; along with the manufacturing process itself, including fabrication of the plant, as well as outputs such as waste streams, emissions and effluents (Hill 2006). More recently, there have been a number of LCAs conducted on modified wood products, and these data from LCA are required in Environmental Product Declarations (EPDs) for new products being approved for use in European markets (Hill & Norton 2014). There are now international standards (ISO 14040, 14044) specifying how a LCA needs to be conducted, as the setting of system boundaries can influence the results obtained. There are also standards for conducting EPDs (ISO 14025), and while these are prescriptive in nature, reducing the amount of flexibility when conducting such evaluation, they will allow better comparison between products using the same systematic approach (Hill & Norton 2014). However, the latter standard (ISO 14025) only includes the cradle to the gate assessment and does not consider end-of-life disposal impacts, and so will not capture all the environment benefits presented by modified wood products.

Hill and Norton (2014) demonstrated that comparisons using the LCA tools and EPD evaluations according to these standards can provide a compelling case for timber products in general due to their natural sources for raw materials, their ability to sequester carbon over the long term, and their potential disposal methods that extract energy. This can be helpful when making a case to replace non-wood products (e.g. Aluminium, PVC) in such applications as window joinery with modified wood products. The case for modified wood products compared to conventionally treated wood products is less clear as the current system boundaries for the EPDs exclude end of life disposal requirements and maintenance cycles, where modified wood products show significant benefits. This is still a developing field, as currently there are only two published EPDs of modified wood materials (Accoya® and Kebony®), with a published LCA for ThermoWood®, available from the ThermoWood Association website (Hill & Norton 2014).

The calculations and evaluations that Hill & Norton (2014) presented give estimates for the life span increases required to balance the environmental impacts (compared to unmodified wood). These were 2.5 times for both Accoya® and Kebony®, which should be feasible given the improvement in durability that these modified materials achieve. They note also that these evaluations did not include the effect of longer maintenance cycles, which should have an additional positive impact.

Another metric that designers and architects are interested in is the embodied energy of building materials. It is increasingly common that clients specify the use of “green” building materials to reduce the carbon footprint and environmental impact of the building. There are two forms of embodied energy: initial (representing the quantity of non-renewable energy in the production of the material) and recurring (the amount of energy used to maintain a material in service). Embodied energy is expressed as units of energy per unit mass or volume of material (i.e. Joules per kg, tonne or m^3). Thus embodied energy gives an estimate of the global warming potential of a material, but it does not include all potential environmental impacts (Hill 2006).

Accurately quantifying embodied energy in a material is complex and highly dependent on where the systems boundaries are placed. The energy required to make all the processing plants used to manufacture the material needs to be included and one could argue in the case of wood products, all the energy also used in growing, managing, harvesting and transporting the wood resource to the processing facilities should also be included. This has led to difficulties with the analyses themselves and any comparisons between different materials (Hill 2006; Cabeza, L. F., et al. 2013).

However, since 2004 researchers at the University of Bath, along with other colleagues, have been working on compiling a database that determines embodied energy and carbon of building materials. This is the Inventory of Energy & Carbon (IEC), and is downloadable freely (University of Bath, n.d.). In this database there is a list of 12 ideal boundary conditions, but the authors, Geoff Hammond and Craig Jones note that sometimes secondary sources are used to obtain the data and these do not always use the same boundary conditions. The IEC database is one of the most widely used to compare embodied energy. The values provided for a range of timber products come with a note that these values have “high data variability”. Currently there are no values in this database for modified wood materials, leaving a gap in the knowledge, making it difficult to compare with other building materials (or other modified materials) using similar boundaries. It is highly likely as more LCAs are completed for modified materials that these data will be added to this database.

Cultural issues

There might be shifts in behaviour or ways of operating required to successfully implement wood modification technologies that present challenges and could be considered as cultural issues.

Wood modification owners have a systems approach when looking to implement their technologies in new markets, often with a licencing process. Selection of the appropriate coatings, adhesives and fastening systems has been the subject of research for most commercial modifications. For example, ThermoWood handbook contains extensive information on handling and use of ThermoWood® from selection of glues, to configuration of machining operations (Thermowood Handbook). This extensive information of the down-stream processing requirements significantly de-risks the in-service performance of these novel materials and suitability of applications. These aspects appear to be critical success factors for maintaining quality of material performance for such technologies.

This systems approach to deliver complete solution to the customer differs somewhat from that of the traditional preservatives where how the treated material is used and installed at the builders discretion (and according to requirements in codes and standards).

Industry and regulatory structures

The wood processing industry tends to be state-based, not well integrated vertically and relatively conservative. However, there are associations and bodies that bring various parts of the sector to work on projects together along the value chain. An example of this is the frame & truss project presented at a recent industry conference (Woodard, 2014). Here the Frame & Truss Manufacturers Association (FTMA) was brought together with wood suppliers, pre-fabricators, connector suppliers and builders, with the FWPA funding, BRANZ providing testing and TPC Solutions coordinating the whole project. This example is in the commodity product segment of subfloors but these kinds of projects can be strong enablers of the wood processing industry to innovate their way back into recently lost markets in Australia. For modified wood materials to increase their market share, it may well be necessary to collectively fund projects covering feasibility studies and removing potential barriers to uptake for such unfamiliar materials.

The regulatory environment in Australia has been changing to align more strongly with international standards (ISO) in the area of test methods and required performance for durability, fire performance and other aspects of performance in the built environment. The Building Code Australia (BCA) is a large complex series of documents that cover every aspect of buildings and construction (ABCB, 2014). The documents of most relevance are the National Construction Code series (NCC) Volumes 1 & 2, which cover the different classes of buildings.

The BCA has a hierarchical structure as shown in the Figure 4. There is an overarching set of objectives and functional statements for guidance and then are the compliance levels involving performance requirements, building solutions with Deemed-to-satisfy and Alternative solutions outlined, and assessment methods specified. A number of experts in the area of codes, standards and wood-based building solutions have presented recently the issues facing the wood processing industry with regard to complying with the current BCA and how the NZ and Australian codes and standards do or do not align (Greaves, 2014; Drysdale, 2014). The key issues outlined are the challenge for wood products to meet the fire performance required, especially in the areas deemed to be bushfire prone, and using alternative solutions to meet durability requirements.

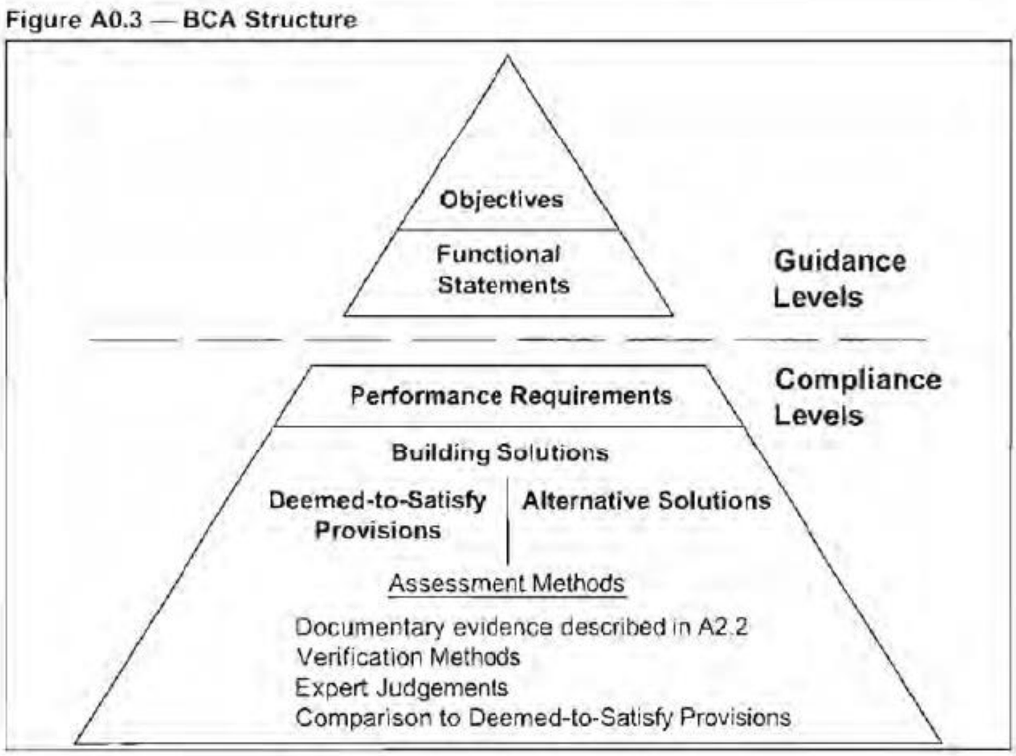

Figure 4. The BCA structure from NCC Volume 1 (ABCB, 2014)

In particular, a lack of data on fire performance of wood products that provide the “deem-to-satisfy” requirements that the Building Code Australia (ABCB, 2014) places on timber and wood products and which is expensive to obtain with larger scale fire testing often required (Timber Development Association 2011).

For durability performance, the retention rates and penetration depths that are specified in the codes and standards would not apply to modified wood materials but they would follow the Alternative Solutions route, giving evidence that the material is fit for the purpose intended. This includes decay resistance testing, comparison with conventionally treated wood and other performance data. This would usually be supplied by the modification owners as part of the package they bring, with much of this information openly available in literature, but in some cases, further data might be required to demonstrate fitness for purpose in Australian conditions. For thermal modification, it is likely that data would need to be supplied for each wood species.

Barriers to adoption

There are a number of barriers to the implementation of production facilities for modification technologies in Australia. The first barrier to overcome is the lack of key data for some technologies that demonstrate acceptable performance in exterior applications (i.e. meeting Hazard Class H3). In particular, there are concerns that thermal modified radiata pine will not meet H3 standard in Australia, as it does not currently meet the H3.2 standard in New Zealand. However, thermally modified American ash, poplar and maple (non-durable species) are being sold as decking into Australia (Britton Timbers n.d), so durability concerns may be overcome by using other species.

One potential barrier to overcome would be the fire performance required for the modified wood, especially for use in the areas deemed to be bushfire prone. With the relatively recent change to the codes and standards, many wood products are struggling to meet the standards, even with fire retardants applied. This is an area that could be worth further investigation to explore alternative options and combinations of modifications.

Further potential barriers to overcome are the need for a high quality feedstock and efficient processing operations. Wood modifications target high value products, so would likely be smaller operations with an emphasis on consistent high-quality production. This would likely require investment in new equipment to meet quality requirements. High quality products also require high quality appearance grade wood, and it is not known how much of this is available in Australia for species that are able to be modified successfully.

Modification of radiata pine has been studied extensively, but there is very little or no information readily available for on the suitability of other Australian species for modification. While many species look promising, research would need to be conducted to confirm this.

Differences between states in locally available timber resource, regulatory requirements, suitable processing operations, and local market demand will need to be carefully considered, and could present a barrier to adoption in certain states.

All these potential barriers would need to be addressed via feasibility studies or technical investigations, to fully evaluate each modification opportunity and requirements for success. Even those technologies already commercial would require a feasibility study to confirm the viability of implementation in Australia, considering wood species availability and quality, market demands and fit to regulations.

4.3 Opportunities for Australia

The opportunities to produce modified wood materials and products locally in Australia are covered in this section, and include; which of the modification technologies are currently best suited for application to Australia; and what potential is there to further develop and adapt the technologies so that they are even better suited to the market and regulatory requirements. Suitability for application in Australia covers the ability to apply modification to Australian-grown wood species, supply of good quality wood resource, performance advantages the modification brings and the fit to the standards and built environment applications.

The overall market for treated and modified timber products is relatively large in Australia, and so the high value end of the segment is likely to be of sufficient size to sustain the relatively small modification operations that are in place elsewhere in the world. However, actual market demand for specific products in each state has not been considered here and this information would need to be gathered to confirm any opportunity.

Ranked options for Australia

The wood modification technologies that would be most suited for application in Australia are ranked in this section according to three criteria:

- fit to **built environment** applications particularly residential and light commercial construction, which includes decking, cladding, windows and other joinery and interior applications such as flooring and fit-out,
- **greatest benefits** (business and environmental), including cost-effectiveness, which covers capital and production costs, and material performance, and
- highest **potential for success in Australia**, which includes ability to apply to a range of Australian wood species and potential for achieving performance that meets Australian standards,

Structural commodity applications such as wall framing, floor cassettes, ceiling and roofing systems have not been included when considering segments of the construction sector for modified wood. This was due to the lack of fit of the properties gained by modification with these applications' requirements and the high-value, low-volume nature of modified wood products. However, value-added combinations of such applications with some modified solid wood might be possible in pre-fabricated systems.

Six specific modification technologies were selected and ranked (Table 1) to cover the three types of modifications that are the focus of this review: thermal modifications, chemical reactions with wood and impregnation/polymerisation modifications. In addition, the possibility of using other additives such as fire retardant and termiticides with a base commercial technology is included, even though these technologies are not yet combined in a form that meets fire performance required in Australia, and so classified as a potential "emerging" technology. Fuller details of each modification are listed in Appendix 2, with the features for potential application to Australia relevant to the ranking given in Appendix 3.

Table 1: Wood modification options ranked for suitability for application in Australia, as at May 2015

Modification (commercial/emerging)	Fit to built environment (L-M-H)	Benefits (L-M-H)	Potential for Australia (L-M-H)	Overall ranking
ThermoWood® with radiata pine (commercial)	M	M	M	M
Accoya® (commercial)	M	M-H	L-M	L-M
Kebony® (commercial)	M	L	L	L
TMT with alternative species (emerging)	M?	M?	M?	M?
TMT with additive (emerging)	M?	unknown	M?	M?
HartHolz™ (DMDHEU, emerging)	M	L-M	M?	L-M?

Key: L = low, M = medium, H = High, ? = a number of unknown features which might change ranking

Note: These rankings are subjective based on literature and data gathered for this review (further details are listed in Appendix 3 for each modification technology as to why these rankings were awarded).

It should be noted that these rankings are subjective based on the data available, and represent an assessment at this point in time. The rank given is not an endorsement or otherwise for any specific commercial technology. In Table 1, the wood modification option that appears to have the best potential in the short term to be applied commercially in Australia is a thermal modification with steam, such as ThermoWood®, applied to clear radiata pine. There are two thermal modifications with steam on radiata in New Zealand and numerous operations worldwide on other species. Therefore there would be relatively low commercial risk in implementing this technology on Australian-grown radiata pine.

Thermal modification is a relatively low capital cost process, and could be easily integrated into an existing wood processing operation. It is unknown if thermally modified radiata meets Hazard Class H3 in the Australian standard. It is unlikely to achieve Hazard Class H4 (in-ground contact) for applications such as posts. In New Zealand, it reaches the H3.1 requirements (cladding) but has not yet been shown to meet the H3.2 requirements (decking). In some applications, there would be issues with the probable lack of fire and/or termite performance. However, a more detailed analysis of market size for such applications would need to be conducted, on a state-by-state basis, along with price point compared to main competing products to confirm this opportunity.

The option of building an Accoya® production facility in Australia was ranked lower than thermal modification, as Accoya® is only just starting to look at building additional production facilities, with a commitment to build the second commercial plant in Europe. It is possible that a third production facility would be located in Australasia, close to the pruned radiata pine resource. The location of such a plant would greatly improve the embodied energy of the Accoya® product in the Australian and New Zealand markets, which may enhance its desirability as a “green” building material. The high capital and chemical costs would make the building of production facilities more challenging, compared to some of the other modifications. Accoya® is showing increased growth and good commercial prospects, and so may be a good investment in the relatively near future.

Kebony® was ranked relatively low for a range of reasons including its relatively recent commercialisation, with limited current sales, its moderate property gains for relatively high cost (similar in cost to Accoya® with lower property gains), and its only commercial plant estimated not yet to be at capacity. It is still probably too early for this technology to evaluate commercial success, and be looking to expand production facilities.

Longer term, the emerging option to extend thermal modifications to other species is an area that shows promise for further research. Slash pine is of particular note, because thermal modifications have been done successfully with Southern Yellow Pine, and this grouping includes slash pine.

Thermal modifications such as the ThermoWood® process have been applied to many hardwoods worldwide, and research suggests that Australian-grown eucalypts may also be suitable for this modification. This could either be used to lift lower-grade eucalypts such as *E. nitens* into appearance applications (as is currently done by Mininco in Chile), or to further enhance the properties of higher value plantation species to meet rising consumer expectations for product performance.

Another emerging option in Table 1 that was ranked relatively highly in the longer term was a TMT process with additive. There are a number of options for non-toxic additives that improve fire performance and termite resistance. Some of these modifications are in the research space (e.g. TMT plus boron-based agents) and some are commercial (sodium silicate or other Si-based agents). These either do not currently meet Australian fire standards, or are likely to meet the standards but are not yet combined with a TMT process. These options would require significant investment in research and development to combine these modifications effectively. It is not known the loadings that would be required to reach fire performance standards, as many fire retardants require high retention rates making them prohibitively expensive (O'Callahan et al 2015).

The final emerging technology, HartHolz™ (DMDHEU) was ranked as having low to medium potential as it is not yet commercialised, and there remain many unknowns in its suitability for Australian implementation. However, TimTechChem is planning to licence production in Australia after a successful launch in New Zealand (Eddy 2014). This technology claims to have relatively low capital cost and is based on water-based chemistry, so would make implementation easier than some other modifications. Field tests have been established in many locations globally including Australia so there will be good information available about the performance under local conditions. Therefore this technology would warrant a watching brief, as successful commercialisation in NZ would suggest reasonable commercial prospects for Australia.

Research and development potential

There is significant potential to conduct targeted R&D into the application of wood modification technologies to Australia. There are three streams of research that are recommended: feasibility studies, longer term investigations and technology comparisons.

Feasibility studies

This would require specific intelligence gathering on state and Australian-wide product markets and logistics, including quantities of suitable timber resources available, manufacturing operations that could most easily include a specific wood modification technology, and the overall feasibility of a specific product segment being supplied by locally manufactured modified wood material. Feasibility of a local operation would need to be compared with equivalent products made using imported modified wood material, and an analysis of competing products and their relative prices points.

For the application of ThermoWood® to Australian-grown pruned radiata pine, the exercise would be relatively straight-forward, as it has already been successfully implemented in NZ. However, some specific information would be necessary such as market size and estimated prices points, as well as the ability to meet Hazard Class H3 requirements in Australia.

The application of ThermoWood® (or other similar thermal modification processes) to other Australian-grown softwoods and hardwoods or in combination with an additive would need to be investigated by producing pilot scale samples with thorough testing before for their feasibility is assessed.

Longer term investigations
These would involve lab and pilot studies of a thermal modification process on a selected Australian wood species (with or without additive). ThermoWood® appears to be promising for application to a range of Australian softwood and hardwood species. Thermal modification with an additive could be applied to softwood species which are able to be pressure-impregnated, e.g. sapwood of pine species. Any additives would need to be of low toxicity and not include halogenated flame retardants (i.e. not on the Red List: Living Building Challenge, 2014), in keeping with modified wood's mandate to be non-toxic in service. There has already been some promising research into the addition of a termiticide to ThermoWood® (Salman, et al., 2014). There is also the potential to apply these modifications to engineered wood products such as finger-jointing and laminates. It is likely that a short feasibility study would be required at this stage to identify the wood species and modification combination that were most likely to succeed commercially, given resource availability and the likely market for the modified wood product.

For each new additive or species, initial lab-scale investigations (say on <1m lengths of full cross-section boards) would be required to determine the degree of modification required and the properties improvements that are gained. Once a modification is successful on the lab scale, pilot-scale trials (on 2.4 m lengths) help to determine the processing parameters that give the required degree of modification, and to show if there are any macro-scale effects from the modification (e.g. the presence of numerous annual rings, or of features such as knots). This also allows more accurate measurement of the likely in-service properties of the modified wood. Once the modification has been demonstrated successfully at the lab scale, an in-depth feasibility study, as described for radiata pine, would be required before implementing the process commercially, so would probably be conducted in parallel to the pilot-scale trials.

Technology comparisons
The ability to compare proposed technologies with real data inputs is considered to be very important. This could involve a technology assessment model such as WoodScape that has already been developed for the New Zealand context. This model gives more accurate evaluations on technology comparisons using processing costs such as capital cost, feedstock cost, product (and by-product) prices (ex-mill), product and by-product yields, labour, energy inputs and costs, other consumable costs (such as catalysts and solvents), R&M costs and any other significant processing costs (Hall 2015). This kind of model does not consider market demand.

In order to develop a WoodScape model for Australia that includes modified wood, an understanding of product performance and prices point is required. However, much of the performance data for Australian conditions needed to make these assessments are not available. Therefore, benchmarking to Australian standards e.g. durability (decay, termite, weathering) in Australian conditions and to the H3 requirements for a range of modified wood materials and comparison to conventional preservative-treated wood would be necessary.

There are some significant gaps in the data available on the environmental impact of modified wood materials. This includes Life Cycle Assessments (LCAs) and embodied energy values which are used to give comparisons on environmental impacts of different building materials. There is an opportunity to fill these gaps and provide reliable data to assist architects and clients who require ”green” credentials to include modified wood material in new builds. These data would provide a comparison of modified wood, conventionally treated wood and other building materials, using similar methodology and boundary conditions. In the current Inventory of Energy & Carbon (IEC, University of Bath, n.d.), no treated timber products are listed.

5.0 Conclusions

The commercialisation of wood modification technologies such as Accoya®, ThermoWood®, Lignia™, Kebony® and others have been in progress for a number of decades globally, and sales of modified wood products have started to increase rapidly over the last few years. Modified wood materials and products are being imported into many countries including Australia. Therefore it was timely to review the technical wood modification literature and consider the importance of a number of aspects in applying wood modification technologies to the Australian context.

The availability of a suitable wood resource including species, quality and supply is the first aspect to consider when applying wood modification technologies to Australia. For thermal modifications, quality (including knottiness), ability to kiln dry and treatment level required for targeted performance need to be considered. For modifications involving chemical impregnation, the ability to achieve even penetration through the wood is also crucial.

Three main modification approaches were covered in some depth: thermally modified timber (TMT), chemical reactions with wood, and impregnation/ polymerisation modifications. Other approaches were briefly mentioned.

There are some important differences between different modification approaches, in terms of the process (involving heat, various chemicals or solvents, range of plants), property gains achieved and changes to the wood itself (physical, chemical, colour). Different modifications have been applied to selected wood species and performance gains are often dependant on treatment level and wood species.

For each type of modification approach, an example of a commercial operation was outlined, along with specific data on property improvements, commercial history and current status. Information was given on plant capacity and production volume of commercial operations (where available).

Six modifications, both commercial and emerging, were ranked for their suitability for production facilities to be located in Australia, with three specific criteria of: fit to the built environment; greatest benefits and highest potential for success in Australia. The modifications selected for ranking were: ThermoWood®, Accoya®, Kebony®, thermal modification with other species, HartHolz™ (DMDHEU) and thermal modification with additive.

The wood modification option that appears to have the best potential in the short term was ThermoWood® using pruned radiata pine for applications such as window and door joinery. However, there are still a number of gaps in current knowledge, including quantity of suitable (high quality) wood supply, market demand and fit for specific products, degree of competition with other Australian and imported products. Critically important are the level of durability performance gained and compliance to all aspects of the Building Code Australia, especially if there are different requirements in each state.

The extension of thermal modification to other Australian-grown wood species would be a medium term option with good potential. It appears that there is at least one operation in Australia that is producing thermal modified local wood, but it is unknown what volumes are currently being produced or sold. Both lab and pilot scale trials would be required to confirm performance data for different treatment intensities. Another emerging option with similar potential was the combination of a thermal modification process with an additive to improve fire performance or termite resistance. These options of using an additive with a thermal modification would require significant investment in research and development, in particular to achieve the necessary fire performance.

Accoya® was ranked below the thermal modification options. While this technology has good potential, it is too early to consider an Australian production facility (with the second global production facility still in planning for Europe).

The HartHolz™ (DMDHEU) technology was ranked similarly to Accoya®, as it appears to have good potential for Australia, would be relatively easy to implement but it is too early to assume commercial success.

It would be worthwhile reassessing the potential for both Accoya® and HartHolz™ once some of the uncertainties around key factors such as market growth and size, and plans for further production facilities have reduced.

Kebony® was ranked as having the lowest overall potential for application for production in Australia. It was thought to be too early to properly evaluate its commercial success with the first production facility still probably not yet at full capacity.

Recommendations for future work fall into three categories: feasibility studies (including intelligence gathering); technical investigations and technology comparisons. In particular, for the shorter term thermal modification option the availability and location of a sufficiently high quality wood resource needs to be confirmed, and the overall commercial viability of the modified wood product needs to be confirmed (including compliance with Australian standards e.g. durability). For the longer term options, R&D projects are required to extend existing modifications to new species and additive to enhance fire performance or termite resistance. Once the investigations are complete, these options would also require the feasibility studies outlined above.

6.0 Recommendations

1. In the short term, an FWPA-funded feasibility study could be performed into a thermal modification, using pruned radiata pine as a feedstock, and supplying a specific product segment such as window and door joinery. Alternatively, given that this has been commercialised elsewhere, and so does not have as much technical risk, this could be undertaken by an individual investor who is considering investing in wood modification. In addition, assessment of durability (i.e. H3) would be required for many potential applications such as decking and cladding.

2. In the longer term, FWPA could fund research into applying a thermal modification to other Australian-grown species (hardwood or softwood). This would require significant research investment, and also a feasibility study to ensure the greatest chance of success for the modified wood product being developed; this would cover wood supply, properties needed for end products, and customer demand for these products.

3. For both the recommendations above, consider implementing a vertically integrated value chain so that the development of a modified wood product includes forest owners, mill and modification process operators, to the builder who installs finished product. New modified wood products will be targeting high-value applications, and this integrated model would ensure the consistent delivery of a quality product.

4. Long term, FWPA could invest into researching thermal modification in combination with additives to improve fire performance or termite resistance to meet Australian standards. These options would also require feasibility studies as described previously.

5. Enable technology comparisons by increasing investment into techno-economic assessments such as a WoodScape model for Australia, which compares technologies using a range of input data. Additionally benchmarking data for modified wood against conventionally-treated products would provide information on which products meet Australian standards, and would be required to predict markets and prices points in WoodScape.

6. Environmental credentials of building materials are becoming increasingly important. Very little of these data exist for modified wood. So there is an opportunity to fill gaps in knowledge and provide reliable data to assist architects and clients. Comparison of modified wood, conventionally treated wood and other building materials, using similar methodology and boundary conditions would assist the utilisation of treated and modified wood products.

7.0 Appendices

Appendix 1. Base data for the estimation of modified wood volume globally.

(a) ThermoWood Production Statistics 2013 (ThermoWood Association 2013)

Year	Sale production (m3)	
2003	21631	
2004	31146	
2005	39324	
2006	56279	
2007	72485	
2008	79367	
2009	74258	
2010	92069	
2011	109757	
2012	122594	
2013	127791	
2014	132000	est
2015	135000	est

(b) Accoya's production statistics (Pratt 2014)

	2011 m3/year	2012-13 m3/year	2013-14 m3/year
Production vol	12,000	17400	30972

(c) Estimated total modified wood volumes produced annually to 2015

Total Wood mod 2015 (est)	m/3	
ThermoWood	135000	
Accoya	35000	at capacity
Plato	12000	2005 figure
Kebony	12000	
other minor ones incl Lignia	2500	Estimated
Total WMs (volume)	196500	

Note: the above estimate is likely to be conservative as the total does not include other TMTs which might add up collectively but individual volumes were unobtainable.

Appendix 2. Summary of commercial wood modification technologies with process, species, property gains and status

Modification	**Process**	**Main wood species (other minor species)**	**Property gains**	**Status**	**Website**
ThermoWood®	Thermal modification process using steam and high temperature (>180 °C)	Wide range of softwoods: pine, spruce, larch Some hardwoods: birch, aspen, ash, , European beech, oak	Softwoods able to have improved decay resistance (above ground applications), moderate stability (e.g. 50% reduction in swelling) but gains depend on treatment intensity	Many plants globally, estimated current volume 135,000 m^3/year Beehive boxes TW radiata were slightly less (8%) than equivalent TanE boxes (NZ)	http://www.thermowood.fi
Accoya®	Acetylation in high quality stainless steel plant, with low MC wood	Radiata pine (Southern yellow pine, alder)	25% uptake gives >75% reduction in swelling, very good decay resistance, good termite resistance	One commercial scale plant (35,000 m^3/year), at capacity, second plant in plant (due 2016), rapid sale growth. Retail prices NZ$3740-5710/$m^3$ (TimSpec 2015, price list)	www.accoya.com
Kebony®	Furfurylation conducted in modified	Scots pine (Southern yellow pine,	30-50% uptake gives 60-70% reduction in swelling, improved	Estimated production 12,000 m^3/year (2014).	http://kebony.com/en/content/company

	treatment plant (to deal with toxic monomers & solvent) on KD wood	radiata pine, maple)	decay resistance, 15-30% increase in hardness with some termite resistance	Small bespoke order for Kebony radiata was NZ$7500/m^3	
HartHolz™ (DMDHEU, not available commercially yet)	Impregnation of N-methylol monomers (water-based solution) via standard vacuum-pressure treatment vessels	Radiata pine, Scots pine	Improved surface hardness (25-35%), stability (60-70%), compression strength (30-50%) and durability (Class 1, EN113, ENV 807, H4 Australia) (no specific data sighted, website claims) (Friday Offcuts, 2014; Müchinger n.d.)	Previously one pilot plant in Germany, commercial scale plants planned for New Zealand and Australia. No retail price available.	http://www.timtech.info/timtech_nz/pdf_file/TimTech%20HartHolz.pdf Belmadur: http://www.muenchinger-holz.de/english/produkte7.html
Lignia™	Pressure treated in treatment plant	Radiata pine	Improved hardness (by 50-60%), small improvement in stability (15-25%?) [1]	One small operation (NZ) Estimated NZ$2500/m^3 retail	www.fibre7.co.uk

[1] Estimated property improvements not conducted on recent commercial product.

Appendix 3: Detailed information for each modification for ranking awarded in Table 1:

(a) ThermoWood® with radiata (commercial)

Criteria	Rank given	Detail
Fit to built environment	M	• Range of exterior applications, where increase stability is desired such as cladding & joinery. • Potential surface mould issue
Benefits	M	• Derisked commercially in many locations on some species (+ range of process options) • Low relative cost, good stability & some durability gains – unknown if reaches Australian H3 requirements • Darker colours attractive to market • Lower impacts to environment • Some mechanical properties reduced (can be designed around)
Potential for Australia	M	• Relatively low capital cost • Issues with applications needing fire or termite resistance • Local supply of sufficient high quality wood resource unknown

(b) Accoya® (commercial)

Criteria	Rank given	Detail
Fit to built environment	M	• Some residential applications (specialty window joinery, decking, cladding) • Good fit to light commercial (e.g. Carl Jr fit outs) • Good resistance to termites • Potential surface mould issue
Benefits	M-H	• Commercial in UK with rapid growth (with 2nd European plant planned) • Good potential for regional exports (e.g. to Asia-Pacific) • Very good stability, very good durability gains, with good termite resistance , but high costs • Very low environmental impact (non-toxic, long life, low maintenance cycles) • Relative high capital & production cost
Potential for Australia	L-M	• Limited applicability to Australian wood species (e.g. currently requires radiata, high quality clears) • Potential plant & chemical compliance issues to overcome • Major issue meeting fire performance

		stds (unlikely to meet fire stds with existing FR)

(c) Kebony® (commercial)

Criteria	Rank given	Detail
Fit to built environment	M	• Good fit for European exterior applications (unknown for Australia) • Some resistance to termites • Unlikely for interior applications (VOCs)
Benefits	L	• Commercial in Norway but with limited sales currently, in market for 5 years • Potential to be regional supplier (e.g. to Asia) • Moderate stability & durability gains, but high costs • Mixed environmental impact (improved maintenance cycles) but toxic agent & solvents used • Relatively high plant & production costs, with possible plant compliance issues to overcome
Potential for Australia	L	• Limited applicability to Australian wood species (radiata, other pine) • Market still not established for first production plant so unknown for Australia • Issue meeting fire performance stds

(d) TMT with alternative species (emerging)

Criteria	Rank given	Detail
Fit to built environment	M?	• Range of applications depending on species as stability & durability achieved will vary with species • Properties would need to be determined. (durability, stability, VOCs) • Potential surface mould issue
Benefits	M?	• Derisked commercially in many locations on some species (+ range of process options) • Low relative cost, good stability & unknown durability gains • Darker colours attractive to market • Lower impacts to environment • Some mechanical properties reduced (can be designed around)
Potential for Australia	M?	• Widest applicability to Aus hardwood spp • Relatively low capital cost

		• Potential issues with applications needing fire or termite resistance • Local supply of sufficient high quality wood resource unknown

(e) HartHolz™ (DMDHEU, emerging)

Criteria	Rank given	Detail
Fit to built environment	M	• Good fit for exterior and interior applications • Possible resistance to Australian termites (depends on wood & termite spp and location)
Benefits	L-M	• Pilot scale trial in Germany but with no sales currently • Moderate stability, durability & weathering resistance gains, improved compression & hardness (medium costs, unconfirmed) • Low environmental impact (improved maintenance cycles) with non-toxic modification agent with water-based formulation • Assumed drop-in for current treatment plants (lower capital & production costs)
Potential for Australia	M?	• Limited/unknown applicability to Australian wood species • Company announced plans to expand, including into Australia. • Issue meeting fire performance stds

(f) TMT with additive (emerging)

Criteria	Rank given	Detail
Fit to built environment	M?	• Wider range of exterior applications (assume improved fire & durability performance) • Possible interior applications (e.g. multi-storey)
Benefits	unknown	• Base TMT derisked elsewhere • Unknown cost for performance (existing FR needs further development to meet Aus stds) • Good stability, assumed improved fire and durability performance • Unknown effect on mechanical properties • Darker colours attractive to market • Unknown environmental impact (process and end-use e.g. indoor air quality,

		added chemical)
Potential for Australia	M?	• Limited/unknown applicability to range of Aus wood spp • Greater potential to meet both fire and durability standards (but high technical risk) • Local supply of sufficient high quality wood resource unknown

Notes for Appendix 3:

1. Local wood supply is defined as being domestically available in Australian (rather than state-based)
2. Suitability for application in Australia means the building of production facilities not importing the modified wood.
3. An emerging technology is one that is not yet fully commercial

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