ATMAC – Splinters to Structures: Value added to exported wood fibre – Literature Review

Milestone report 1

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Queensland Government

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Contents

Executive abstract

Objectives

This report presents a literature review on (1) the challenges and best practices in processing fibre-managed plantation eucalyptus globulus logs in terms of sawing, peeling, recovery rate and drying, (2) the expected mechanical properties of Laminated Veneer Lumber (LVL) and glulam (GLT) manufactured from these logs, and (3) the obstacles in gluing and finger jointing the resource. This report aims at guiding the next stages of the Agricultural Trade and Market Access Cooperation (ATMAC) funded project "Splinters to Structures: Value adding to Exported Wood Fibre" which looks at manufacturing LVL and GLT out of the Green Triangle lesser value logs which used to be exported to China. Both globulus and hybrid radiata pine/globulus LVL and GLT are considered in the project.

Note that the report focusses on globulus as it is the predominant hardwood species grown in the Green Triangle and therefore of interest to this project. While small diameter softwood *Pinus radiata* logs are also of interest, they are not covered in this report as it was agreed by the executive committee that the Green Triangle softwood industry possesses enough knowledge and experience on the challenges in processing its resources and on some of its mechanical properties.

Key findings

1 – In terms of processing and drying, the following aspects need to be considered for both sawing and peeling:

- Tension wood is common in fibre-managed globulus plantations and creates challenges sawing the logs and drying the boards. These growth stresses are more present in small diameter trees than large ones. It is important to carefully select trees, so tension wood is avoided. European experience tends to indicate that boards with high mechanical properties are achievable with large diameter log selection.
- Successful studies in Spain on fibre-managed globulus logs, which obtained sawn boards of high mechanical properties, used carefully selected trees, likely of at least 40 to 45 cm in diameter.
- For less than 40 cm diameter logs to be encountered in this project, back-sawing is recommended. Back-sawing was reported to result in higher recovery than quarter-sawing, it assists in reducing the amount of bow and spring and it facilitates drying.
- Twin-saws, as opposed to single saws, are also highly recommended when processing small diameter eucalyptus logs as they release growth stresses more symmetrically, resulting in centre cants with limited warping. The use of chipper canters to practically remove wood simultaneously from all sides of the logs is also suggested to increase board recovery by further mitigating the effect of growth stresses.
- Spindleless lathe technology has proven to be efficient in rotary peeling small diameter logs into veneers, recovering up to nearly 60% of the billet volume into dry, trimmed and saleable veneers. Studies on 13-16-year-old fibre-managed globulus logs from Victoria showed similar recoveries.
- Thin boards (< 30-40 mm) sawn from fibre-managed eucalyptus plantations are more likely to be successfully dried with higher recovery and lesser drying defects.
- Literature suggests starting drying globulus boards with low temperature (≤ 30°C), which increases as the boards dry. Vacuum drying has showed promising results on globulus.
- Steam reconditioning generally allows recovering boards that collapsed during drying.

2 – For globulus sawn timber boards and associated GLT, the following is to be expected:

- While a high percentage of boards (>50% in the literature) from fibre-managed or young plantation hardwood logs failed meeting a visual structural grade, destructive testing resulted in all boards meeting a structural grade, but also high grade recoveries. The literature suggests that visual grading is not adapted for unpruned and unthinned plantations. A new visual grading system adapted to fibre-managed globulus plantations has been proposed in Europe.
- Appearance structural sawn products cannot be manufactured from fibre-managed plantations due to the high presence of defects. “High feature” boards typically dominate.
- For globulus, density is usually not a good indicator of the mechanical properties while the modulus of elasticity is.
- Finger-jointing globulus boards is possible, but even if high strength joints will result (greater than 80% of the strength of non-jointed boards), failure is likely to occur in the glueline and not pass the minimum requirement for bond durability in Australian standards.
- Globulus GLT has been investigated in Europe resulting in average mechanical properties higher than the characteristic values of a GL18 grade, i.e., the highest grade in the Australian standards. This indicates that the lower GLT grades currently manufactured in Australia may be achievable with the resource targeted as part of the current project. However, it is likely that in the European projects, the logs were carefully selected to achieve boards with high mechanical properties.
- Manufacturing hybrid hardwood/softwood GLT is possible and will result in similar bending properties to hardwood only GLT, but with lower shear strength. Such a solution allows to maximise the utilisation of resources.

3 – For veneers and associated LVL, the literature shows that:

- High strength veneered-based products can be manufactured from fibre-managed plantation logs, with the mechanical properties usually increasing as the trees age.
- The modulus of elasticity may be the limiting factor for grade classification and typically appears to be low relative to the strength values. Studies on 13-16-year-old fibre-managed globulus logs from Victoria provided veneers with an average modulus of elasticity of nearly 16,000 GPa, still allowing high stiffness LVL products to be manufactured from the resource.
- Appearance veneered-based products cannot be manufactured from fibre-managed resources due to the high presence of defects unless veneers from other resources are used as face veneers. D grade veneers usually dominate. Even thinned and pruned 16-year-old globulus logs from Victoria resulted in nearly 81% of visual D-grade veneers.
- Hybrid hardwood/softwood LVL can be manufactured and present an opportunity to maximise the use of hardwood and softwood resources by manufacturing a range of structural products.

4 – In terms of gluing, the following adhesives represent the best bets to manufacture LVL and GLT:

- 1-component PUR showed promising results for globulus GLT applications, both to glue boards and finger joints. However, contradictory European results are published with successful and unsuccessful trials.
- For veneers, phenol-formaldehyde have been showed to successfully glue globulus veneers. Commercial globulus plywood, using formaldehyde-based adhesive, reach a Type A bond for external applications.

1 Introduction

In November 2020, China stopped importing lesser value Australian logs consisting of hardwood plantation logs grown for pulpwood purposes and small diameter softwood logs. Since China represented the major market share of the total Australian log export market and no domestic processing capacity exists for these resources, this decision presented a challenge. To find an export market for and facilitate the establishment of Australian manufactured Engineered Wood Products (EWP) from these resources, the "Splinters to Structures: Value adding to Exported Wood Fibre" project was awarded by the Agricultural Trade and Market Access Cooperation (ATMAC) to Forest and Wood Products Australia (FWPA) in partnership with the Green Triangle Forest Industries Hub (GTFIH).

Demand for wood products is growing nationally and internationally. For instance, in 2020, domestic sawn timber sales were slightly below 2.9 million m^3 while demand was slightly above 3.4 million m^3, driven almost exclusively by structural grade. Regarding EWP, Australia produced 60,000 m^3 of Laminated Veneer Lumber (LVL) in 2020 but imported another 140,000 m^3 to meet the demand. Similarly, the annual production of glulam (GLT) of 25,000 m^3 represented half the demand (IndustryEdge Pty Ltd, 2021). IndustryEdge Pty Ltd (2021) also pointed out that "demand for products that are more engineered continues to increase to accommodate tighter building footprints, refined tolerances, increased off-site manufacturing and so on."

In 2020, there was only one particleboard facility in the Green Triangle, supplying about 25% of the market (IndustryEdge Pty Ltd, 2021), with plans to expand the EWP manufacturing capacity of the region. Adding to the worldwide growing market of EWP, the executive committee of the "Splinters to Structures" project decided to investigate the potential of manufacturing both LVL and GLT products out of the lesser value resources of the Green Triangle. The resources of interest include *Eucalyptus globulus*, which dominates the hardwood plantations in the Green Triangle (121,000 ha) and softwood *Pinus radiata* (176,400 ha) (ABARES, 2019, 2022). The former plantations are mainly grown for pulpwood purposes while the latter are managed for sawn timber. *Eucalyptus nitens* is also present in the Green Triangle, but to a lesser extent than globulus (ABARES, 2019), less than 100 ha according to ABARES (2022).

This decision correlates with the report by Freischmidt et al. (2009) which outlined the opportunities for hardwood resources available to VicForests. The authors noted that wood products manufactured from eucalyptus timbers generally exhibit high strength and stiffness. From past Commonwealth Scientific and Industrial Research Organisation (CSIRO) research, Freischmidt et al. (2009) also recommended preferred wood basic densities to manufacture various types of EWP. The reported basic densities by Freischmidt et al. (2009) of nitens (524 kg/m^3) and young globulus (561 kg/m^3) make these two species suitable candidates for LVL and GLT.

This report presents a literature review to guide the next steps of the research by understanding (1) the challenges and best practices in processing the resources in terms of sawing, peeling, recovery rate and drying, (2) the expected mechanical properties of LVL and GLT manufactured from the resources, and (3) the obstacles in gluing and finger jointing the species.

The report focuses on globulus as it is the dominant hardwood resource of the Green Triangle. However, relevant learnings from different eucalyptus species, including nitens, are also covered in the report. The softwood resource is nevertheless not covered as it was agreed by the Project's executive committee that the Green Triangle softwood industry possesses enough knowledge and experience on the challenges in processing its resources and on some of its mechanical properties. Reports on softwood resources, such as McKinley et al. (2004) on the Green Triangle region, typically look at log diameters larger than the less than 25 cm diameter logs targeted in this study.

First, an overview of EWP, other than LVL and GLT, manufactured from eucalyptus logs and which may present further opportunities for the Green Triangle is provided. Second, challenges and best practices to process fibre-managed and young eucalyptus logs into sawn boards and veneers are covered. Third, the challenges and expectations for globulus GLT, including hybrid softwood/hardwood GLT to maximise the use of the two resources, are covered. Fourth, the report reviews the use of eucalyptus and globulus in the manufacture of LVL, or other types of relevant veneer-based products. Hybrid softwood/hardwood LVL are also discussed. Finally, the report summarises the key findings and provides recommendations for the next stages of the project.

Note that review studies published by FWPA and CSRIO (Freischmidt et al., 2009; Hague, 2013; Washusen, 2013) are already available on the potential uses and processing of eucalyptus logs for EWP. The current literature review (1) only summarises the key points of these published reviews and (2) refers to them for the reader to obtain additional information when appropriate.

2 Products other than GLT and LVL from young eucalyptus and globulus

2.1 General

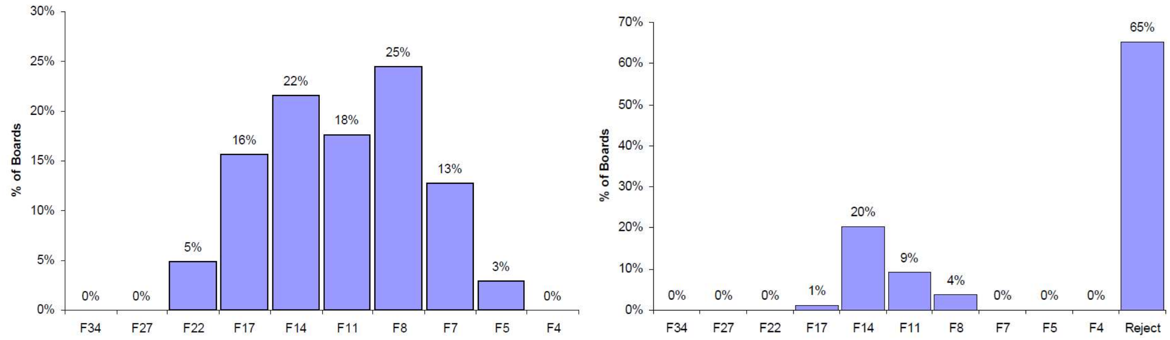
This section summarises key studies looking at manufacturing products other than GLT and LVL from either young (small) diameter eucalyptus and globulus logs. It focuses on structural products which may present opportunities for the Green Triangle. Products with no manufacturing facilities in Australia and large capital cost associated with setting up such facilities are excluded. Nevertheless, information on the potential use of native and plantation eucalyptus logs to manufacture such products, for instance Oriented Strand Board (OSB) and Medium-density fibreboard (MDF), can found in Freischmidt et al. (2009) and Hague (2013).

Additionally, emphasis is put on sawn timber boards in this section due to their use in the manufacture of GLT. The lessons learnt on the sawn timber boards provide valuable information on the expected properties of the raw material to be used in the GLT to be manufactured as part of this project.

2.2 Sawn timber boards

McGavin et al. (2006) assessed the processing and utilisation options of 8-9-year-old sub-tropical and tropical eucalypt plantation thinnings, all sourced from Queensland and Northern New South Wales. While globulus was not looked at in the study, the outcomes of unpruned plantation logs generally apply to the fibre-managed resource of interest in the current project. Bending tests performed on the recovered sawn boards showed large variability in the Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), with coefficients of variation (CoV) on the MOR varying between 22% and 39%. The variability was principally due to the occurrence of defects, mainly in the knotty central core, which significantly reduced the MOR when present. Results also showed that visual grading was not a good indicator of the actual mechanical properties of the boards. While more than 50% of the boards failed to meet a structural F-grade in the former Australian standard AS 2082 (2000) when visually graded, destructive testing showed significantly higher F-grade recoveries. Figure 1 shows the difference between visual grading and actual grade, based on MOR tested values, of *Eucalyptus cloeziana*

(Gympie messmate) boards. The authors suggested that the difference between visual grading and structural testing was because "the visual grading standard was prepared for a native forest hardwood resource in mind and implies that this standard is not appropriate for the grading of plantation-grown sawn structural material".



(a) (b)

Figure 1: F-Grade recovery of Gympie messmate plantation thinning boards in McGavin et al. (2006) based on (a) actual MOR values from destructive testing and (b) visual grading

A similar finding to McGavin et al. (2006) was previously encountered by Yang et al. (1996) who studied the mechanical properties of boards recovered from three globulus plantation stands in Tasmania. The stands were 19-, 21- and 33-year-old, with average Diameter at Breast Height Over Bark (DBHOB) ranging from 278 mm (19-year-old trees) to 411 mm (33-year-old tress). While not explicitly mentioned in the paper, the text suggests that the trees were extracted from fibre-managed plantations. Recovered sawn boards were first visually graded for structural purposes to former AS 2082 (1979) and then destructively tested in bending. Visual grading led to 31% to 58% of the boards being graded as "reject". The remaining boards had visual grades ranging from F14 to F27 (AS 1720.1, 2010), with the higher grades more commonly found in older stands. For the younger stands, boards were mainly rejected due to the presence of pith or heart material. From the destructive test results, all boards combined would lead to F4 grade. Only considering the boards not containing heartwood would result in a F8 grade. In comparison, the average bending MOR and MOE of 63.4 MPa and 15,326 MPa, respectively, of the tested boards correspond to a F17 grade. These values reflect the large variability in the mechanical properties of the resource and provide indications on a sizeable presence of high F-grades, presumably not fully captured by the visual structural grading. Additionally, the authors noted that all boards were intentionally loaded with the defects located at the tension side, i.e, at the most detrimental location, resulting in the calculated grades and bending MOR to be conservative.

Pangh et al. (2019) also found that structural visual grading was inappropriate for fibre-managed nitens and globulus boards, but not to the same extent as McGavin et al. (2006) and Yang et al. (1996).

The potentially inadequacy of the structural visual grading system in AS 2082 (2007) for plantation-grown boards may be overcame by the new visual grading system, named MEF, proposed by Fdez-Golfin et al. (2007). The authors characterised 452 boards of globulus cut from four different Spanish plantations (age of plantations not provided), and while not explicitly mentioned, the plantations were likely fibre-managed and the logs carefully selected (Washusen, 2013). The new grading system, better suited for the resource, resulted in characteristic bending values of 18,430 MPa for the MOE and 47.9 MPa for the MOR. These values are greater than the characteristic values of a F17 structural grade (AS 1720.1, 2010).

Further regarding the mechanical properties of globulus boards, Derikvand et al. (2020) converted 26-year-old globulus fibre-managed plantation logs from Tasmania and determined correlations between the bending properties (MOE and MOR) and visual characteristics, such as strength reduction factors. The logs had an average Small End Diameter Under Bark (SEDUB) of 403 mm. The slope of grain, amount of clear wood and total number of knots in the loading zone were found as the parameters influencing the MOR and MOE values the most. Average bending MOE and MOR of 11,800 MPa and 49.5 MPa, respectively, were encountered, values close to the characteristics values of a F14 structural grade (AS 1720.1, 2010). Some correlations were found between log MOE and board MOE (R^2 = 0.534), but not between log MOE and board MOR (R^2 = 0.104). No correlation was found between density and either MOE or MOR. Artificial neural network was used to predict MOE and MOR based on measured parameters.

Lara-Bocanegra et al. (2020) selected 300 plantation globulus boards (age of plantation not provided), visually graded to a D40 minimum strength in UNE 56546 (2013). Boards were only selected from the heartwood of the logs. No indication was given if the plantations were managed for structural or pulpwood purpose. 183 boards were tested in four-point bending and reached an average bending MOE and MOR of 18,108 MPa and 91.4 MPa, respectively, with a characteristic bending MOR value of 53.1 MPa, i.e. corresponding to a F27 structural grade in AS 1720.1 (2010). Similar to Derikvand et al. (2020), results showed no correlation between the density of the boards and bending MOR. However, a correlation existed between bending MOE and MOR, with the authors proposing to grade the boards based on the MOE value.

Franke et al. (2014) tested boards sawn from 20-year-old globulus logs from Portugal, with no information on the silviculture regime applied to the trees. However, according to Washusen (2013), globulus trees in Europe are carefully selected from fibre-managed plantations. Results showed average bending MOE and MOR, tensile strength parallel to grain (performed on small dog bone samples), compression strength parallel to grain, shear strength and bending MOE of 24,000 MPa, 115.4 MPa, 115.6 MPa, 83.2 MPa and 15.4 MPa, respectively. Such average values correspond to the characteristic values of a F34 grade, the highest structural F grade in the AS 1720.1 (2010).

Other studies encountered in the literature on eucalyptus typically did not look at structural grades but visually graded boards based on features and desired aesthetic appearance in AS 2796.1 (1999). When looking at globulus, as well as nitens, plantations, “high feature” (also referred to as “utility” or “merch” grade) boards were principally recovered if plantations were not thinned and pruned:

- Innes et al. (2008) explored producing sawn timber boards from both thinned/pruned and fibre-managed globulus (from 13- to 47-years-old) and nitens (from 13- to 26-years old) plantations. The boards were only visually graded. The percentage of high value “select” grade boards from the trial was much lower than the one obtained by the hardwood mills used in the study on their day-to-day resource, this being especially significant for young and unpruned trees. For instance, for 19-year-old thinned/pruned globulus, it ranged from 6% to 23% of the volume of the logs, depending on the log grade. It may be noted that Washusen (2013) raised doubts regarding the report by Innes et al. (2008) stating that the report “is lacking in detail […] making it inappropriate to draw conclusions about the suitability of plantation-grown E. nitens or E. globulus for sawn timber production”.
- Washusen et al. (2008) predominately obtained “high feature” boards from 21-years-old thinned and unthinned nitens plantation logs.
- Reid et al. (2001a) analysed the recovery of a small quantity (nine) of 10-year-old pruned nitens trees in southwest Victoria. The logs were only pruned up to a certain height. Between about 12%

(unpruned part of the logs) and 30% (pruned part of the logs) of the dried boards were graded as "select" or better.

- Washusen et al. (2009b) examined the log quality/volume yield, wood quality and selected mechanical properties of three 18-year-old eucalyptus species (globulus, viminalis and saligna) from clearwood trials in Western Australia. Globulus logs came from a high rainfall site. Only select boards were considered in the recovery process and boards from the centre cant were not attempted to be recovered. Recovery of the globulus select graded boards, as a percentage of log volume, was 20.7%.
- Brennan et al. (2004) studied the recovery of a limited number (five) of 17-year-old globulus "dominant" trees cut from a pruned and thinned plantation in Western Australia. The trees had a SEDUB ranging from 39.3 cm to 45.6 cm. 30% of the log volume was recovered as appearance grade boards based on the Western Australia Industry Standard (FIFWA, 1992), corresponding to 85% of the dried and dressed boards.

2.3 CLT

A few studies on Cross Laminated Timber (CLT) manufactured from globulus exist. Pangh et al. (2019) manufactured CLT panels out of unthinned and unpruned nitens (16-year-old) and globulus (26-year-old) plantation logs, with the globulus CLT samples performing better than the nitens ones. Ettelaei et al. (2022a) looked at the rolling shear strength of nitens and globulus CLT, also from unthinned and unpruned plantations, and found superior properties than softwood CLT.

In Tasmania, CUSP commercialises CLT manufactured from nitens (CUSP, 2022; Ettelaei et al., 2022a; Ettelaei et al., 2022b; Ettelaei et al., 2022c; Pangh et al., 2019).

2.4 Vineyard posts and natural rounds

Vineyard posts and naturals rounds represent solutions for small diameter logs which do not require large capital investments. McCarthy et al. (2005) studied the suitability of using thinnings, from either hardwood, softwood plantations or natural regrowth, into 2.4 m long vineyard posts, with diameter between 75 mm and 100 mm. Seven and two hardwood and softwood species, respectively, including globulus and radiata pine, were investigated. After treatment, all posts met a H4 hazard class (AS/NZS 1604.1, 2021). Globulus proved suitable for the targeted application. McGavin et al. (2006) looked at the possibility of using 8-9-year-old sub-tropical and tropical eucalypt plantation thinnings for round woods for vineyard posts, but also applications such as construction poles, landscaping products and fence posts. The limited results suggest that high structural grades of F14 to F17 (AS 1720.1, 2010) may be applicable.

2.5 Particleboards

In a review on the available information on the utilisation of plantation eucalypts in Engineered Wood Products (EWP), Hague (2013) mentioned that "there is no published work on the use of Australian-grown plantation eucalypts for particleboard production. Published data from overseas are … dominated by South American researchers". None of the overseas studies reported by Hague (2013) were performed with either globulus or nitens. Freischmidt et al. (2009) also outlined that the literature is limited on the use of eucalyptus species in the manufacture of particleboards. However, the authors mentioned that particleboards from hardwood species is possible as hardwood is known to be used in Europe for this purpose, however with species of lower density than the one typically encountered in eucalyptus. Trials by CSIRO, reported by Freischmidt et al. (2009), on eucalyptus and non-eucalyptus species resulted in boards with properties comparable to radiata control boards. Freischmidt et al. (2009) also warned that "there is also an issue of chip quality and fines with using eucalypts as detritus from chips and fines results in increased surface area and thus increased resin consumption, which may lead to poor panel performance if resin starved". Citing Pan et al. (2007), Hague (2013) mentioned that pre-treating particles in hot water significantly improved board properties. For a more detailed literature review on the potential use of Eucalyptus in the manufacture of particleboards, the reader is kindly referred to the reports by Freischmidt et al. (2009) and Hague (2013).

2.6 Strand/flake-based EWPs

In 2013, Hague concluded in a literature review that "no plantation eucalypts have been utilised anywhere in the world for the commercial production of strand/flake-based EWPs". More recently, Chen et al. (2019); (2020) proposed an orientated strand lumber from fast growing eucalyptus urophylla and grandis. The authors claimed that the product can be used in structural applications, especially columns. The company Lignor (Burton, 2021) promotes orientated strand lumber made from both globulus and nitens, with declared bending MOE and MOR for the globulus product just under 14,000 MPa and 124 MPa, respectively.

2.7 Medium Density Fibreboard (MDF)

In a literature review, Freischmidt et al. (2009) summarised studies made by CSIRO on manufacturing MDF out of eucalyptus species. The authors concluded that "it is possible to produce MDF from a eucalypt furnish but with higher densities than those currently used in the industry". They also noted that globulus is used in Europe and North Africa in the manufacture of MDF, but also likely in Asia and South America. Another study by U.S. Department of Agriculture's Forest Product Laboratory on manufacturing MDF from *Eucalyptus saligna* also proved the possibility of manufacturing MDF from eucalyptus species (Krzysik et al., 2001).

Since Freischmidt et al.'s literature review in 2009, additional studies on using eucalyptus species in the manufacturing of MDF have been published to which the interested reader is kindly referred to. A non-exhaustive list includes Kargarfard et al. (2010), Kargarfard (2012), Belini et al. (2012) and Gouveia et al. (2018).

3 Processing, recovery and drying

3.1 General

This section reviews the processing, recovery and drying of globulus logs to produce either sawn timber boards or veneers. Lessons learnt from processing young eucalyptus logs are also covered. The section aims at providing relevant information to support the decision making on the most suitable methods to process the fibre-managed globulus logs, investigated as part of this project, for the manufacturing of GLT and LVL.

3.2 Sawn timber boards

3.2.1 Processing and recovery

Washusen (2013) reviewed methods of producing solid wood products from Australian plantation-grown eucalyptus. The author noted that tension wood, defined by "abnormal wood produced by hardwoods as a reaction to bending stresses within the tree stem" and characterised by high peripheral tensile stresses (Washusen, 2013), commonly occurs in globulus. These growth stresses have been perceived by the industry to be a major constraint when processing plantation-grown eucalyptus (de Fégely, 2004a, 2004b). Growth stresses principally pose problems when sawing small diameter trees as opposed to larger ones (de Fégely, 2004b). Furthermore, Washusen (2013) mentioned that tension wood in thinned and pruned globulus stands is minor. However, in unthinned globulus stands, these growth stresses are especially common in young globulus plantation trees (Washusen et al., 2000). Therefore, careful selection methods need to be applied to eliminate logs with high tension wood when processing fibre-managed plantations.

It is worth noting that tension wood does not only affect sawing, but it also makes drying difficult (see next sub section). When analysing the effect of growth strain (measured as per Nicholson (1971)) on back-sawn 10-year-old unpruned plantation globulus logs from sites near Mt Gambier, Yang et al. (2002) found that increasing growth stress and decreasing log diameter had a direct negative effect on the percentage of excessively distorted sawn boards.

Problems associated with tension wood in nitens is less common. Nolan et al. (2005) reported that pruning is a good practice to overcome defects in sawn products which lead to downgrade of boards for both appearance and structural applications. Recovery in product quality seems to be substantially improved by early pruning.

Innes et al. (2008), looking at producing high value sawn boards from globulus and nitens plantations, concluded that sawing equipment adapted to the resource is needed to optimise recovery rate. Quarter-sawing, as shown in Figure 2, is not prescribed in the literature as a good strategy to process small diameter logs (less than small end diameter (SED) of 40 cm) (de Fégely, 2004b), but better suited for larger diameter logs. Quarter-sawing is typically used for Victorian native forest ash (Washusen, 2013). For this strategy and according to Washusen (2013), "growth stress release in small diameter logs has a major adverse effect on sawing accuracy, board distortion and board end-splitting". Additionally, Washusen (2013) refers to a study performed by the Neville Smith Timbers mill on 28 m^3 of large diameter (approximately 47 cm in diameter) unpruned globulus logs and to the study on 32 year-old thinned globulus logs in Washusen et al. (2004). In these works, the mills used the quarter-sawing strategy shown in Figure 2 and similar recoveries, calculated as the ratio of the volume of the dried boards to the volume of the green logs, to what is expected for ash were encountered.

For small diameter logs, Washusen (2013) recommends back-sawing, as shown in Figure 3, and referred to the studies by Washusen et al. (2007) and Washusen et al. (2009a) on pruned 22-year-old nitens. In these studies, back-sawing allowed recovering between 30% and 40% of the log volume into sawn boards, when compared to 25% to 30% for quarter-sawn. However, a higher percentage of "select" and "standard" boards, between 4% and 18% of the total log volume, were recovered from the quarter-sawn logs against 1% to 13% for the back-sawn logs. Another disadvantage of back-sawing was pointed out by de Fégely (2004b) who mentioned that quarter-sawing permits better recovery for collapse prone species, as occurring with globulus (Yang et al., 2003), during reconditioning. Also, when compared to back-sawing, quarter-sawing resulted in a reduction in internal and surface checking in nitens (Innes et al., 2008; Washusen et al., 2009a; Washusen et al., 2007). However, Washusen (2013) argued that little surface checking will occur for back-sawn logs if the boards are dried with care. On the plus side, when looking at processing fast-growing *Eucalyptus regnans*, Waugh et al. (1991) found that drying back-sawn boards "required low temperatures, high humidity and low air flow in the early drying stages" and that back-sawing strategies have "the potential to provide both higher sawlog yields from the forest and higher mill-door values than traditional quarter-sawing practices". When studying sawn boards from 17-year-old (SEDUB < 45 cm) pruned and thinned globulus logs, Brennan et al. (2004) stated that "cutting logs into short lengths and using a back-sawing cutting pattern assisted in reducing the amount of bow and spring".

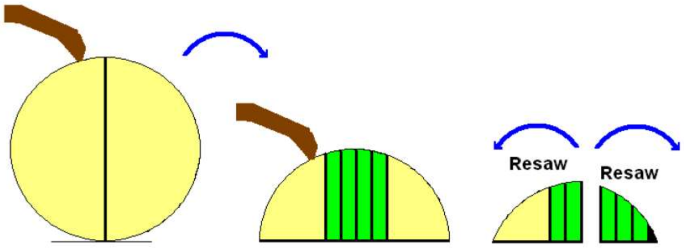


Figure 2: Quarter-sawing strategy suitable to logs of SED greater than 40 cm (Washusen, 2013)

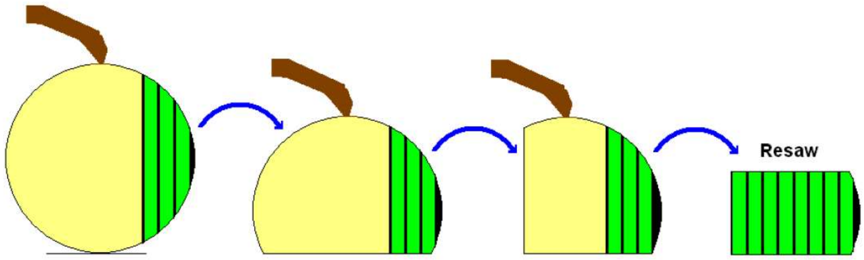


Figure 3: Back-sawing strategy suitable to logs of SED less than 40 cm (Washusen, 2013)

Washusen (2013) and de Fégely (2004b) also prescribe to use twin-saws, as opposed to single saws, when processing small diameter eucalyptus. Twin-saw systems release growth stresses more symmetrically, which result in centre cants with limited warping. However, Washusen (2013) outlined that twin-saws have more limitations on the maximum log diameter which can be processed than single saws. Splitting ahead of saws is also an issue that has emerged frequently in trials and Washusen (2013) recommends to further "release growth stresses uniformly from around the log". To do so, the author suggests to use chipper canters which practically remove wood simultaneously from all sides of the logs. Washusen (2013) added that if the logs "can be back-sawn with multi-saw systems, growth stress release is controlled better, sawing accuracy improved, board width increased and higher recoveries obtained, in comparison to quarter-sawing". The author further recommends the elimination of end-dogging in the sawing process as it contributes to preventing log end splitting. Additionally, for improved recovery, Washusen (2013) noted that the use of "a line-bar to single saw log break-down systems, coupled with multi-saws in down-stream processing, will help reduce the thickness and width variation".

The saw-dry-rip (Larson et al., 1983) and tangential processing methods (Figure 4) have been investigated by Franke et al. (2014) on 20-year-old globulus logs from Portugal. In the saw-dry-rip method, wide flitches are first cut and dry. As the flitches are wide, it reduces warping during drying and as "the flitch dries the growth stresses are largely relieved due to slippage of the wood wells relative to one another while the piece holds it shape" (Larson et al., 1983). The flitches are then cut into boards and further dry. Before final drying, the saw-dry-rip method exhibited superior board recovery than the tangential method, with the production of boards showing nearly half less bow and spring distortion.

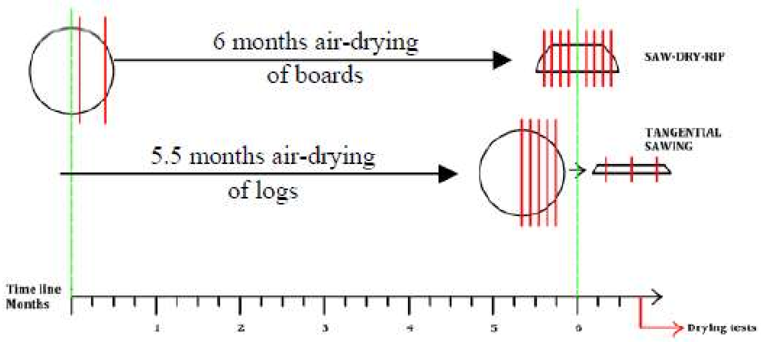


Figure 4: Saw-dry-rip and tangential processing technique used by Franke et al. (2014)

In terms of recovery:

- McGavin et al. (2021) looked at the recovery of small diameter pruned and thinned *Khaya senegalensis* (African Mahogany) logs. The logs were extracted from four sites with average DBHOB ranging from 253 mm to 356 mm. Logs were sawn into 20 mm and 25 mm thick boards using a Kara-Master processing system. After grading to AS 2796.2 (2006) for visual appearance, the sawn graded recovery (i.e., the ratio of the volume of dried non-reject boards to the volume of the green logs) ranged between 16% to 30%, depending on the site.
- Washusen et al. (2004) and Reid et al. (2001b) processed various diameter globulus and nitens plantation logs, respectively, harvested in Victoria, into appearance quality solid timber. The effect of pruning and thinning on the quality of the boards was investigated. Results showed that recovery, and product quality and value, improved with time, i.e., with the diameter of the logs since thinning.
- Recovery of graded boards (AS 2796.1, 1999) ranged between 27% (quarter-sawn) and 31% (back-sawn) in Washusen et al. (2008) for 21-years-old unthinned nitens plantation logs.
- From back-sawn 10-year old nitens logs, which were only pruned on a given portion of the trees, Reid et al. (2001a) recovered about 41% of the logs into boards (graded and non-graded all together).
- Recovery, calculated as the volume of the dried undressed boards to volume of the logs, was 31.8% out of 26-year-old fibre-managed Tasmanian globulus logs (Derikvand et al., 2020). The logs were processed with a plain sawing pattern and had an average SEDUB of 403mm.
- An unpublished trial from the Green Triangle processed 54 m^3 of globulus logs using a Hew saw 250. Bow in flitches were encountered immediately. Smaller diameter logs seemed to run better than larger ones. No information was provided on how the boards behaved when dried (GTFIH, 2022).

3.2.2 Drying

Tension wood does not only affect processing logs but also the quality of the boards recovered after drying. Washusen (2013) noted that “tension wood is extremely unstable during drying and has very high transverse and longitudinal shrinkage” and concluded that “internal checking is not a serious problem in plantation-grown globulus provided that logs with high levels of tension wood are avoided and appropriate sawing strategies are applied”. Tension wood accounts for some of the drying defects.

Neumann et al. (1992) found that checking will reduce in 30- to 40-year-old globulus if the initial drying temperature of the kiln is kept as low as possible, preferably below 30°C. Regular high humidity treatment also helped reducing honeycomb. However, Chafe et al. (1996) found that pre-steaming radially sawn boards cut from 40-year-old globulus logs provided little reduction in internal checking, a result different from Neumann et al. (1992). Bekele (1994, 1995) studied different drying methods of young plantation globulus boards from Ethiopia, consisting of air, one high (between 40°C and 65°C) and one low (between 22.5°C and 35°C) temperature kiln drying regimes. The full schedules for kiln drying are provided in the paper with the temperature increasing as the boards dry. Selected trees had an average SEDUB of 15.2 cm. For kiln drying, while taking longer, 840 h instead of 520.5 h, low temperature drying resulted in less, but still comparable, geometric imperfections (bow, twist and cup) and internal checking. In comparison, higher degradations were observed for air drying over 14 months. In all cases and after planning, the authors claimed that mainly utility boards according to former Australian standard AS 2796 (1985) were produced.

Washusen et al. (2000) compared two different drying regimes on conventionally back-sawn 40 mm thick boards from 15-year-old unpruned and unthinned plantation globulus logs, harvested from the Murray darling basin. In the first drying regime, the boards were air dried to 26.5% MC and then kiln dried, whereas, in the second drying regime, the boards were kiln dried directly from green. The drying schedules are provided in the paper, with the dry bulb temperature increasing from 30°C to 80°C for the latter schedule. Results showed that "drying degrade in the form of either surface checking, internal checking or distortion and splitting or combination of these defects was severe and led to serious degrade under both drying regimes." Low recovery (less than 2%) of Select grade or better was achieved. Tension wood accounted for some of the drying defect.

Hansmann et al. (2008) reported that globulus is known to be susceptible to drying stresses leading to "collapse, case hardening, honeycomb, checking and cupping". Collapse can also occur during air drying, and controlled drying is important. The authors used vacuum drying with high-frequency energy (400W @ 13.6MHz) to best dry a limited number of "quality" globulus boards, i.e., without cracks, cell collapse, warp, or obvious discoloration. The vacuum aimed at decreasing the boiling point of water. The authors claimed of reduced cell collapse with this drying method, but no benchmarking to other drying method was performed. Still on vacuum drying, Franke et al. (2014) compared different drying techniques on 20-year-old globulus logs from Portugal. Vacuum drying took place after air-drying, with a schedule for European oak, and performed better than kiln drying.

Brennan et al. (2004) kiln dried 28 mm to 50 mm thick globulus boards, with the drying conditions increasing as the MC decreased. The authors found that some of the thicker boards (50 mm) collapsed after drying, with the collapse being recovered with a 8 hour steam recondition. Bow and spring of flitches were not found to be an issue when drying. Overall, after dressing, collapse and surface checking were not observed. In a literature review, Washusen (2013) also found that "substantial reduction in visible internal checking in E. nitens is possible with good drying practices and it can be largely eliminated by sawing thin-section boards" (less than 25 mm thick). "Sawing thin section back-sawn and quarter-sawn boards <25 mm thickness will improve drying results if boards are dried carefully above fibre saturation point and a steam reconditioning treatment applied at a mean moisture content of 15%". Washusen (2013) also pointed out that "the defect in dried boards appears as high shrinkage, surface and internal checking and distortion in the form of spring, bow (that may not be present after sawing), cupping and twist". Boards up to 43 mm thick can be achieved with good results.

Other drying schedules encountered in the literature for globulus, but not specific to studying how to dry the resource, include:

- Yang et al. (2002) air-dried 20 mm to 40 mm thick boards cut from 10-year-old globulus to 18% MC for 13 months, then kiln dried.
- Derikvand et al. (2020) processed 26-year-old globulus plantation logs from Tasmania, with the boards being pre-dried for 9 weeks under weights, then airdried for 3 weeks and finally dried in a conventional kiln to target 12% MC.

3.3 Veneers

The Queensland Department of Agriculture and Fisheries has investigated for the last decade the opportunity to use spindleless lathe technology and maximise the recovery of small diameter logs into veneers (McGavin et al., 2015b; McGavin et al., 2014a; McGavin et al., 2013; McGavin et al., 2014b; Venn et al., 2020). Australian plantation globulus and nitens have been included as part of the studies (McGavin et al., 2015a; McGavin et al., 2015b; McGavin et al., 2014a; McGavin et al., 2014b). The technology, commonly used in South-East Asia, China and Vietnam, is emerging in Australia. Contrary to traditional spindled lathes, which use spindles or 'chucks' to hold the logs on its sides and rotate it against the blade, spindleless lathes have rollers which apply pressure to the back of the logs, resulting in 20-50 mm diameter peeler cores, as opposed to 110 mm and above for spindled lathes (McGavin, 2017). This technology is therefore well adapted for small diameter logs and high recovery of the log volume into veneers. To illustrate, for trees having average DBHOB between 20 cm and 37 cm, green recovery rates (calculated as ratio of the volume of the recovered green veneers to the billet volume) ranges between 68% and 84% and net recovery rates (calculated as the ratio of the volume of the saleable trimmed veneers to the billet volume) between 48% and 58% (McGavin et al., 2015b; McGavin et al., 2014a). For 13-16-year-old globulus of average DBHOB of 30.6 cm and harvested from three sites in Victoria, net recoveries were between 49% and 52% (McGavin et al., 2015b; McGavin et al., 2014a). These numbers are superior to the sawn recovery (calculated as the ratio of the volume of the dried back-sawn boards to the volume of the green logs) of about 30% in Washusen et al. (2009a) for average DBHOB between 36 cm and 41 cm plantation nitens. In McGavin et al. (2013) the recovery using spindleless lathe technology was up to six times higher than what would be recovered from the same resource if it was converted into sawn timber products.

For further comparison, when peeling with spindleless lathe technology 7.5-year-old to 19-year-old African Mahogany logs, McGavin et al. (2021) found net recovery ranging between 42% to 57%. This compares to a recovery for sawn graded boards extracted from trees of the same site between 16% to 30%. The trees selected had DBHOB between 25 cm and 36 cm, depending on the site.

Farrell et al. (2011) assessed the possibility of using 16- to 26-year-old fibre managed nitens and pruned 33-year-old globulus logs in the manufacture of plywood and LVL, with a focus on nitens. For the nitens, no veneers met a visual appearance grade higher than D in the former Australian standard AS/NZS 2269.0 (2008) and between 50% to 60% did not meet a visual grade at all. For the globulus veneers, the majority of the veneers (96%) was visual grade D. Similarly and more recently, McGavin et al. (2014b) studied the grade recovery of veneers peeled from plantations established from various purposes, including (1) 10- to 16-year-old spotted gum, Gympie messmate and *Eucalyptus pellita* (red mahogany) sawn timber plantations, (2) 11- to 16-year-old *Eucalyptus dunnii* (Dunn's white gum) and globulus fibre-managed plantations and (3) 20- to 22-year-old nitens fibre-managed plantation. Results showed that D-grade veneers (AS/NZS 2269.0, 2012) dominated, with less than 1% classified as A-grade veneers for all investigated plantations. For globulus and nitens, D-grade veneers represented 84.3% and 67.7%, respectively, of the peeled veneers. Even for 16-year-old thinned and pruned globulus plantations in McGavin et al. (2015b), D-grade veneers represented nearly 81% of the trial, with no veneers meeting the requirements for A-grade. The above results indicate that visual appearance veneer-based structural products are unlikely to emerge from fibre-managed plantations alone.

In terms of the mechanical properties of veneers, MOE between 8,000 MPa and 15,000 MPa, 16,000 MPa and 22,000 MPa, and 22,000 MPa and 32,000 MPa were recovered by Farrell et al. (2011) from fibre-managed 16-year-old nitens, 26-year-old nitens and 33-year-old globulus, respectively. The authors considered "that young unpruned E. nitens has low usefulness for higher value veneer and ply production". However, while the visual grade recovery of the veneers was low (see paragraph above), the high MOE of the veneers and the resulting high mechanical properties of manufactured plywood panels, further detailed in Section *Laminated Veneer Lumbers*, indicate that if face grade veneers are not required, fibre-managed logs can be used in the manufacture of valuable structural products.

Additionally, McGavin et al. (2015a) extended the research in McGavin et al. (2014b) by looking at the density and MOE distributions of the resources cited in the above paragraphs. The 13-16-year-old globulus logs, with an average DBHOB of 30.6 cm, resulted in an average MOE of the veneers of 15,896 MPa, with a CoV of 30.8%. The nitens veneers, with the trees having an average DBHOB of 34.0 cm, showed an average MOE of 14,520 MPa, with a CoV of 25.9%. Relative to sawn timber grades, the average MOE values for the globulus veneers in Farrell et al. (2011) and McGavin et al. (2015a) correspond to the characteristic values of F34 and F17 structural grades (AS 1720.1, 2010), respectively. The MOE distributions from the two fibre-managed nitens and globulus resources in McGavin et al. (2015a) are shown in Figure 5.

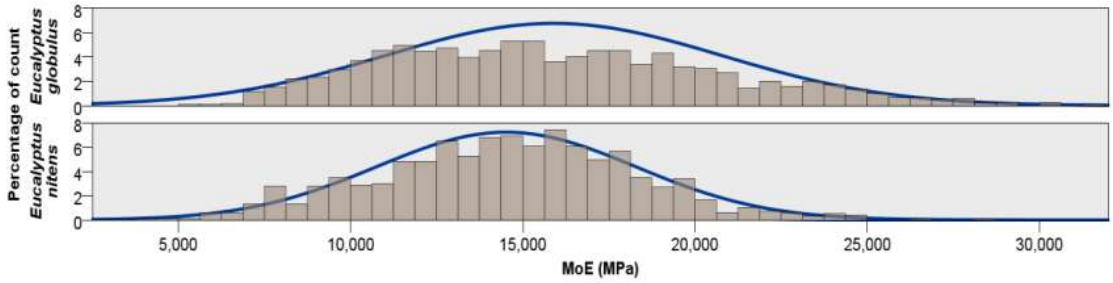


Figure 5: MOE distributions of veneers recovered by McGavin et al. (2015a) for (top) globulus and (bottom) nitens

A technical guide to rotary peel small diameter logs has been published by the Australian Centre for International Agricultural Research (ACIAR, 2017), and can be used as a reference in the project.

4 GLT beams

4.1 General

This section reviews studies investigating the manufacture of globulus and hybrid hardwood/softwood GLT. The section focusses on the published mechanical properties of the beams, solutions to finger joint and glue globulus boards.

It is worth mentioning that investigations have been performed on either using young eucalyptus logs to manufacture GLT or using globulus boards in applications which could relate to GLT:

- McGavin et al. (2006) looked at the possibility of manufacturing GLT beams from plantation Gympie messmate thinned logs. No information was provided on the glue type, finger joints geometry and manufacturing process. Tests on the finger joints alone complied with a F8 stress grade. While the number of GLT beams manufactured and tested was low (four beams), results suggested that a GL10 or GL12 GLT grade may be expected (AS 1720.1, 2010). Additionally, in a 2013 literature review, Hague (2013) reported that no "published work in Australia on the use of plantation eucalypts for glulam are evident in the literature". GLT manufactured from other hardwood species, such as spotted gum and Victorian ash, are now manufactured and commercialised in Australia by Hyne timber (2022), Vicbeam (2022) and ASH (2022).

- Jiao et al. (2019) and Derikvand et al. (2019) analysed the possibility of manufacturing nail laminated and glued laminated floor panels manufactured from nitens and globulus boards. The boards were sawn from 15-year-old nitens (average SED = 345 mm) and 26-year-old globulus (average SED = 403 mm) thinned and unpruned logs. Results showed that by sharing the load, the composite floor panels offered superior performance than individual boards.

4.2 Globulus GLT

4.2.1 Mechanical properties

Studies on globulus GLT are scarce and have solely been performed in Europe. Martins et al. (2020) manufactured non-finger jointed, 5-layer, globulus GLT beams. The beams were 120 mm deep and 92 mm wide. No indication was given on the silviculture regime, but the trees were likely carefully selected from unthinned and unpruned plantations (Washusen, 2013). The seven tested globulus GLT reached an average apparent bending MOE and MOR of 22,341 MPa and 114.9 MPa, respectively. This corresponds to a GL18 structural grade in AS 1720.1 (2010), i.e., the highest grade.

Lara-Bocanegra et al. (2020) looked at the mechanical properties of 2-layer finger jointed GLT globulus beams, manufactured with 1-component polyurethane (PUR) and D40 or above graded boards (UNE 56546, 2013). The small GLT beams reached an average and characteristic bending MOR of 61.3 MPa and 45.2 MPa, respectively, i.e., also corresponding to a GL18 structural grade (AS 1720.1, 2010).

4.2.2 Finger jointing

Producing strong finger joints is important to manufacture useable GLT out of shorter boards. Lara-Bocanegra et al. (2017) investigated the strength of finger-jointed globulus boards, with the boards solely being selected from the heartwood of the trees and with a “radial annual ring orientation”. It was not mentioned if the boards were sawn from trees planted for structural or pulpwood purpose, but as mentioned earlier, the trees were likely carefully selected from fibre-managed plantations (Washusen, 2013). The joints were glued with 1-component PUR (Purbond HB S 109), with the applied amount of glue not specified. The fingers were orientated vertically and glued immediately after being cut. 10 mm and 15 mm long finger joints were investigated with end pressure ranging from 4 MPa to 20 MPa. Recommendations in EN 14080 (2013) and EN 15497 (2014) on finger geometry limitations were followed. The 15 mm long fingers provided superior better mechanical performance. End pressure was found not to be critical in enhancing the strength, while small variation in the tip width of the 15 mm long fingers allowed increasing the joint strength. 58% of the joints failed in the glue, i.e., representing a Mode I failure type in Appendix D of the AS 5068 (2006). Modes III and IV (AS 5068, 2006), i.e., combined failure at the finger roots and wood failure, were only encountered for the boards with the lowest MOE (between 14,000 MPa and 20,000 MPa). Despite the predominant failure mode in the glue, the finger jointed boards reached on average up to 80% of the strength of the non-finger jointed boards, with high average bending MOR up to 87 MPa. This corresponded to characteristic bending MOR ranging from 49.9 MPa (10 mm joints and worst tested configuration) to 76.2 MPa (15 mm joints and best tested configuration). Such results would allow high grade GLT beams to be manufactured, but the joints would however not meet the requirement for bond durability in the AS 5068 (2006).

When manufacturing GLT, Lara-Bocanegra et al. (2020) used the optimum finger configuration and pressure from the work mentioned in the above paragraph using either 1-component PUR (Loctite HB

S309 Purebond) or Melamine-Urea-Formaldehyde (MUF) (GripPro Design Adhesive A002). Relative to the solid boards, the bending strength of the finger jointed boards were 6% to 9% lower with the PUR adhesive and equal to with the MUF adhesive.

González-Prieto et al. (2022) analysed the possibility of finger jointing green and dry globulus clear wood. 10 mm finger joints were glued under a pressure of 7 MPa and 12.5 MPa for the green and dry boards, respectively, with 1-component PUR (Jowapur 686.60). The green finger jointed boards resulted in equal performance, in terms of bending stiffness and strength, to the control non finger jointed boards. However, the dry finger jointed boards showed a bending strength 23% lower than the control samples. Note that the green finger jointed boards had a higher average density and more density variability within the group than the dry and control boards which may have influenced the results. A mix failure mode occurring both in the wood and glueline was observed.

Gluing

In view of manufacturing globulus GLT, López-Suevos et al. (2009) investigated the use of hydroxymethylated resorcinol (HMR) and novolak-based HMR (n-HMR) primers to bond the boards together, with n-HMR having longer pot life and less waiting period than HMR before applying the glue. GLT samples were manufactured with and without primer, and with either 1-component PUR (Jowpur 686.60) or MUF (Kauramin glue 683 with Kauramin hardener 688). Control samples were also bonded with resorcinol-phenol-formaldehyde (Aerodux 185 with HRP 155 hardener) with no primer. The samples were 6-layer and boards primed with n-HMR were either planed or not. The bond between boards were evaluated for service class 3 following Method A in now EN 14080 (2013), i.e., equivalent to Method A in AS/NZS 1328.1 (1998). With longer press time (5 h), only using PUR with no primer was shown to be effective preventing delamination (2.3% delamination). Delamination significantly increased when the press time was reduced to 2.25 h (19.4% delamination). However, for the same press time of 2.25 h, the use of the HMR primer with PUR, resulted in a 0.6% delamination. Without primer, MUF didn’t perform well (24.1% delamination), while its use with HMR reduced the delamination to 3.1%. The reference samples with resorcinol-phenol-formaldehyde did not perform well, with 19.6% delamination. Even when boards that were not planed prior to bonding, the use of n-HMR was efficient in preventing delamination.

Franke et al. (2014) glued globulus boards with 1-component PUR, with or without primer. The names of the PUR and primer used were not mentioned in the reference. Similar to López-Suevos et al. (2009), results showed that the use of prolonged curing time in the press and primer significantly improved adhesion. However, the samples did not pass the minimum delamination criteria in the European standard. Martins et al. (2020) also reported contradictory results to López-Suevos et al. (2009) when using single component PUR adhesives (either Purbond HB S709 with PR 3105 primer or Jowapur 686.60) in the manufacture of 5-layer globulus GLT. When tested following Method A in EN 14080 (2013), the samples showed inadequate performance, despite the samples being pressed longer (7h) than in López-Suevos et al. (2009) and with the same adhesive.

Suleimana et al. (2020) investigated the gluing of globulus boards using MUF (AkzoNobel MUF 1247/2526). No detailed information was provided on the resource, apart from the species, and the gluing process, apart from that it was done in an industrial facility. Only block shear tests were performed, and results showed failure in the wood. No durability assessment of the gluelines was undertaken.

4.3 Hybrid hardwood/softwood GLT

Hybrid hardwood/softwood GLT have been investigated in the literature to optimise the use of the two resources. Only one study was found on hybrid GLT using globulus. Notwithstanding, lessons learnt from other published studies are covered in this section.

Regarding globulus, on top of manufacturing globulus only GLT, Martins et al. (2020) manufactured 5-layer, 120 mm deep and 92 mm wide, hybrid globulus/poplar beams. Globulus boards were positioned as the top and bottom lamellas. The hybrid samples reached average bending MOE and MOR of 18,302 MPa and of 91.0 MPa, respectively, corresponding to a reduction of 18.1% for the MOE and of 20.8% for the MOR relative to the globulus only GLT.

Blaß et al. (2006) looked at 10 lamellas hybrid GLT beams made of softwood and beech, with beech being located as the two top and bottom lamellas. Simulations indicate that European grade GL32 to GL48 (EN 14080, 2013) could be achieved. Hybrid oak and spruce 150 mm deep GLT beams, composed of 5 lamellas, were manufactured and tested by Muraleedharan et al. (2016). Different configurations were analysed with the oak lamellas either positioned as the bottom lamella or as both the top and bottom lamellas. When compared to spruce only beams, replacing the bottom lamella by oak increased the bending MOR by a factor of 1.5 while replacing both top and bottom lamellas increased it by a factor 2. However, no significant bending strength difference was found between the latter and all oak beams. In terms of bending MOE, likely because there was no meaningful difference in stiffness between the oak and spruce lamellas, the influence of the layout on the MOE was significantly less than on the bending MOR. Finally, Sciomenta et al. (2022) manufactured beech and hybrid beech/Corsica pine 144 mm deep (8 lamellas) GLT beams. For the hybrid beams, the beech lamellas were located as the top and bottom lamellas. When compared to the beech only beams, the bending MOE and MOR of the hybrid specimens were 12% and 9% lower, respectively. However, the shear capacity dropped by 32%.

Commercially, Hess produces hybrid GLT beams with the inner layers manufactured from softwood and the outer layers from oak, chestnut or Western Red Cedar (Hess, 2022).

Regarding a slightly different hybrid product, Dill-Langer et al. (2014) glued a beech LVL as the bottom lamella of a softwood GLT beam. Results showed a promising high strength product, with the LVL lamella more than doubling the bending MOR of the softwood GLT alone, reaching values of about 50 MPa.

Hybrid GLT manufactured using low-grade timber were only found in the literature in a combination of material other than wood, such as fibre reinforced polymer (FRP), see Raftery et al. (2011), Raftery et al. (2014), O’Ceallaigh et al. (2014) and Raftery et al. (2015) for instance.

5 Laminated Veneer Lumbers

5.1 General

Published mechanical properties on globulus LVL and adhesive used to bond globulus veneers are scarce. Nevertheless, various studies can relate to the current project and investigated either producing globulus plywood or using eucalyptus logs to manufacture veneer-based products. Consequently, this section first reviews studies looking at either globulus plywood or other eucalyptus LVL. Second, the mechanical properties of globulus LVL and of various adhesives used to bond globulus veneers are discussed. Finally, hybrid hardwood/softwood LVL are reviewed.

5.2 Globulus plywood or LVL from other eucalyptus species

5.2.1 Mechanical properties

McGavin et al. (2006) found that F17 to F22 plywood sheets (AS 1720.1, 2010) were to be expected from red mahogany thinnings. Plywood boards (5-ply) and LVL beams (13-ply) were further investigated by McGavin et al. (2013) using plantation thinnings of different species, including Dunn's white, spotted gum hybrid and Gympie messmate. Different construction strategies consisting of segregating the veneers based on their MOE values were investigated. In terms of stiffness and strength, the plywood panels typically resulted in F14 to F22 grades (AS 1720.1, 2010), irrespective of the construction strategies, with the F grades per species and mechanical property provided in Table 1.

Table 1: Assigned F-grades for plywood face grain parallel and perpendicular in McGavin et al. (2013)

Species	Bending MOE		Bending MOR f'b		Tension f't		Panel shear f's		Compression in the plane f'c	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	F11	F14	F8	F11	F14	F11	F14	F14	F17	F17
Spotted gum	F22	F22	F22	F27	F27	F34	F34	F34	F17	F27
Gympie messmate	F14	F17	F14	F14	F17	F17	F34	F34	F14	F22
Spotted gum hybrid	F14	F14	F17	F17	F22	F22	F34	F34	F22	F27

Regarding the LVL beams, average edge bending MOE and MOR greater than 12,500 MPa and 70 MPa, respectively, were found. This corresponds to the characteristic values of a F14 equivalent sawn timber grade (AS 1720.1, 2010), with the MOE being the limiting factor for higher grade classification. The lowest average compressive and shear strengths, out of the four studied resources, were greater than 55 MPa and 30 MPa, respectively.

Additionally, in a literature review on the utilisation of plantation eucalypts in EWP, Hague (2013) found that LVL manufactured from unpruned 15-year-old New-Zealand nitens "had strength and stiffness properties which were higher than those of LVL made from New Zealand-grown Pinus radiata veneer". Freischmidt et al. (2009) referred to a 1996 CSIRO study which manufactured LVL out of various Eucalyptus species (not including globulus and nitens). The products showed overall excellent mechanical properties but with a shear strength lower than softwood LVL.

Farrell et al. (2011) manufactured plywood out of 16- to 26-year-old nitens and 33-year-old globulus fibre-managed logs. The plywood panels were fabricated with different strategies, including optimising the MOE of the final products by positioning the stiffer veneers as faces. The strength and stiffness of the plywood panels typically increased with the age of the trees. Overall F7 to F8 grades (AS 1720.1, 2010) were encountered, with the shear strength being the limiting factor for higher grade classification. The 33-year-old globulus, 26-year-old nitens and 16-year-old nitens plywood reached a grade of F34, F27 and F11, respectively, relative to their parallel to face bending characteristic values.

5.2.2 Gluing

Hopewell et al. (2008) used phenol-formaldehyde (PF) (Type A) and MUF (Type B) adhesives to manufacture plywood from veneers peeled from 15-year-old red mahogany and 19-year-old Gympie messmate pruned and thinned plantation logs. Type A adhesive performed satisfactory for all plywood types in accordance to former Australian and New-Zealand standard AS/NZS 2269 (2004), while Type B bonds were usually unsatisfactory.

A MUF adhesive was used in the production of plywood from red mahogany thinnings in McGavin et al. (2006) and complied with the requirements for Type B bond in the former AS/NZS 2098.2 (2006). Additionally, when manufacturing plywood and LVL from thinnings of various eucalyptus species, McGavin et al. (2013) tested several formulations of PF adhesive which generally showed satisfactory performance for Type A bond (AS/NZS 2098.2, 2012), overall producing superior results than the various formulations of MUF and PUR adhesives tried.

Lumin is commercialising plywood from eucalyptus species using a formaldehyde-based adhesive (Molinari, 2020).

5.3 Globulus LVL

5.3.1 Mechanical properties

Gilbert et al. (Gilbert, 2018; Gilbert et al., 2017b) developed a new methodology to predict the strength and characteristic values of LVL beams and columns based on the properties of the individual veneers. The methodology was verified and applied to LVL manufactured from rotary peeled veneers from 13- to 16-year-old globulus logs harvested from fibre-managed plantations in Victoria. The strength of individual veneers was first measured and found to be strongly correlated to the veneer MOE and the presence of knots (Gilbert et al., 2017a; Gilbert et al., 2018). Then, using the expected MOE distribution of the veneers entering the mill (obtained from McGavin et al. (2015a) and Figure 5), the known mechanical properties of the veneers and the validated numerical model, the authors found that for a 300 mm deep reference LVL: (1) if veneers were segregated in the mill in terms of MOE, the characteristic bending MOR ranged from 52.2 MPa (equivalent to F17 for sawn timber (AS 1720.1, 2010)) for the lowest MOE veneers to 75.0 MPa (equivalent to F27 for sawn timber (AS 1720.1, 2010)) for the highest MOE veneers, (2) if no veneer segregation was performed, a characteristic MOR of 64.3 MPa (equivalent to F22 for sawn timber (AS 1720.1, 2010)) was expected. For 300 mm deep LVL columns, characteristic compressive strength ranged from 39.5 MPa (equivalent to F17 for sawn timber (AS 1720.1, 2010)) to 51.9 MPa (equivalent to F27 for sawn timber (AS 1720.1, 2010)). Characteristic bending MOE were not analysed but in view of the MOE distribution in McGavin et al. (2015a), not segregating the veneers in the mill would result in an average MOE of the LVL equivalent to a F22 grade for sawn timber.

5.3.2 Gluing

The use of tannin–phenol–formaldehyde (Stefani et al., 2008; Vázquez et al., 1996; Vázquez et al., 2003) or lignin–phenol–formaldehyde (Vázquez et al., 1995) adhesives were proposed to glue globulus veneers with the aim of reducing formaldehyde emission, improving spreading, allowing higher moisture content of veneers at the time of gluing and decreasing adhesive consumption. Substituting the phenol by tannin or lignin seemed to decrease the adhesion, measured in terms of wood failure percentage (Stefani et al., 2008; Vázquez et al., 1995). When tested for bond quality according to EN 314.1 (1993) and EN 314.2 (1993) by Vázquez et al. (2003), tannin–phenol–formaldehyde passed the requirements for exterior conditions.

Farrell et al. (2011) used PF to manufacture plywood out of 33-year-old globulus. Panels were first cold-pressed and then hot-pressed. When tested in accordance with former AS/NZS 2098.2 (2006), samples passed the criteria for a A-bond quality.

Iwakiri et al. (2013) looked at the possibility of manufacturing plywood from nine eucalyptus species, including 18-19-year-old globulus. Veneers were glued with PF resin with a solid content of 49%, a pH of 11.5 and a Brookfield viscosity of 420 cP. The globulus samples passed the bond quality tests for exterior applications in EN 314.1 (2004) and EN 314.2 (1993).

Spanish company Garnica manufactures poplar and globulus plywood boards (Martínez, 2022) using a formaldehyde-based adhesive and achieved a Class 3 bond durability, i.e., for external applications, following EN 636:2012+A1 (2015).

5.4 Hybrid hardwood/softwood LVL

Several studies have looked at mixing hardwood and softwood to manufacture hybrid LVL products, none with globulus or nitens.

Keskin (2004) manufactured oak and Scotch pine LVL. The samples were tested on flat bending, shear and compression parallel to grain. For all construction strategies, high strength bending MOR were obtained, greater than 100 MPa on average, while the associated bending MOE did not reach 11,000 MPa. Difference between construction strategies were principally noticeable regarding the compression and shear strengths.

Burdurlu et al. (2007) looked at manufacturing hybrid LVL from beech and poplar veneers. Using species of significantly different stiffness, the combination of the two types of veneers resulted in products with significantly improved bending properties (greater than 25% for MOR and 50% for MOE) relative to the LVL manufactured from poplar alone. Similar improvements than above were found by Wong et al. (1996) when reinforcing rubberwood LVL with acacia veneers. H`ng et al. (2010) also strengthened low density LVL, made either from pulai, sesendok or kekabu hutan, with high density Keruing veneers. PF adhesive was used in the manufacture and the products passed the boil-dry delamination cycle test in the Japanese standard SIS-24 (1993). While the number of samples manufactured was small and the LVL were only tested on flat bending, not on edge as in most structural applications, results indicated that the hybrid products meet the requirements for various LVL grades, in terms of strength and stiffness, in the Japanese standard SIS-24 (1993).

Cihad Bal (2016) manufactured hybrid LVL made from poplar and Eucalyptus grandis veneers. PF adhesive was used in the manufacture and the bound quality satisfied the requirements for external uses in the EN 314.1 (2004) and EN 314.2 (1993). The hybrid products showed high average bending MOR, greater than 70 MPa, but relatively low MOE in comparison, less than 7,100 MPa. However, it was unclear how the deflection of the LVL under load was measured in the calculation of the MOE.

McGavin et al. (2019) looked at mixing plantation hoop pine veneers with either native forest white cypress or spotted gum veneers in the manufacture of LVL. MUF was used to achieve a Type-B bond in the AS/NZS 2754.1 (2016). Flat and edge bending, longitudinal shear, tension perpendicular to grain and bearing strength perpendicular to grain were assessed. The research showed the opportunity to optimise the construction strategies by mixing species to produce fit-for-purpose LVL. Building on this finding, Nguyen et al. (2019) proposed an algorithm to optimise the use of available resources to manufacture a family of mixed species LVL products based on the distribution of the veneer MOE and the importance given by the manufacturer of each veneer grade. The algorithm also considered the manufacturing of cross-banded LVL (Nguyen et al., 2020).

Murata et al. (2021) looked at manufacturing LVL with Chinese poplar and eucalyptus plantation veneers. Softwood and hardwood veneers were alternated to improve gluing by not having two hardwood veneers glued together. No indication on the specific eucalyptus species used was provided.

In Australia, Wesbeam (Wesbeam, 2021) commercialises hybrid LVL products manufactured from maritime pine and Karri, with characteristic bending MOE and MOR of 13,200 MPa and 50 MPa, respectively, i.e., corresponding to a F14 equivalent sawn timber grade (AS 1720.1, 2010).

6 Conclusion and recommendations

This report outlined the challenges, best practices and opportunities to manufacture globulus and hybrid radiata pine/globulus LVL and GLT as part of the "Splinters to Structures" project. The dot points below summarise the key findings and provide recommendation for the next stages of the project:

- *Logs selections*: Fibre-managed globulus logs must be carefully selected to avoid tension wood which creates challenges in sawing the logs and drying the boards. Selected large diameter logs are recommended as growth stresses tend to be more present in small diameter trees.
- *Processing (sawn boards)*: (1) back-sawing is recommended to saw the less than 40 cm diameter logs to be encountered in this project. Additionally, twin-saws are advised as they release growth stresses more symmetrically. The use of chipper canters to practically remove wood simultaneously from all sides of the logs is also suggested to increase board recovery. (2) Thin boards (< 30-40 mm) sawn from fibre-managed eucalyptus plantations are more likely to be successfully dried with higher recovery and lesser drying defects. Vacuum drying has showed promising results on globulus and steam reconditioning generally allows recovering boards that collapsed during drying.
- *Sawn timber board properties*: (1) European experience indicates that boards with high mechanical properties are achievable from fibre-managed globulus if the logs are carefully selected. (2) However, visual structural grading used in Australia for hardwood sawn timber is not a good indicator of the mechanical properties of fibre-managed or young plantation hardwood logs. This grading technique significantly underestimates the mechanical properties of the boards and is not recommended to be used in the project. (3) A new visual grading system adapted to fibre-managed globulus plantations has been proposed in Europe and is suggested to be verified. (4) Appearance structural products cannot be manufactured from fibre-managed plantations, including globulus, due to the high presence of defects. "High feature" boards typically dominate. Therefore, appearance GLT is not to be targeted in this project.
- *GLT products*: (1) GLT with properties equivalent to GL18 grade, i.e., the highest grade in the Australian standards, have been achieved in Europe from carefully selected globulus logs. This result indicates that GLT products are possible from fibre-managed globulus logs. (2) Finger-jointing globulus boards is possible, but despite high strength joints, failure is likely to occur in the glueline and not pass the minimum requirement for bond durability in Australian standards. Work will have to be done with the product certifier to clarify this requirement. (3) 1-component PUR showed promising results for globulus GLT applications and is suggested to be used as a first priority for a structural adhesive. (4) Manufacturing hybrid hardwood/softwood GLT is possible and will result in similar bending properties than hardwood only GLT, but with lower shear strength.
- *Processing (veneers)*: Spindleless lathe technology has proven to be efficient and is recommended to rotary peel logs into veneers, recovering up to nearly 60% of the volume of small diameter billets into dry, trimmed, and saleable veneers. The technology has been successfully applied to 13-16-year-old globulus fibre-managed plantation logs.
- *Veneer properties and LVL products*: (1) D grade veneers usually dominate fibre-managed plantations, even for a 16-year-old thinned and pruned globulus plantation in Victoria. Appearance veneered-based products should not be targeted in this project unless veneers from other resources

are used as face veneers. (2) Studies on 13 to 16-year-old fibre-managed globulus logs from Victoria resulted in veneers with an average MOE of nearly 16,000 GPa. This indicates that the resource can generate high stiffness LVL products, and it recommended that such products are targeted from the high MOE veneers. (3) Hybrid hardwood/softwood LVL can be manufactured and present an opportunity to maximise the use of hardwood and softwood resources by manufacturing a range of structural products. (4) Phenol-formaldehyde has been shown to successfully glue globulus veneers (Type A bond for external applications) and is recommended as a first bet as structural adhesive in this project.

References

ABARES. (2019). *Australia's forests at a glance 2019*, Australian Bureau of Agricultural and Resource Economics and Sciences

ABARES. (2022). *Australian plantation statistics 2022 update*, Australian Bureau of Agricultural and Resource Economics and Sciences

ACIAR. (2017). *A guide to manufacturing rotary veneer and products from small logs* (MN182), Australian Centre for International Agricultural Research.

AS 1720.1. (2010). Timber structures, Part 1: Design methods. *Standards Australia*

AS 2082. (1979). Visually stress-graded hardwood for structural purposes. *Standards Australia*

AS 2082. (2000). Timber - Hardwood - Visually stress-graded for structural purposes. *Standards Australia*

AS 2082. (2007). Timber - Hardwood - Visually stress-graded for structural purposes. *Standards Australia*

AS 2796. (1985). Timber - Seasoned hardwood - Milled products. *Standards Australia*

AS 2796.1. (1999). Timber - Hardwood - Sawn and milled products, Part 1: Product specification. *Standards Australia*

AS 2796.2. (2006). Timber - Hardwood - Sawn and milled products Grade description. *Standards Australia*

AS 5068. (2006). Timber - Finger joints in structural products - Production requierements. *Standards Australia*

AS/NZS 1328.1. (1998). Glued laminated structural timber, Part 1: Performance requirements and minimum production requirements. *Standards Australia*

AS/NZS 1604.1. (2021). Preservative-treated wood-based products. *Standards Australia*

AS/NZS 2098.2. (2006). Methods of test for veneer and plywood, Bond quality of plywood (chisel test). *Standards Australia*

AS/NZS 2098.2. (2012). Methods of test for veneer and plywood, Bond quality of plywood (chisel test). *Standards Australia*

AS/NZS 2269. (2004). Plywood - Structural. *Standards Australia*

AS/NZS 2269.0. (2008). Plywood - Structural, Part 0: Specifications. *Standards Australia*

AS/NZS 2269.0. (2012). Plywood - Structural, Part 0: Specifications. *Standards Australia*

AS/NZS 2754.1. (2016). Adhesives for timber and timber products Adhesives for manufacture of plywood and laminated veneer lumber (LVL). *Standards Australia*

ASH. (2022). *Mass timber* (Retreived on 15/12/2022 at https://ash.com.au/application/mass-timber/),

Bekele, T. (1994). Kiln drying of sawn boards of young Eucalyptus globulus Labill. and Eucalyptus camaldulensis Dehnh. grown on the Ethiopian Highlands. *Holz als Roh- und Werkstoff, 52*, 377-382

Bekele, T. (1995). Degradation of boards of Eucalyptus globulus Labill. and Eucalyptus camaldulensis Dehnh. during air drying. *Holz als Roh- und Werkstoff, 53*(6), 407-412

Belini, U. L., F.M., T., Louzada, J. L. P. C., de Carvalho Rodrigues, J. C., & Astolphi, J. R. S. (2012). Pilot study for MDF manufacture from sugarcane bagasse and eucalyptus fibers. *European Journal of Wood and Wood Products, 70*(4), 537-539

Blaß, H. J., & Frese, M. (2006). *Biegefestigkeit von Brettschichtholz-Hybridträgern mit Randlamellen aus Buchenholz und Kernlamellen aus Nadelholz (in German)*, Unversitat Karlsruhe.

Brennan, G. K., Hingston, R. A., & Moore, R. W. (2004). Processing 17-year-old Tasmanian blue gum sawlogs grown at wide spacing. *Australian Forestry, 67*(4), 240-246

Burdurlu, E., Kilic, M., Ilce, A. C., & Uzunkavak, O. (2007). The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech (Fagus orientalis L.) and lombardy poplar (Populus nigra L.). *Construction and Building Materials, 21*(8), 1720-1725

Burton, P. (2021). *CLST Comparison of properties of laminae that compose mass panels* (Retreived on 08/12/2022 at https://lignor.com/wp-content/uploads/2021/03/LIGNOR-CLST%C2%AE-v2.2.pdf), Lignor.

Chafe, S. C., & Ananias, R. A. (1996). Effect of presteaming on moisture loss and internal checking in high-temperature-dried boards of Eucalyptus globulus and Eucalyptus regnans. *Journal of the Institute of Wood Science, 14*, 72-77

Chen, J., Xiong, H., Wang, Z., & Yang, L. (2019). Mechanical Properties of a Eucalyptus-Based Oriented Oblique Strand Lumber for Structural Applications. *Journal of Renewable Materials, 7*(11), 1147-1164

Chen, J., Xiong, H., Wang, Z., & Yang, L. (2020). Experimental buckling performance of eucalyptus-based oriented oblique laminated strand lumber columns under centric and eccentric compression. *Construction and Building Materials, 262*, 120072

Cihad Bal, B. (2016). Some technological properties of laminated veneer lumber produced with fast-growing Poplar and Eucalyptus. *Maderas. Ciencia y tecnología, 18*(3), 413-424

CUSP. (2022). *Products/Services* (Retreived on 22/12/2022 at https://cusp.com.au/products/),

de Fégely, R. (2004a). *Sawing Regrowth and Plantation Hardwoods with Particular Reference to Growth Stresses Part A Literature Review* (PN02.1308), Forest & Wood Products Research & Development Corporation.

de Fégely, R. (2004b). *Sawing Regrowth and Plantation Hardwoods with Particular Reference to Growth Stresses Part B Survey results* (PN02.1308), Forest & Wood Products Research & Development Corporation.

Derikvand, M., Jiao, H., Kotlarewski, N., Lee, M., Chan, A., & Nolan, G. (2019). Bending performance of nail-laminated timber constructed of fast-grown plantation eucalypt. *European Journal of Wood and Wood Products, 77*(3), 421-437

Derikvand, M., Kotlarewski, N., Lee, M., Jiao, H., & Nolan, G. (2020). Flexural and visual characteristics of fibre-managed plantation Eucalyptus globulus timber. *Wood Material Science & Engineering, 15*(3), 172-181

Dill-Langer, G., & Aicher, S. (2014). High performance glulam beams made of beech LVL and solid wood lamellas: experiments and modelling

Proceedings of the 2014 World Conference on Timber Engineering, Electronic proceedings

EN 314.1. (1993). Plywood - Bonding quality - Part 1: Test methods. *European Committee for Standardization*

EN 314.1. (2004). Plywood - Bonding quality - Part 1: Test methods. *European Committee for Standardization*

EN 314.2. (1993). Plywood - Bonding quality - Part 2: Requirements. *European Committee for Standardization*

EN 636:2012+A1. (2015). Plywood - Specifications. *European Committee for Standardization*

EN 14080. (2013). Timber structures - Glued laminated timber and glued solid timber - Requirements. *European Committee for Standardization*

EN 15497. (2014). Structural finger jointed solid timber - Performance requirements and minimum production requirements. *European Committee for Standardization*

Ettelaei, A., Taoum, A., & Nolan, G. (2022a). Rolling shear properties of cross-laminated timber made of fibre-managed plantation eucalyptus under short-span bending. *Wood Material Science & Engineering, 17*(6), 744-751

Ettelaei, A., Taoum, A., Shanks, J., lee, M., & Nolan, G. (2022b). Evaluation of the bending properties of novel cross-laminated timber with different configurations made of Australian plantation Eucalyptus nitens using experimental and theoretical methods. *Structures, 42*, 80-90

Ettelaei, A., Taoum, A., Shanks, J., & Nolan, G. (2022c). Rolling Shear Properties of Cross-Laminated Timber Made from Australian Plantation Eucalyptus nitens under Planar Shear Test. *Forests, 13*(1), 84

Farrell, R., Blum, S., D., W., & Blackburn, D. (2011). *The potential to recover higher value veneer products from fibre managed plantation eucalypts and broaden market opprtunities for this resource: Part A* (PNB139-0809), Forest and Wood Products Research and Development Corporation.

Fdez-Golfin, J. I., R., D., Hermoso, E., Baso, C., Casas, J. M., & González, O. (2007). Caracterización de la madera de E. globulus para uso estructural (in Spanish). *Boletín del CIDEU, 4*, 91-100

FIFWA. (1992). Industry Standard for Seasoning, Sawn and Skip-Dressed WA Hardwoods. *Forest Products Federation (WA), Perth*

Franke, S., & Marto, J. (2014). Investigation of Eucalyptus globulus wood for the use as an engineered material. *Proceedings of the 2014 World Conference on Timber Engineering*, Electronic proceedings

Freischmidt, G., & Blakemore, P. (2009). *Potential applications of the native hardwood resource available to VicForests as wood composite products* (CMSE(C)-2008-312), CSIRO.

Gilbert, B. P. (2018). Compressive Strength Prediction of Veneer-Based Structural Products. *ASCE Journal of Materials in Civil Engineering, 30*(9), 04018225

Gilbert, B. P., Bailleres, H., Fischer, M. F., Zhang, H., & McGavin, R. L. (2017a). Mechanical Properties of Rotary Veneers Recovered from Early to Midrotation Subtropical-Hardwood Plantation Logs for Veneer-Based Composite Applications. *ASCE Journal of Materials in Civil Engineering, 29*(10), 04017194

Gilbert, B. P., Bailleres, H., Zhang, H., & McGavin, R. L. (2017b). Strength modelling of Laminated Veneer Lumber (LVL) beams. *Construction and Building Materials, 149*, 763-777

Gilbert, B. P., Husson, J. M., Bailleres, H., McGavin, R. L., & Fischer, M. F. (2018). Perpendicular to grain and shear mechanical properties of veneer-based elements glued from single veneer sheets recovered from three species of juvenile subtropical hardwood plantation logs. *European Journal of Wood and Wood Products, 76*(6), 1637-1652

González-Prieto, O., Casas Mirás, J. M., & Torres, L. O. (2022). Finger-jointing of green Eucalyptus globulus L. wood with one-component polyurethane adhesives. *European Journal of Wood and Wood Products, 80*(2), 429-437

Gouveia, S., Otero, L. A., Fernández-Costas, C., Filgueira, D., Sanromán, Á., & Moldes, D. (2018). Green Binder Based on Enzymatically Polymerized Eucalypt Kraft Lignin for Fiberboard Manufacturing: A Preliminary Study. *Polymers, 10*(6), 642

GTFIH. (2022). *Personal communication with Green Triangle Forest Industries Hub*.

H`ng, P. S., Paridah, M. T., & Chin, K. L. (2010). Bending Properties of Laminated Veneer Lumber Produced from Keruing (Dipterocarpus sp.) Reinforced with Low Density Wood Species. *Asian Journal of Scientific Research, 3*(2), 118-125

Hague, J. R. B. (2013). *Utilisation of plantation eucalypts in engineered wood products* (PNB290-1112), Forest & Wood Products Australia Limited.

Hansmann, C., Stingl, R., Prieto, O. G., Lopez, C. B., & Resch, H. (2008). High-Frequency Energy–Assisted Vacuum Drying of Fresh Eucalyptus globulus. *Drying Technology, 26*(5), 611-616

Hess. (2022). *GLT Hybrid* (Retreived on 19/12/2022 at https://www.hess-timber.com/en/products/glt-hybrid/),

Hopewell, G. P., Atyeo, W. J., & McGavin, R. L. (2008). *Evaluation of wood characteristics of tropical post-mid rotation plantation Eucalyptus cloeziana and E. pellita: Part (d) Veneer and plywood potential* (PN07.3022), Forest and Wood Products Australia.

Hyne timber. (2022). *Glulam range GLT* (Retreived on 15/12/2022 at https://www.hyne.com.au/documents/Feature%20Documents/Hyne_GlulamCategoryBrochure_2022.pdf),

IndustryEdge Pty Ltd. (2021). *Building the Nation: Growing the Future - Opportunities for Green Triangle Plantation Forestry*, Green Triangle Forest Industries Hub Incorporated.

Innes, T., Greaves, B., Nolan, G., & Washusen, R. (2008). *Determining the economics of processing plantation eucalyptus for solid timber products* (PN04.3007), Forest and Wood Products Research and Development Corporation.

Iwakiri, S., Monteiro de Matos, J. L., Guilherme Prata, J., Trianoski, R., & Soares da Silva, L. (2013). Evaluation of the use potential of nine species of genus Eucalyptus for production of veneers and plywood panels. *Cerne, 19*(2), 263-269

Jiao, H., Nolan, G., Lee, M., Kotlarewski, N., & Derikvand, M. (2019). *Developing high-mass laminated flooring products from fibre-managed plantation hardwood* (PNB387-1516), Forest & Wood Products Australia Limited.

Kargarfard, A. (2012). Investigation on physical and mechanical properties of medium density fiberboard produced from Eucalyptus steriaticalyx fibers. *Iranian Journal of Wood and Paper Science Research, 27*(1), 89-99

Kargarfard, A., Amir, N., & Fardad, G. (2010). Investigation on physical and mechanical properties of medium density fiberboard produced from Eucalyptus camaldulensis fibers. *Iranian Journal of Wood and Paper Science Research, 25*(1), 1-10

Keskin, H. (2004). Technological properties of laminated wood materials made up with the combination of oak (quercus petraea liebl.) wood and scots pine (pinus sylvestris lipsky) wood and possibilities of using them. *gazi university journal of science, 17*, 121-131

Krzysik, A. M., Muehl, J. H., Youngquist, J. A., & Franca, F. S. (2001). Medium density fiberboard made from Eucalyptus saligna. *Forest products journal, 51*(10), 47-50

Lara-Bocanegra, A. J., Majano-Majano, A., Arriaga, F., & Guaita, M. (2020). Eucalyptus globulus finger jointed solid timber and glued laminated timber with superior mechanical properties: Characterisation and application in strained gridshells. *Construction and Building Materials, 265*, 120355

Lara-Bocanegra, A. J., Majano-Majano, A., Crespo, J., & Guaita, M. (2017). Finger-jointed Eucalyptus globulus with 1C-PUR adhesive for high performance engineered laminated products. *Construction and Building Materials, 135*, 529-537

Larson, T., Erickson, R. W., & Petersen, H. D. (1983). Saw-dry-rip processing: Taking the crook out of the stud game. *Proceedings of the 26th annual joint meeting midwest wood seasoning association and Wisconsin-Michigan wood seasoning association*, 13-30

López-Suevos, F., & Richter, K. (2009). Hydroxymethylated Resorcinol (HMR) and Novolak-Based HMR (n-HMR) Primers to Enhance Bond Durability of Eucalyptus globulus Glulams. *Journal of Adhesion Science and Technology, 23*(15), 1925-1937

Martínez, B. (2022). *Declaration of Performance - Reinforced Globulus Maple LG, Reinforced Globulus Poplar LG* (DOP.GAR.39.EN, retrieved on 20/12/2022 at https://www.garnica.one/uploads/140e05e2-c34b-4321-874f-f4a844ea8e7e/140e05e2-c34b-4321-874f-f4a844ea8e7e.pdf), Garnica.

Martins, C., Dias, A. M. P. G., & Cruz, H. (2020). Blue gum: assessment of its potential for glued laminated timber beams. *European Journal of Wood and Wood Products, 78*(5), 905-913

McCarthy, K. J., Cookson, L. J., Mollah, M., Norton, J., & Hann, J. (2005). *The Suitability of Plantation Thinnings as Vineyard Posts* (PN02-3900), Forest and Wood Products Research and Development Corporation.

McGavin, R. L. (2017). *A guide to manufacturing rotary veneer and products from small logs - Chapter 6: Rotary peeling*, Australian Centre for International Agricultural Research,.

McGavin, R. L., Bailleres, H., Fehrmann, J., & Ozarska, B. (2015a). Stiffness and density analysis of rotary veneer recovered from six species of Australian plantation hardwoods. *Bioresources, 10*(4), 6395-6416

McGavin, R. L., Bailleres, H., Hamilton, M., Blackburn, D., Vega, M., & Ozarska, B. (2015b). Variation in rotary veneer recovery from Australian plantation Eucalyptus globulus and Eucalyptus nitens. *Bioresources, 10*(1), 313-329

McGavin, R. L., Bailleres, H., Lane, F., Blackburn, D., Vega, M., & Ozarska, B. (2014a). Veneer Recovery Analysis of Plantation Eucalypt Species Using Spindleless Lathe Technology. *Bioresources, 9*(1), 613-627

McGavin, R. L., Bailleres, H., Lane, F., & Fehrmann, J. (2013). *High value timber composite panels from hardwood plantation thinnings*, Queensland Government.

McGavin, R. L., Bailleres, H., Lane, F., Fehrmann, J., & Ozarska, B. (2014b). Veneer grade analysis of early to mid-rotation plantation Eucalyptus species in Australia. *Bioresources, 9*(4), 6562-6581

McGavin, R. L., Davies, M. P., Macgregor-Skinner, J., Bailleres, H., Armstrong, M., Atyeo, W. J., & Norton, J. (2006). *Utilisation Potential and Market Opportunities for Plantation Hardwood Thinnings from Queensland and Northern New South Wales* (PN05.2022), Queensland Government.

McGavin, R. L., McGrath, J., Fitzgerald, C., Kumar, C., Oliver, C., & Lindsay, A. (2021). Sawn timber and rotary processing and grade recovery investigation of Nothern Australian plantation grown African mahogany. *Bioresources, 16*(1), 1891-1913

McGavin, R. L., Nguyen, H. H., Gilbert, B. P., Dakin, T., & Faircloth, A. (2019). A comparative study on the mechanical properties of laminated veneer lumber (LVL) produced from blending various wood veneers. *Bioresources, 14*(4), 9064-9081

McKinley, R., Ball, R., Downes, G., Fife, D., Gritton, D., Llic, J., . . . Roper, J. (2004). *Resource evaluation for future profit. Part A - Wood propety survey of the green triangle region* (PN03.3906), Forest & Wood Products Research & Development Corporation.

Molinari, A. (2020). *Declaration of performance* (Retreived on 19/12/2022 at https://www.lumin.com/repo/arch/ecdopeucaenglish20201130.pdf),

Muraleedharan, A., & Reiterer, S. M. (2016). *Combined glued laminated timber using hardwood and softwood lamellas*, Master Thesis, Linnaeus University.

Murata, K., Nakano, M., Miyazaki, K., Yamada, N., Yokoo, Y., Yokoo, K., . . . Nakamura, M. (2021). Utilization of Chinese fast-growing trees and the effect of alternating lamination using mixed-species eucalyptus and poplar veneers. *Journal of Wood Science, 67*(1), 5

Neumann, R. J., & Saavedra, A. (1992). Check formation during the drying of Eucalyptus Globulus. *Holz als Roh- und Werkstoff, 50*(3), 106-110

Nguyen, H. H., Gilbert, B. P., McGavin, R. L., & Bailleres, H. (2019). Optimisation of cross-banded laminated veneer lumbers manufactured from blending hardwood and softwood veneers. *European Journal of Wood and Wood Products, 77*(5), 783-797

Nguyen, H. H., Gilbert, B. P., McGavin, R. L., Bailleres, H., & Karampour, H. (2020). Embedment strength of mixed-species laminated veneer lumbers and cross-banded laminated veneer lumbers. *European Journal of Wood and Wood Products, 78*(2), 365-386

Nicholson, J. E. (1971). A rapid method for estimating longitudinal growth stresses in logs. *Wood Science and Technology, 5*(1), 40-48

Nolan, G., Washusen, R., Jennings, S., Greaves, B., & Parsons, M. (2005). *Eucalypt Plantations for Solid Wood Products in Australia – A Review* (PN04.3002), Forest and Wood Products Research and Development Corporation.

O'Ceallaigh, C., Harte, A., Sikora, K., & McPolin, D. (2014). *Enhancing low grade sitka spruce glulam beams with bonded-in BFRP rods.* Paper presented at the Proceedings of the COST Action FP1004 Early Stage researchers Conference – Experimental Research with Timber, Prague, Czech Republic.

Pan, Z., Zheng, Y., Zhang, R., & Jenkins, B. M. (2007). Physical properties of thin particleboard made from saline eucalyptus. *Industrial Crops and Products, 26*(2), 185-194

Pangh, H., Hosseinabadi, H. Z., Kotlarewski, N., Moradpour, P., Lee, M., & Nolan, G. (2019). Flexural performance of cross-laminated timber constructed from fibre-managed plantation eucalyptus. *Construction and Building Materials, 208*, 535-542

Raftery, G. M., & Harte, A. M. (2011). Low-grade glued laminated timber reinforced with FRP plate. *Composites Part B: Engineering, 42*(4), 724-735

Raftery, G. M., & Rodd, P. D. (2015). FRP reinforcement of low-grade glulam timber bonded with wood adhesive. *Construction and Building Materials, 91*, 116-125

Raftery, G. M., & Whelan, C. (2014). Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods. *Construction and Building Materials, 52*, 209-220

Reid, R., & Washusen, R. (2001a). *Sawn timber from 10-year-old pruned Eucalyptus nitens (Deane & Maiden) grown in an agricultural riparian buffer.* Paper presented at the Third Australian Stream Management Conference proceedings: the value of healthy streams. Cooperative Research Centre for Catchment Hydrology, Brisbane, Australia.

Reid, R., & Washusen, R. (2001b). *Sawn timber from 10-year-old pruned Eucalyptus nitens (Deane & Maiden) grown in an agricultural riparian buffer.* Paper presented at the Third Australian Stream Management Conference, Brisbane, Australia.

Sciomenta, M., Spera, L., Peditto, A., Ciuffetelli, E., Savini, F., Bedon, C., . . . Fragiacomo, M. (2022). Mechanical characterization of homogeneous and hybrid beech-Corsican pine glue-laminated timber beams. *Engineering Structures, 264*, 114450

SIS-24. (1993). Japanese agricultural standard for structural laminated veneer lumber. *Japanese Ministry of Agriculture, Forestry and Fisheries*

Stefani, P. M., Peña, C., Ruseckaite, R. A., Piter, J. C., & Mondragon, I. (2008). Processing conditions analysis of Eucalyptus globulus plywood bonded with resol-tannin adhesives. *Bioresource Technology, 99*(13), 5977-5980

Suleimana, A., Sena, C. S., Branco, J. M., & Camões, A. (2020). Ability to Glue Portuguese Eucalyptus Elements. *Buildings, 10*(7), 133

UNE 56546. (2013). Visual grading for structural sawn timber. Hardwood timber. *Asociacion Espanola de Normalizacion*

Vázquez, G., Antorrena, G., González, J., & Alvarez, J. C. (1996). Tannin-based adhesives for bonding high-moisture Eucalyptus veneers: Influence of tannin extraction and press conditions. *Holz als Roh- und Werkstoff, 54*(2), 93-97

Vázquez, G., Antorrena, G., González, J., & Mayor, J. (1995). Lignin-phenol-formaldehyde adhesives for exterior grade plywoods. *Bioresource Technology, 51*(2), 187-192

Vázquez, G., González-Álvarez, J., López-Suevos, F., & Antorrena, G. (2003). Effect of veneer side wettability on bonding quality of Eucalyptus globulus plywoods prepared using a tannin–phenol–formaldehyde adhesive. *Bioresource Technology, 87*(3), 349-353

Venn, T. J., McGavin, R. L., & Ergashev, A. (2020). Accommodating log dimensions and geometry in log procurement decisions for spindleless rotary veneer production. *Bioresources, 15*(2), 23585-22411

Vicbeam. (2022). *GL21 Spotted Gum* (Retreived on 15/12/2022 at https://vicbeam.com.au/product-services/gl21-spotted-gum/),

Washusen, R. (2013). *Processing methods for production of solid wood products from plantation-grown Eucalyptus species of importance to Australia* (PNB291-1112A), Forest & Wood Products Australia Limited.

Washusen, R., Blakemore, P., Northway, R., Vinden, P., & Waugh, G. (2000). Recovery of dried appearance grade timber from Eucalyptus globulus Labill, grown in plantations in medium rainfall areas of the southern Murray-Darling Basin. *Australian Forestry, 63*(4), 277-283

Washusen, R., Harwood, C., Morrow, A., Northway, R., Valencia, J. C., Volker, P., . . . Farrell, R. (2009a). Pruned Plantation-Grown Eucalyptus nitens: Effect of Thinning and Conventional Processing Practices on Sawn Board Quality and Recovery. *New Zealand Journal of Forestry Science, 39*, 39-55

Washusen, R., Harwood, C., Morrow, A., Valencia, J. C., Volker, P., Wood, M., . . . Bojadzic, M. (2007). *Gould's Country Eucalyptus nitens Thinning Trial: Solid Wood Quality and Processing Performance Using Conventional Processing Strategies* (Technical Report 168), CRC for Forestry.

Washusen, R., Menz, D., Morrow, A., Reeves, K., Hingston, R., & Davis, S. (2004). *Processing pruned and unpruned Eucalyptus globulus managed for sawlog production to produce high value products* (PN03-1315), Forest and Wood Products Research and Development Corporation.

Washusen, R., Morrow, A., Ngo, D., Northway, R., Bojadzic, M., Harwood, C., . . . Innes, T. (2008). *Eucalyptus nitens thinning trial: solid wood quality and procesing performance using conventional processing strategies* (PN07.3019), Forest and Wood Products Research and Development Corporation.

Washusen, R., Murrow, A., Ngo, D., Hingston, R., & Jones, T. (2009b). *Comparison of solid wood quality and mechanical properties of three species and nine provenances of 18-year old eucalypts grown in clearwood plantations across southwest Western Australia* (PRC114-0709), Forest and Wood Products Research and Development Corporation.

Waugh, G., & Rozsa, A. (1991). *Sawn products from regrowth Eucalyptus regnans*, The Young Eucalypt Report - some management options for Australia's regrowth forest., CSIRO Publications

Wesbeam. (2021). *Wesbeam e-beam LVL characteristic values and design criteria* (Retreived on 15/12/2022 at https://wesbeam.com/Wesbeam/media/Documents/WESB0552_Design-Criteria-%e2%80%93-e-beam.pdf),

Wong, E. D., A.-K., R., & Shuichi, K. (1996). Properties of Rubberwood LVL reinforced with Acacia Veneers. *Bulletin of the Wood Research Institute Kyoto University, 83*(1), 8-16

Yang, J.-L., & Fife, D. (2003). Identifying check-prone trees of Eucalyptus globulus Labill. using collapse and shrinkage measurements. *Australian Forestry, 66*(2), 90-92

Yang, J.-L., Fife, D., Waugh, G., Downes, G., & Blackwell, P. (2002). The effect of growth strain and other defects on the sawn timber quality of 10-year-old Eucalyptus globulus Labill. *Australian Forestry, 65*(1), 31-37

Yang, J. L., & Waugh, G. (1996). Potential of plantation-grown eucalypts for structural sawn products. I. Eucalyptus globulus Labil, ssp. globulus. *Australian Forestry, 59*(2), 90-98