ATMAC – Splinters to Structures – Resources characterisation, manufacturing and testing of LVL and GLT structural products out of lesser value *Eucalyptus globulus* and *Pinus radiata* logs

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Executive Summary

This report represents the final report of the *ATMAC – Splinters to structures* project aimed at promoting the establishment of an Australian Engineered Wood Product (EWP) manufacturing platform for the Green Triangle lesser value logs, consisting of southern blue gum (*Eucalyptus globulus*) and first (T1) and second (T2) thinning radiata pine (*Pinus radiata*) logs. As agreed with the steering committee, the report investigates the potential of structural Laminated Veneer Lumber (LVL) and Glued Laminated Timber (GLT) to be produced out of the studied resources. The study focused on the manufacturing of structural products either only from the southern blue gum resources or as hybrid products, i.e., containing a mixed of southern blue gum and radiata pine.

As part of the project:

- Sixty 15-year-old and sixty 19-year-old southern blue gum trees were harvested near Hamilton in Victoria. The plantations were established and grown for woodchips, with no prior thinning or pruning.
- Thirty 11-year-old (T1) and thirty 18-year-old (T2) radiata pine logs were harvested near Mt. Gambier in South Australia. The plantations were established for sawn timber.

Two-thirds and 1/3 of the logs were peeled into rotary veneers and sawn into boards, respectively, at the Salisbury Research Facility of the Queensland Department of Agriculture and Fisheries, near Brisbane. In total, (1) 339 billets were rotary peeled which resulted in 2,164 veneer sheets and (2) 124 billets were sawn which resulted in 909 boards. The characteristics of the veneers and sawn boards were analysed, including visual grading (veneers), Modulus of Elasticity (MOE) and density distributions (veneers and boards), and other selected mechanical properties (boards). LVL and GLT, corresponding to products with mechanical properties valued by the market, were manufactured and tested. The GLT were manufactured in a commercial facility (Warrnambool Timber Industry, Dennington, Victoria) to provide commercial feedback on the suitability of the resources to be handled in an industrial setting. The LVL were manufactured at the semi-commercial Salisbury Research Facility. Recovery rates were also estimated for all manufacturing processes.

While the study showed that LVL valued by the market can be manufactured without technical challenges, additional work is still required for the GLT to be commercialised. As explained below and consistent with the literature review, finger jointing southern blue gum boards proved challenging, resulting in the finger joints failing the bond durability requirements in AS 5068 (2006). Further work on gluing the southern blue gum boards is therefore recommended, especially for finger jointing, to be confident that GLT beams manufactured with the studied resources can pass the certification requirements in relevant Australian standards and meet the targeted grades relevant to the market.

The key findings of this report are summarised as follows:

- From the literature review:
  - Tension wood is common in fibre-managed blue gum plantations and creates challenges sawing the logs and drying the boards.
  - Twin-saws, as opposed to single saws, are also 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 was 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.
- It is challenging to manufacture appearance structural products from fibre-managed plantations due to the high presence of visual features.
- Gluing high-density southern blue gum boards, as well as finger jointing these boards, present some challenges.
- High stiffness and high strength LVL and GLT can be achieved from the southern blue gum resource. Hybrid LVL and GLT present an opportunity to maximise the use of hardwood and softwood resources by manufacturing a range of structural products of different grades.

- From rotary peeling the logs into veneers and the manufacturing of LVL in a semi-commercial facility:
  - As expected from the literature review, visual D-grade veneers (AS/NZS 2269.0, 2012) dominated the feedstock, both for southern blue gum and radiata pine, limiting the manufacturing of appearance veneered-based products.
  - On average 17% to 23% and 9.5% (T2) to 32% (T1) of the southern blue gum and radiata pine veneers, respectively, failed to meet the visual grade requirements of AS/NZS 2269.0 (2012) and may have limited use in the manufacturing process of LVL structural products.
  - The average MOE for the peeled veneers was equal to 15,690 MPa, 20,119 MPa, 8,131 MPa and 10,502 MPa for the 15-year-old southern blue gum, 19-year-old southern blue gum, T1 radiata pine and T2 radiata pine logs, respectively.
  - The 19-year-old southern blue gum logs provided veneers with a MOE about 26% higher on average than the 15-year-old southern blue gum logs.
  - The gross veneer recovery was about 50% for the overall southern blue gum analysed resource and ranged from 42% (T1) to 60% (T2) for radiata pine. The net veneer recovery ranged from 43% to 46% for the southern blue gum and from 37% (T1) to 53% (T2) for radiata pine. All above values are consistent with the literature.
  - The overall analysed southern blue gum resource offered enough high MOE veneers to mainly manufacture high performance LVL (characteristic MOE of 15,000 MPa, referred to in this study as LVL15), with low volumes of commodity LVL with a characteristic MOE of 12,000 MPa (referred to in this study as LVL12).
  - The hybrid LVL is well suited to manufacture large volumes of commodity LVL12, while still enabling lower volumes of higher performance LVL (LVL15, LVL18 (characteristic MOE of 18,000 MPa) or LVL21 (characteristic MOE of 21,000 MPa)) to be manufactured, as valued by the market.
  - Using phenol-formaldehyde type resin, Type A bonds were achieved (1) between southern blue gum veneers by increasing the hot press pressure to 2 MPa, and (2) between alternating southern blue gum and radiata pine veneers by following the adhesive manufacturer's recommendations.
  - At similar characteristic MOE, the manufactured and tested LVL had similar or higher characteristic strength values than commercially available LVL, and F27 and F34 grades sawn timber.
  - High stiffness (with a characteristic MOE greater than 20,000 MPa) and high strength (with a characteristic edge bending strength greater than 120 MPa) LVL were successfully manufactured.

- From sawing the logs into boards and the associated manufactured GLT:
  - Planing was efficient in removing the large spring and cup imperfections of the southern blue gum boards, with 72% and 82% of the boards having a spring less

than or equal to 2 mm, and a cup less than or equal to 1 mm, respectively, after planing.

- 20% of the southern blue gum boards had high acoustic MOE and density values, i.e., greater than 21,000 MPa and 850 kg/m^3, respectively. For radiata pine, 20% of the boards had acoustic MOE and density values greater than 10,700 MPa and 465 kg/m^3, respectively.
- The high-density southern blue gum boards reached tensile, compressive and shear strengths up to 100 MPa, 70 MPa and 180 MPa, respectively. These values for the radiata pine boards were significantly lower, with tensile, compressive and shear strengths up to 30 MPa, 30 MPa and 100 MPa, respectively, reached.
- The simulations indicated that GL18 and GL13 grades in accordance with Clause 7 of AS 1720.1 (2010) (product grades identified as favourable by the project's market study), can be achieved from the tested plantation resources in terms of characteristic MOE as long as the correct construction strategies are adopted. The simulations also indicated that the bending strength may be the limiting factor to achieve the targeted grades.
- On average 42% and 46% of the southern blue gum and radiata pine logs, respectively, were recovered into green boards. The net board recovery, reflecting the recovery from logs to finished GLT products, was estimated at 12% and 22% for southern blue gum and radiata pine, respectively. These values are consistent with the literature.
- High density (> 800-850 kg/m^3) southern blue gum boards were found difficult to glue. Resorcinol formaldehyde performed better than polyurethane. Sanding post-planing of the boards before gluing and using resorcinol formaldehyde were found to pass the glueline integrity requirements in AS/NZS 1328.1 (1998). This surface preparation method with resorcinol formaldehyde is recommended in the manufacturing of southern blue gum GLT but needs to be further confirmed on a higher number of samples.
- Consistent with the literature, southern blue gum finger joints failed the bond durability requirements in AS 5068 (2006), with low wood failure percentages, when glued with either resorcinol formaldehyde or polyurethane. Additional work is needed to understand how southern blue gum finger joints should be manufactured to pass the bond durability requirements and therefore allowing the resource to be used in GLT beams. An alternative assessment process could also be investigated.
- In terms of MOE, the tested southern blue gum and hybrid GLT beams achieved GL18 and GL13 grade in accordance with AS 1720.1 (2010), respectively, and meet the targeted markets. However, the characteristic bending strengths of the two types were low due to the beams prematurely failing at the finger joints. This resulted from challenges encountered in the manufacturing and the difficulty in finger jointing southern blue gum boards, as summarised in the dot point above. However, the literature reported that higher bending strength can be achieved for the type of GLT beams tested. It is recommended to manufacture and test new beams after solving the bond durability of the southern blue gum finger joints to confirm the bending strength of the beams.

- From the manufacturing of the GLT beams in a commercial facility, the following feedback was obtained:

  - To minimise waste and optimise recovery, rough sawn timber should be provided by the mill, resulting in less wastage for the mill and an increased volume of resources to work with for the GLT plant. In this scenario, the mill would be sending all timber to the GLT plant and let the GLT plant rework all timber.

- Due to the boards used in this trial being thinner than would normally be targeted in GLT manufacturing, and the large amount of cupping present in the southern blue gum boards, finger jointing short lengths of southern blue gum presented challenges. However, it is believed that if thicker boards were used, the finger jointing operation would be similar to normal commercial operations. Moreover, the cupping which resulted in some of the finger jointing challenges can be removed by planing the boards before finger jointing. This potential additional manufacturing step was not deemed to considerably impact the production operation but would increase wastage. No challenges were reported in finger jointing radiata pine boards.
- If the southern blue gum boards need to be planed to remove cupping before finger jointing and accommodate for thickness variations, thicker boards than normal would need to be delivered by the mill.
- No challenges were reported in planing the lamellas, glue spreading, pressing and final planing of the GLT beams.
- Due to the high level of distortions present in the southern blue gum boards, the resource was deemed less suitable for automation and high-speed production of larger scale GLT plants but is a better fit for more manual small-scale GLT operations.
- The commercial facility believed that southern blue gum is a resource suited for the manufacturing of GLT beams, as the resource has no current market in the framing sector and the presumably low-grade material containing strength reducing characteristics can be removed to manufacture high stiffness and high strength GLT lamellas.
- Hybrid GLT was not a preferred product by the commercial facility due to the difference in unit-tangential-movement during moisture change of the southern blue gum and radiata pine species. This would affect the cross-sectional shape when subjected to moisture fluctuations and the product not being accepted by the market.
- The commercial facility mentioned that GL18 beams should be the target for the southern blue gum GLT as hardwood beams of lower grade are too heavy to install in the residential market without lifting equipment. Preliminary simulations estimated that using the 40% denser southern blue gum boards could result in GL18 graded beams.
- The commercial facility believed that a southern blue gum GL18 is a viable product and could be sold readily.

Table of Contents

Anacronyms

ABP	Australian Blue gum Plantations
CCR	Corn Cob Residue
CDF	Cumulative Distribution Function
CLT	Cross Laminated Timber
CoV	Coefficient of Variation
DAF	Department of Agriculture and Fisheries
DBHOB	Diameter at Breast Height Over Bark
DIC	Digital Image Correlation
EWP	Engineered Wood Products
FEA	Finite Element Analysis
FRP	Fibre Reinforced Polymer
FWPA	Forest and Wood Products Australia
GLT	Glued Laminated Timber
GTFIH	Green Triangle Forest Industries Hub
HMR	Hydroxymethylated Resorcinol
LEDOB	Large End Diameter Over Bark
LEDUB	Small End Diameter Under Bark
LVL	Laminated Veneer Lumbers
MDF	Medium-density fibreboard
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MUF	Melamine-Urea-Formaldehyde
OFO	One Forty One
OSB	Oriented Strand Board
PF	Phenol-Formaldehyde
PUR	Polyurethane
RF	Resorcinol Formaldehyde
SED	Small End Diameter
SEDOB	Small End Diameter Over Bark
SEDUB	Small End Diameter Under Bark
T1	First thinning
T2	Second thinning
WTIBeam	Warrnambool Timber Industry

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). The Forest Product Innovations team of the Queensland Department of Agriculture and Fisheries (DAF) was commissioned to deliver the R&D activities on the potential structural products which can be manufactured out of the resources. These resources consist of hardwood plantation logs grown for pulpwood purposes and softwood plantation logs. Relative to the Green Triangle and this project, they represent:

- Hardwood southern blue gum (*Eucalyptus globulus*) logs, with plantations principally grown for woodchips and which dominate the hardwood resource in the Green Triangle (121,000 ha) (ABARES, 2019, ABARES, 2022).
- First (T1) and second (T2) thinning softwood radiata pine (*Pinus radiata*) logs (176,400 ha in the Green Triangle) (ABARES, 2019, ABARES, 2022), with plantations managed for saw logs.

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 products. 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 Glued Laminated Timber (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 and guided by the market analysis performed as part of the overall project by IndustryEdge, the executive committee of the "Splinters to Structures" project decided to investigate the potential of manufacturing both LVL and GLT products out of the southern blue gum and radiata pine resources from the Green Triangle. These structural products can be manufactured either only from the southern blue gum resources or as hybrid products, i.e., containing a mixed of southern blue gum and radiata pine.

For this project, 120 and 60 southern blue gum and radiata pine logs, respectively, were harvested in the Green Triangle and processed at the Salisbury Research Facility of the Queensland Department of Agriculture and Fisheries in Brisbane. The logs were either rotary peeled for LVL manufacturing or sawn into boards for GLT manufacturing. The properties of the veneers and sawn boards were measured and presented in this report. LVL and GLT were manufactured and tested.

The report is articulated as follows:

- A literature review is first presented in Section 2. The literature review aims at guiding the research and to understand (1) how to best process the resources, (2) the challenges associated with working with the resources and (3) the expected mechanical properties of LVL and GLT manufactured from the resources.
- Section 3 details the resources harvested and processed in this study.
- Section 4 presents the methodology followed to (1) process 2/3 of the harvested logs into rotary peeled veneers and (2) manufacture (in a semi-commercial facility) and test 25 LVL panels of five different construction strategies. The measurements taken on the billets and peeled veneers are presented along with recovery rates. The visual grades of the veneers along with their MOE and density distributions are also reported. Numerical simulations performed to understand which LVL products, and in which proportion, could be manufactured from the resources are also discussed. Gluing trials to obtain Type A bonds for the southern blue gum veneers are reported. Finally, the mechanical properties of the manufactured LVL are analysed and compared with selected commercial products.
- Section 5 presents the methodology followed to (1) process 1/3 of the harvested logs into sawn boards and (2) manufacture and test five GLT beams of two different construction strategies. The measurements taken on the logs and sawn boards are presented along with recovery rates. The mechanical properties of the boards, their MOE and density distributions, as well as their characteristics relevant to GLT manufacturing, are discussed. Numerical simulations performed to understand which GLT products, and in which proportion, could be manufactured from the resources are also examined. Gluing trials to pass the glueline integrity requirements in AS/NZS 1328.1 (1998) are reported along with finger joint testing. Finally, the mechanical properties of the manufactured GLT are analysed and compared with GL grades in AS 1720.1 (2010).
- The outcomes of a production trial at Warrnambool Timber Industry, manufacturing the GLT beams tested in Section 5 in an industrial setting, is presented in Section 6. It provides feedback on how the resources performed in a commercial facility.
- Section 7 concludes the report and summarises the key findings and recommendations from the study.

2 Literature review

2.1 Foreword

This section 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.

This section focuses on *Eucalyptus globulus* as it is the dominant hardwood resource of the Green Triangle. However, relevant learnings from different eucalyptus species, including *Eucalyptus nitens* (shining gum), 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 of the Green Triangle region, such as McKinley, et al. (2004), are available.

First, an overview of EWP types, other than LVL and GLT, manufactured from eucalyptus logs 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 southern blue gum GLT, including hybrid softwood/hardwood GLT to maximise the use of the two resources, are covered. Fourth, the use of eucalyptus and blue gum in the manufacture of LVL, or other types of relevant veneer-based products has been reviewed. Hybrid softwood/hardwood LVL options are also discussed. Finally, the section summarises the key findings and provides recommendations for the next stages of the project.

Note that review studies published by FWPA and CSIRO (Freischmidt, et al., 2009, Hague, 2013, Washusen, 2013) are already available on the potential uses and processing challenges of eucalyptus logs for the purpose of EWP production. 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.

2.2 Products other than GLT and LVL from young eucalyptus and blue gum

2.2.1 General

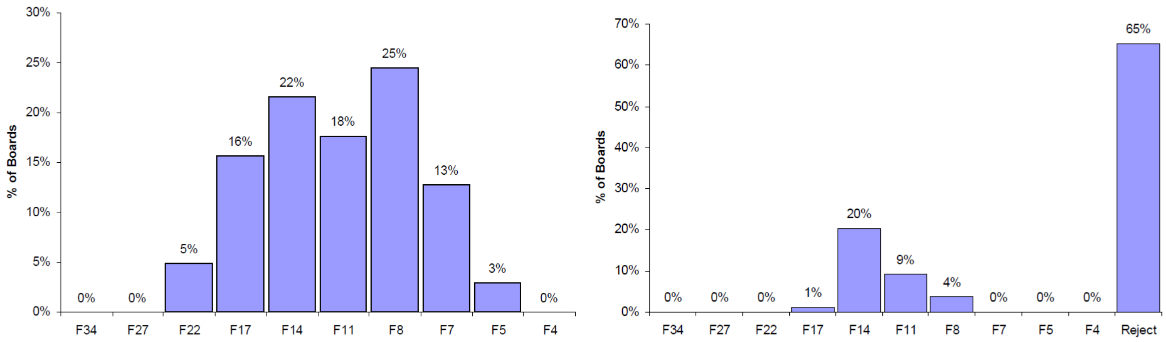
This subsection summarises key studies looking at manufacturing products other than GLT and LVL from young, small diameter eucalyptus, and blue gum logs. It focuses on structural products which may present opportunities for the Green Triangle. Products with no manufacturing facilities in Australia and 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 subsection due to their use in the manufacture of GLT. The lessons learnt from 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.

2.2.2 Sawn timber boards

McGavin, et al. (2006) assessed the processing and utilisation options of 8 to 9-year-old sub-tropical and tropical eucalypt plantation thinnings, all sourced from Queensland and Northern

New South Wales. While blue gum 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) values for 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 blue gum 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 shining gum and blue gum boards, but not to the same extent as McGavin, et al. (2006) and Yang, et al. (1996).

The potential inadequacy of the structural visual grading system in AS 2082 (2007) for plantation-grown boards may be overcome by a new visual grading system proposed by Fdez-Golfin, et al. (2007). The authors characterised 452 boards of blue gum 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 blue gum boards, Derikvand, et al. (2020) converted 26-year-old blue gum fibre-managed plantation logs from Tasmania and observed 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 blue gum 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 blue gum logs from Portugal, with no information on the silviculture regime applied to the trees. However, according to Washusen (2013), blue gum 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, and shear strength (from a shear block test set-up) 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 blue gum, as well as shining gum, 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 blue gum (from 13- to 47-years-old) and shining gum (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 blue gum, it ranged from 6% to 23% of the volume of the logs, depending on the log grade.

- Washusen, et al. (2008) predominately obtained "high feature" boards from 21-years-old thinned and unthinned shining gum plantation logs.
- Reid, et al. (2001) analysed the recovery of a small quantity (nine) of 10-year-old pruned shining gum 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 (*Eucalyptus globulus*, *Eucalyptus viminalis* and *Eucalyptus saligna*) from clearwood trials in Western Australia. Blue gum 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 blue gum 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 blue gum "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.

2.2.3 CLT

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

2.2.4 Vineyard posts and natural rounds

Vineyard posts and natural 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 blue gum and radiata pine, were investigated. After treatment, all posts met a H4 hazard class (AS/NZS 1604.1, 2021). Blue gum 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.

2.2.5 Particleboards

In a review on the available information on the utilisation of plantation eucalypts in 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 blue gum or shining gum. 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 ones 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 pine 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).

2.2.6 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 *Eucalyptus 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 blue gum and shining gum, with declared bending MOE and MOR for the blue gum product just under 14,000 MPa and 124 MPa, respectively.

2.2.7 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 blue gum 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).

2.3 Processing, recovery and drying

2.3.1 General

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

2.3.2 Sawn timber boards

2.3.2.1 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 blue gum. These growth stresses have been perceived by the industry to be a major constraint when processing plantation-grown eucalyptus (de Fégely, 2004a, de Fégely, 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 blue gum stands is minor. However, in unthinned blue gum stands, these growth stresses are especially common in young blue gum 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 subsection). When analysing the effect of growth strain (measured as per Nicholson (1971)) on back-sawn 10-year-old unpruned plantation blue gum 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 shining gum 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), looked at producing high value sawn boards from blue gum and shining gum plantations and concluded that sawing equipment adapted to the resource is needed to optimise recovery rates. 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 blue gum logs and to the study on 32 year-old thinned blue gum 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 shining gum. 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 blue gum (Yang, et al., 2003), during reconditioning. Also, when compared to back-sawing, quarter-sawing resulted in a reduction in internal and surface checking in shining gum (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 blue gum 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".

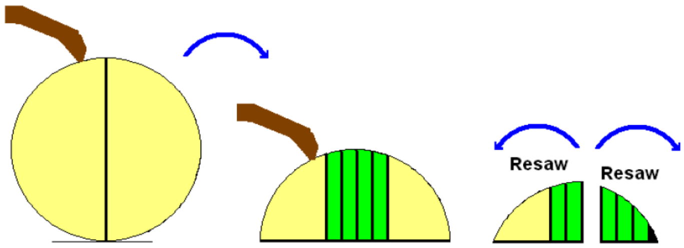


Figure 2: Quarter-sawing strategy suitable to logs of SED greater than 40 cm (Washusen, 2013).

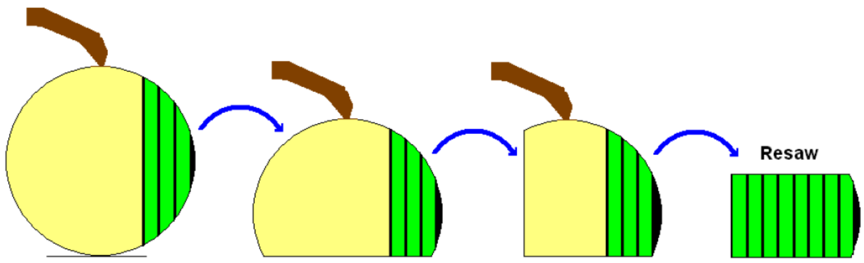


Figure 3: Back-sawing strategy suitable to logs of SED less than 40 cm (Washusen, 2013).

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 blue gum 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.

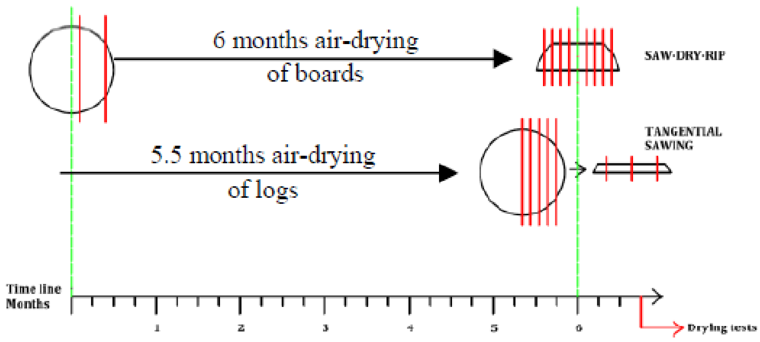


Figure 4: Saw-dry-rip and tangential processing technique used by Franke, et al. (2014).

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. (2001) processed various diameter blue gum and shining gum 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 shining gum plantation logs.
- From back-sawn 10-year old shining gum logs, which were only pruned on a given portion of the trees, Reid, et al. (2001) 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 blue gum 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 blue gum 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).

2.3.2.2 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 blue gum 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 blue gum if the initial drying temperature of the kiln is kept as low as possible, preferably below 30ºC. 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 blue gum 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 blue gum boards from Ethiopia, consisting of air, one high (between 40ºC and 65ºC) and one low (between 22.5ºC and 35ºC) 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 blue gum 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 30ºC to 80ºC 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 blue gum 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" blue gum 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 blue gum 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 blue gum 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 blue gum, 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 blue gum to 18% MC for 13 months, then kiln dried.
- Derikvand, et al. (2020) processed 26-year-old blue gum 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.

2.3.3 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 southern blue gum and shining gum 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 spindleless peeling 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 southern blue gum of average DBHOB of 31 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 shining gum. 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 shining gum and pruned 33-year-old blue gum logs in the manufacture of plywood and LVL, with a focus on shining gum. For the shining gum, 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 blue gum 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 for various purposes, including (1) 10- to 16-year-old spotted gum (*Corymbia citriodora*), Gympie messmate (*Eucalyptus cloeziana*) and red mahogany (*Eucalyptus pellita)* sawn timber plantations, (2) 11- to 16-year-old Dunn's white gum *(Eucalyptus dunnii)* and southern blue gum fibre-managed plantations and (3) 20- to 22-year-old shining gum 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 southern blue gum and shining gum, D-grade veneers represented 84% and 68%, respectively, of the peeled veneers. Even for 16-year-old thinned and pruned southern blue gum 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 shining gum, 26-year-old shining gum and 33-year-old southern blue gum, respectively. The authors considered "that young unpruned shining gum had 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 2.5, 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 southern blue gum logs, with an average DBHOB of 301 cm, resulted in an average MOE of the veneers of 15,896 MPa, with a CoV of 31%. The shining gum veneers, with the trees having an average DBHOB of 34 cm, showed an average MOE of 14,520 MPa, with a CoV of 26%. Relative to sawn timber grades, the average MOE values for the southern blue gum 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 shining gum and southern blue gum resources in McGavin, et al. (2015a) are shown in Figure 5.

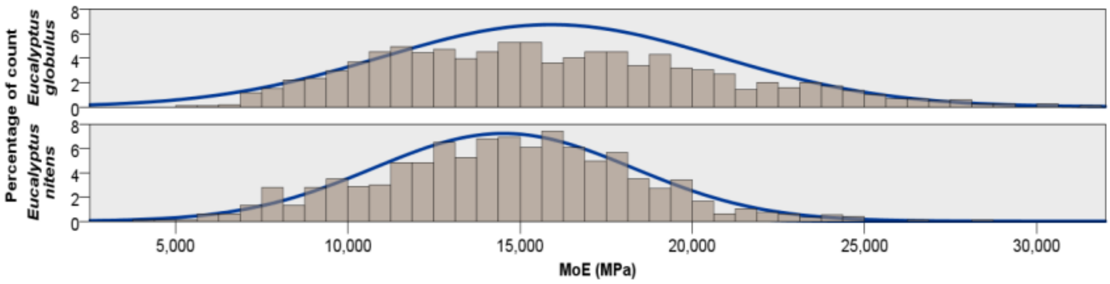


Figure 5: MOE distributions of veneers recovered by McGavin, et al. (2015a) for southern blue gum (top) and shining gum (bottom).

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.

2.4 GLT beams

2.4.1 General

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

It is worth mentioning that investigations have been performed on either using young eucalyptus logs to manufacture GLT or using blue gum 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 (2022a).
- Jiao, et al. (2019) and Derikvand, et al. (2019) analysed the possibility of manufacturing nail laminated and glued laminated floor panels manufactured from shining gum and blue gum boards. The boards were sawn from 15-year-old shining gum (average SED = 345 mm) and 26-year-old blue gum (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.

2.4.2 Blue gum GLT

2.4.2.1 Mechanical properties

Studies on blue gum GLT are scarce and have solely been performed in Europe. Martins, et al. (2020) manufactured non-finger jointed, 5-layer, blue gum 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 blue gum 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 blue gum beams, manufactured with single-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).

2.4.2.2 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 blue gum 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 single-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 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 single-component PUR (Loctite HB S309 Purbond) 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 blue gum 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 single-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.

2.4.2.3 Gluing

In view of manufacturing blue gum 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 single-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 blue gum boards with single-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 blue gum 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 blue gum 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.

2.4.3 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 blue gum. Notwithstanding, lessons learnt from other published studies are covered in this subsection.

Regarding blue gum, on top of manufacturing blue gum only GLT, Martins, et al. (2020) manufactured 5-layer, 120 mm deep and 92 mm wide, hybrid blue gum/poplar beams. Blue gum 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 blue gum 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.

2.5 Laminated Veneer Lumbers

2.5.1 General

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

2.5.2 Blue gum plywood or LVL from other eucalyptus species

2.5.2.1 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 F11 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 shining gum "had strength and stiffness properties which were higher than those of LVL made from New Zealand-grown radiata pine veneer". Freischmidt, et al. (2009) referred to a 1996 CSIRO study which manufactured LVL out of various Eucalyptus species (not including blue gum and shining gum). 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 shining gum and 33-year-old blue gum 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 blue gum, 26-year-old shining gum and 16-year-old shining gum plywood reached a grade of F34, F27 and F11, respectively, relative to their parallel to face bending characteristic values.

2.5.2.2 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).

2.5.3 Blue gum LVL

2.5.3.1 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 blue gum 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.

2.5.3.2 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 blue gum 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 blue gum. 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 blue gum. 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 blue gum 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 blue gum 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).

2.5.4 Hybrid hardwood/softwood LVL

Several studies have looked at mixing hardwood and softwood to manufacture hybrid LVL products, none with blue gum or shining gum.

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).

2.6 Concluding remarks

This section outlined the challenges, best practices and opportunities to manufacture blue gum and hybrid radiata pine/blue gum 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*: Tension wood in fibre-managed blue gum logs 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 were 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 blue gum 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 blue gum 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 blue gum plantations has been proposed in Europe and is suggested to be verified. (4) It is challenging to manufacture appearance structural products from fibre-managed plantations, including blue gum, 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 blue gum logs. This result indicates that GLT products are possible from fibre-managed blue gum logs. (2) Finger-jointing blue gum 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) Single-component PUR showed promising results for blue gum 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 for 13 to 16-year-old southern blue gum 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 southern blue gum 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 southern blue gum logs from Victoria resulted in veneers with an average MOE of nearly 16,000 MPa. 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 blue gum veneers (Type A bond) and is a recommended structural adhesive to be trialled in this project.

3 Resources harvested

3.1 Foreword

This section details the logs harvested as part of this project. 2/3 of the logs were processed into veneers (Section 4) and 1/3 were sawn into boards (Section 5) at the Salisbury Research Facility, Department of Agriculture and Fisheries (DAF), Queensland Government, in Brisbane.

3.2 Harvested resources

3.2.1 Southern blue gum

3.2.1.1 Harvested trees

120 southern blue gum trees were harvested in June 2023 from two different sites near Hamilton, Victoria. The sites are referred to as "Caves" and "Barker" and are described in Section 3.2.1.2. The trees were selected by Australian Blue gum Plantations (ABP) to meet their "peeler grade", targeting straight, round, and undamaged logs. Relevant log selection criteria to this project consist of, over a length of 5 m, (1) a sweep less than ¼ of the Small End Diameter (SED), (2) a "wobble" not exceeding 5 cm from the centreline, and (3) the large end diameter no greater than 1.2 times the short end diameter. Figure 6 shows photos of the harvesting and of the numbered logs waiting to be transported.

(a) (b)

***Figure 6**: (a) Southern blue gum logs being harvested and (b) numbered logs waiting to be transported.*

Trees with two different ranges of Diameter at Breast Height Over Bark (DBHOB) were selected. The DBHOB ranges were recommended by the technical steering committee to be representative of logs encountered in ABP's southern blue gum plantations at harvesting. The following 120 logs were obtained from the harvested trees:

- 30 × 8.5 m long logs, aiming at DBHOB ranging from 17 cm to 23.6 cm (average 19.5 cm), from Caves.
- 30 × 8.5 m long logs, aiming at DBHOB ranging from 23.6 cm to 31.8 cm (average 27.7 cm), from Caves.
- 30 × 8.5 m long logs, aiming at DBHOB ranging from 17 cm to 23.6 cm (average 19.5 cm), from Barker.

- 30 × 8.5 m long logs, aiming at DBHOB ranging from 23.6 cm to 31.8 cm (average 27.7 cm), from Barker.

For each site, the logs were numbered from 1 to 60, with numbers 1 to 30 corresponding to the higher DBHOB range.

An additional four logs, numbered A to D and of DBHOB greater than 40 cm, were also harvested from Barker to gather supplementary information on larger diameter logs. In this report, these logs are treated separately in the analyses from the previous 120 logs, i.e., not included in the recovery calculations.

To limit the moisture loss between harvesting in the Green Triangle and final processing in Brisbane, the following measures were implemented: (1) the logs were not debarked, (2) immediately after felling, the ends of the logs were sealed with Blackseal heavy duty bitumen waterproofing membrane from Crommelin, (3) the logs were transported to Brisbane in closed containers, and (4) after unloading and before being processed, the logs were stored outside under wet hessian meshes.

Table 2 shows the timeframe from harvesting to processing.

Table 2: Timeframe from harvesting to processing for southern blue gum logs.

Activity	Dates
Harvesting	01/06/2023 and 02/06/2023
Loading into containers	02/06/2023 to 05/06/2023
Transportation to Brisbane	05/06/2023 to 13/06/2023
Unloading containers in Brisbane	13/06/2023
Logs merchandising	13/06/2023 to 25/06/2023
Sawing	26/06/2023 to 03/07/2023
Peeling	04/07/2023 to 14/07/2023

3.2.1.2 Harvested sites

Information regarding the two harvested sites for the southern blue gum logs were provided by ABP and summarised below.

- Caves:
  - *Age*: 15-year-old (established in 2008).
  - *Location*: -37.919862 (latitude), 141.981462 (longitude).
  - *Density*: 833 trees per hectare with no pruning or thinning.
  - *Rainfall*: 725 mm per year.
  - *Geology*: Quaternary basalt.
  - *Land use Prior to plantation*: Grazing.
  - *Soil type*: Sandy Clay Loam/Clay Loam.
  - *Landscape*: Undulating rolling hills.
  - *Drainage*: Good.
  - *Fertilising*: None.
- Barker:
  - *Age*: 19-year-old (established in 2004).
  - *Location*: -38.1988297 (latitude), 142.043573 (longitude).
  - *Density*: 1,090 trees per hectare with no pruning or thinning.
  - *Rainfall*: 785 mm per year.
  - *Geology*: Quaternary lacustrine.

- *Land use Prior to plantation*: Grazing.
- *Soil type*: Loamy sands.
- *Landscape*: Gently Undulating with a number of low lying wet areas.
- *Drainage*: Poor.
- *Fertilising*: Blend 1, NPK + Cu + S 2006.

3.2.2 Radiata pine

3.2.2.1 Harvested trees

60 radiata pine trees were harvested in July 2023 from two different sites near Mt Gambier, South Australia. The sites for the first (T1) and second (T2) thinning are referred to as "Snowgums" and "Kilsbys", respectively, and are described in Section 3.2.2.2. The trees were selected by One Forty One (OFO) to meet the DBHOB ranges recommended by the technical steering committee and representative of T1 and T2 logs. Figure 7 shows photos of the harvesting and of the numbered logs waiting to be transported. The following 60 logs were obtained from the harvested trees:

- 40 × 7.5 m long T1 logs, aiming at DBHOB ranging from 15 cm to 20 cm, from Snowgums.
- 40 × 7.5 m long T2 logs, aiming at DBHOB ranging from 20 cm to 25 cm, from Kilsbys.

(a) *(b)*

***Figure 7**: (a) Radiata pine logs being harvested and (b) numbered logs waiting to be transported.*

For each site, out of the 40 harvested logs, 30 were selected to be processed based on the amount of bark left and straightness. These logs were numbered from 1 to 30.

As moisture loss is less critical in softwood than hardwood, with the logs being less susceptible to end splitting, less precautions than for the southern blue gum logs were taken to prevent the softwood logs from drying before being processed. Precautions include: (1) debarking during harvesting was kept to a minimum and (2) the ends of the logs were sealed with Blackseal heavy duty bitumen waterproofing membrane from Crommelin immediately after felling. The logs were transported on an open deck truck to Brisbane.

Table 3 shows the timeframe from harvesting to processing.

Table 3: Timeframe from harvesting to processing for radiata pine logs.

Activity	Dates
Harvesting	10/07/2023 and 11/07/2023
Loading onto truck	12/07/2023 to 14/07/2023
Transportation to Brisbane	15/07/2023 to 17/07/2023
Unloading logs in Brisbane	18/07/2023
Logs merchandising	19/07/2023 to 06/08/2023
Peeling	31/07/2023 to 02/08/2023
Sawing	07/08/2023 to 09/08/2023

3.2.2.2 Harvested sites

Information regarding the two harvested sites for the radiata pine logs were provided by OFO and summarised below.

- Snowgums (T1):
  - *Age*: 11-year-old (established in 2012).
  - *GPS coordinates*: -37.929767 (latitude), 140.945746 (longitude).
  - *Density*: 1,472 trees per hectare (survival stocking).
  - *Rainfall*: about 750 mm per year.
  - *Soil*: deep sand over clay.
  - *Extra info*: first thinned in 2023.
- Kilsbys (T2):
  - *Age*: 18-year-old (established in 2005).
  - *GPS coordinates*: -37.929767 (latitude), 140.945746 (longitude).
  - *Density*: 1,519 trees per hectare (survival stocking).
  - *Rainfall*: about 750 mm per year.
  - *Soil*: deep sand over clay.
  - *Extra info*: first thinned in 2016 to a mean stocking of 792 trees per hectare.

4 Peeling: Log processing, veneer characteristics, recoveries and associated LVL

4.1 Foreword

2/3 of the logs harvested in Section 3 were rotary peeled in this section. The veneers were then used to manufacture and test southern blue gum and hybrid LVL. This section details and presents:

- The methodology followed to process the logs into rotary peeled veneers.
- The measurements taken on the billets and peeled veneers, including dimensions, MOE and density distributions, and the visual grade of the veneers.
- The veneer recovery rates calculated for different transformation processes.
- The numerical simulations performed to understand which LVL products, and in which proportion, could be manufactured from the southern blue gum and radiata pine resources.
- The gluing trials performed to obtain Type A bond between veneers.
- The LVL types manufactured and tested in this section.
- The characteristic properties of the tested LVL and their comparison with commercial products.

4.2 Methodology

4.2.1 Log processing, rotary peeled veneers and recoveries

4.2.1.1 Log preparation and processing into rotary peeled veneers

For each southern blue gum site, logs ID 1 to 20 and ID 31 to 50, and for each radiata pine site, logs ID 1 to 20 were merchandised into peeling billets as shown in Figure 8. Additional logs C and D harvested from Barker (see Section 3.2.1.1) were also merchandised into peeling billets. Each log was cut into three 2.6 m long billets along the length of the logs to match the locations which would typically be processed in a commercial lathe. Each 2.6 m billet was eventually cut into 1.3 m long billets to then accommodate the size of the peeling lathe at the Salisbury Research Facility. Therefore, the wood quality of each billet investigated as part of this study is representative of what would be encountered in commercial facilities.

The billets were numbered as the site ID, followed by the tree ID and finally the billet ID. The site ID corresponds to an internal DAF reference ID, with ID 45, 46, 50 and 51 corresponding to the logs harvested from Caves, Barker, Snowgums (T1) and Kilsbys (T2), respectively. For instance, billet 45-18-3 is the 3rd billet (top one) cut from tree number 18 harvested from Caves (southern blue gum).

25 mm thick disks were also cut out of the logs on each end of the billets to perform the measurements outlined in Section 4.2.1.2.1. Disk numbering followed the billet numbering, by adding “1” or “2” to the billet ID to distinguish between the disks cut at the large and small end diameters, respectively. For instance, disk 45-18-3-2 is the disk cut at the small end diameter of the previously explained billet.

Distinctions were made when merchandising and conditioning the two species before peeling:

- The radiata pine logs were directly merchandised to the dimensions shown in Figure 8. The 1.3 m long billets were steamed overnight in a kiln at wet and dry bulb temperatures of 65.2°C and 63.5°C, respectively.

- To limit end splitting of the billets before being placed in the rotary lathe, the southern blue gum logs were merchandised the day before peeling by adding 200 mm on both side of the 1.3 m long billets to be peeled and shown in Figure 8. These 1.7 m long billets were then steamed overnight in a kiln at wet and dry bulb temperatures of 85°C and 83°C, respectively. The final 1.3 m long billets and the 25 mm thick disks were then cut from the 1.7 m long steamed billets just before peeling.

Billets with a Small End Diameter Over Bark (SEDOB) less than 150 mm or billets with excessive defects were not processed.

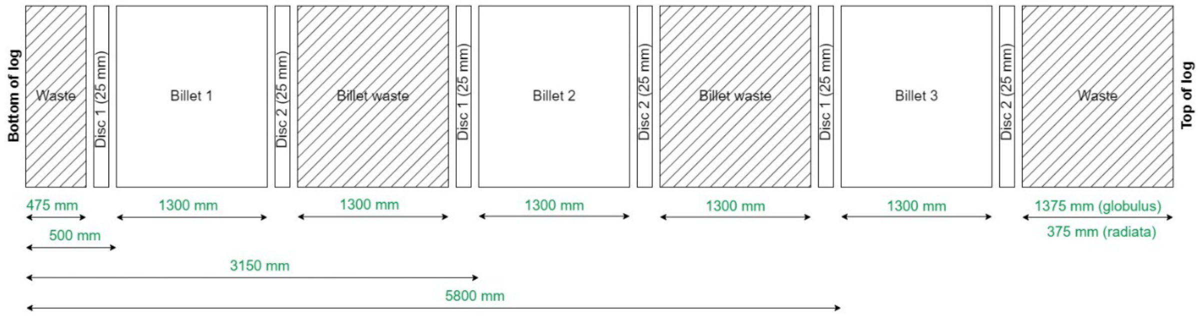


***Figure 8**: Log merchandising for peeling.*

After the overnight steaming process, the billets were first debarked and rounded using a spindleless rotary debarker (Figure 9 (a)). The rounded billets were then peeled using a spindleless lathe (Figure 9 (b)) to a nominal peeling core of 40 mm in diameter and into nominal 3.2 mm thick green veneers.

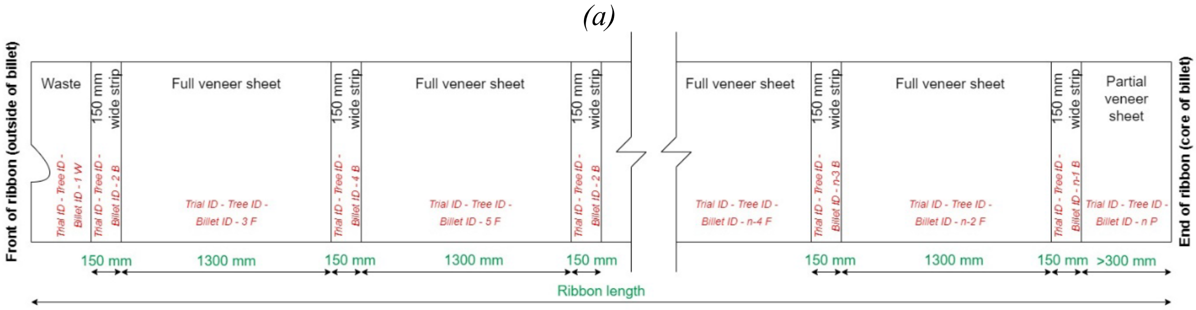
(a) *(b)*

***Figure 9**: (a) A radiata pine billet being debarked and rounded and (b) radiata pine rounded billets loaded in the spindleless lathe ready to be peeled.*

The veneer ribbon obtained from each billet (Figure 10 (a)) was marked and clipped following the schematic presented in Figure 10 (b) into a succession of 150 mm wide strips and 1.3 m wide veneer sheets. The waste part at the front of the ribbon in Figure 10 (b) corresponds to either the ribbon not being at its nominal thickness or the presence of undesirable characteristics, such as wane. Sheets less than 1.3 m but greater than 300 mm at the end of the ribbons were considered as partial sheets. The 150 mm wide strips were principally used to measure the MOE along the length of the ribbon (see Sections 4.2.1.2.3 and 4.2.1.2.5). The 1.3 m veneer sheets were graded (see Section 4.2.1.2.4) and will be used to manufacture LVL as the project progresses. Each clipped piece was numbered sequentially, as shown in Figure 10 (b), by adding the piece ID to the billet ID followed by either the letter “W”, “B”, “F” or “P”, corresponding to either a waste piece (W), a 150 mm strip (B), a 1.3 m wide full sheet (F) or a partial sheet (P), respectively.

After clipping and the measurements outlined in Section 4.2.1.2.2 on the green veneers were taken, the F and P veneer sheets were dried using a conventional jet box veneer drying system at Austral Plywoods, Brisbane. The 150 mm wide B strips were dried in a solar kiln at the Salisbury Research Facility.

(a)



(b)

Figure 10: *(a) Veneer ribbon showing presence of wane at the front and (b) clipping plan of veneer ribbon (showing numbering in red).*

4.2.1.2 Measurements and grading

4.2.1.2.1 Billet measurements

The small and large end dimensions of each billet were obtained from measurements performed on the disks cut at each end of the billet. The following measurements were taken for each billet:

- Billet small end diameter over bark (*SEDOB*) and large end diameter over bark (*LEDOB*): Measured using a diameter tape measure. If too much bark was removed during the harvesting process, then no measurement was taken.
- Billet small end diameter under bark (*SEDUB*) and large end diameter under bark (*LEDUB*): Measured using a diameter tape measure after chiselling the bark off the disks.
- Billet shortest small end diameter under bark (*SSEDUB*) and longest small end diameter under bark (*LSEDUB*): the shortest and longest diameters, respectively, of the small end of the billet, measured with a steel ruler.

The following measurements were measured directly from the billets before debarking and rounding:

- Billet length (L_B): measured with a tape measure.
- Billet sweep (S_B): measured as the maximum distance from a straight line extending between the billet ends and the curved billet.

Finally and before peeling, the following measurement was taken on the debarked and rounded billets, i.e., of a constant diameter along their length:

- Billet rounded diameter (RD_B): measured with a diameter tape measure.

4.2.1.2.2 Green veneer measurements

Immediately after peeling, the following measurements were performed on the ribbon and clipped veneers. These measurements are principally used to calculate the recoveries detailed in Section 4.2.1.3 and not explicitly reported herein. They consist of:

- Ribbon overall length (L_R): measured with a tape measure.
- Distance (d) from the front of the ribbon to each clipping lines, i.e., corresponding to the location of the full and partial veneer sheets and the 150 mm wide strips. Measured with a tape measure.
- Green thickness of each 150 mm wide strip (t_{sg}): measured with a vernier calliper as the average of three measurements taken at the ends and middle of the strip.
- Green thickness of each full and partial veneer sheet (t_{vg}): calculated as the average green thickness of the 150 mm wide strips on each side of a sheet. If only one strip was cut next to a veneer sheet (mainly at the end of the ribbon), then t_{vg} was taken as the green thickness t_{sg} of that one strip.
- Green width of each full and partial veneer sheet (w_{vg}): measured with a tape measure.

4.2.1.2.3 Dry veneer measurements

After drying, the measurements detailed hereafter were taken from the veneer sheets and strips. Geometric measurements on the veneers were used to calculate the recoveries detailed in Section 4.2.1.3 and not explicitly reported herein. All measurements taken on the dry veneers include:

- Dry thickness of each 150 mm wide strip (t_{sd}): measured with a vernier calliper as the average of three measurements taken at the ends and middle of the strip.
- Dry thickness of each full and partial veneer sheet (t_{vd}): calculated as the average dry thickness of the 150 mm wide strips on each side of a sheet. If only one strip was cut next to a veneer sheet, then t_{vd} was taken as the dry thickness t_{sd} of that one strip.
- Dry width of each full and partial veneer sheet (w_{vd}): measured with a tape measure.
- Density of each 150 mm wide strip (d_{sd}): calculated as the ratio of the measured mass to the product of the measured thickness, width and length of the strip.
- Density of each full and partial veneer sheet (d_{vd}): calculated as the average density of the 150 mm wide strips on each side of a sheet. If only one strip was cut next to a veneer sheet, then d_{vd} was taken as the density d_{sd} of that one strip.
- Acoustic (dynamic) MOE of each 150 mm wide strip (E_{sd}): measured by simply supporting the strip on rubber bands and impacting it in its longitudinal direction. The sample natural frequency of the strip was then recorded using a microphone and analysed using the software BING (Beam Identification by Non-destructive Grading) (Brancheriau, et al., 2002, CIRAD, 2012) to determine the MOE.
- Acoustic (dynamic) MOE of each full and partial veneer sheet (E_{vd}): calculated as the average acoustic MOE of the 150 mm wide strips on each side of the sheet. If only one strip was cut next to a veneer sheet, then E_{vd} was taken as the MOE E_{sd} of that one strip.

4.2.1.2.4 Veneer visual grading

All full dried veneer sheets were graded based on the visual appearance listed in the Australian and New-Zealand standard AS/NZS 2269.0 (2012). The following grades were attributed to the veneers as defined in the standard:

- A-grade: A high quality appearance grade, suitable for clear finishing.
- B-grade: An appearance grade suitable for high quality paint finishing.
- C-grade: A non-appearance grade with a solid surface.
- D-grade: A non-appearance grade with permitted open characteristics.
- F-grade: A reject grade for veneers that fail to meet the above grade requirements, and which are excluded from the manufacturing process.

***Figure 11**: Veneer grading in action.*

During the grading process, the appearance of the veneers was verified against all permitted visual characteristics in Clause 2 of AS/NZS 2269.0 (2012). For each veneer, the grade was recorded along with the most noticeable characteristic determining the grade. If other characteristics also limited the veneers to the same grade as the most noticeable one, they were not recorded.

Veneers were also graded based on additional characteristics not listed in the AS/NZS 2269.0 (2012) which impact the manufacturing process. These characteristics are provided in Table 4.

Figure 11 shows a photo of a veneer being graded.

Table 4: Additional grading characteristics to AS/NZS 2269.0 (2012) affecting the quality of the veneers.

	Characteristics	
Grade	**Compression (Waviness of veneer after drying)**	**Grain breakout**
A	Fairly flat	Not permitted
B	Wavy	Not permitted
C	Splits which will likely overlap when gluing	Not permitted
D	Splits which will overlap when gluing	No limitations
F	N/A	N/A

4.2.1.2.5 MOE and density distributions

Acoustic MOE (E_{vd}) and density (d_{vd}) distributions of the full veneer sheets are analysed and reported herein as:

- The average value with associated coefficient of variation (CoV) of the recovered veneers per species, site and billet ID (i.e., height of billet relative to log).
- The cumulative distribution function (CDF), i.e., showing the probability that a randomly selected veneer is less or equal to a given value, are also plotted per species, site and billet ID. For the numerical model presented in Section 4.2.2 and future analyses, the shape (α), scale (β) and location (γ) parameters of three-parameter Weibull distributions, found to well match the MOE distributions, are provided in this report. The CDF $F(x)$ of a random variable x in terms of the probability p of a three-parameter Weibull distribution is given as,

$$F(x) = 1 - e^{-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}} \quad (1)$$

The evolution of the acoustic MOE (E_{sd}) of the 150 mm wide strips along the radius of the log are also plotted in this report. The radial position r of each veneer strip (from the centre of the log) is calculated from the distance d of the strip from the front of the ribbon as,

$$r = \sqrt{\frac{1}{\pi}\left(\overline{t_{sd}}d - RD_B^2\pi\right)} \quad (2)$$

where $\overline{t_{sd}}$ is the average value of t_{sd} from the front of the ribbon to d.

The relationship between acoustic MOE (E_{vd}) and density (d_{vd}) is also analysed.

One-way analysis of variance (ANOVA) was used to determine if there were statistically significant differences between the mean MOE and mean density of varying billet ID, sites and targeted DBHOB.

4.2.1.3 Veneer recoveries

Four different types of veneer recoveries were calculated in this report following the methodology described in McGavin, et al. (2014a) and McGavin, et al. (2015b). The recoveries were calculated per species, site and billet ID. They consist of:

- Green veneer recovery (*GNR*): this measures the maximum recovery, taking into account the geometry of the log and lathe limitations but disregarding internal log quality (McGavin, et al., 2014a). It is calculated as,

$$GNR = \left(\frac{L_B \sum_{all\ veneers}(t_{vg} w_{vg})}{\sum_{billets}(V_B)}\right) \times 100 \quad (3)$$

  where V_B is the volume of a billet given as,

$$V_B = \left(\frac{SEDUB + LEDUB}{2}\right)^2 \frac{\pi}{4} L_B \quad (4)$$

- Gross veneer recovery (*GSR*): this measures the maximum recovery of the dried veneers that meet a visual grade (A to D) in the AS/NZS 2269.0 (2012) (see Section 4.2.1.2.4). When compared to the green veneer recovery, it includes the losses associated from visual grading and the drying process (McGavin, et al., 2014a). *GSR* is obtained as,

$$GSR = \left(\frac{L_B \sum_{veneers\ that\ meet\ a\ grade}(t_{vd} w_{vd})}{\sum_{billets}(V_B)}\right) \times 100 \quad (5)$$

- Net veneer recovery (*NR*): this measures the process efficiency by identifying the saleable products, considering product manufacturing limitations. This includes the losses due to the trimming of the veneers before, during and after product manufacturing, with losses estimated to be of 11.4% (McGavin, et al., 2014a). It is calculated as,

$$NR = 0.886 \times GSR \quad (6)$$

- Graded veneer recovery: this corresponds to the net veneer recovery for each visual grade in the AS/NZS 2269.0 (2012). They are referred to as NR_A, NR_B, NR_C and NR_D for the net veneer recoveries corresponding to visual A-, B-, C- and D-grades, respectively.

4.2.2 Potential LVL products out of the resources (numerical simulations)

The preliminary market analysis (IndustryEdge, 2023) indicated that LVL12, LVL15 and LVL18, i.e., LVL with characteristic (or design) MOE of 12,000 MPa, 15,000 MPa and 18,000 MPa, respectively, are the main LVL products to be targeted out of the resources of interest in this study. LVL12 represents a commodity product (large volume), while LVL15 and LVL18 would have applications where higher performing products are needed, such as in flooring, stairwells and lintels. Additionally, LVL21, i.e., with characteristic MOE of 21,000 MPa, may be of interest to the market. LVL21 would be needed in small volumes when high performance products are needed.

Numerical simulations with different manufacturing scenarios are performed in this report to understand the LVL types and the associated volumes that could be manufactured using the southern blue gum and radiata pine veneers recovered as part of this project. The simulations are explained hereafter and use the MOE distributions of the different species and sites obtained from the methodology detailed in Section 4.2.1.2.5.

4.2.2.1 Assumptions of the numerical model

The following assumptions were made in the numerical simulations.

- Work in Gilbert, et al. (2017a) showed that the MOE of the veneers, measured through the non-destructive acoustic method described in Section 4.2.1.2.3, is between 6% and 13% higher than the MOE of the manufactured LVL, obtained from quasi-static mechanical tests and used to calculate the characteristic MOE. Therefore, the acoustic MOE of the veneers measured in this study was reduced by 10% to estimate the quasi-static MOE of the LVL and consequently the characteristic MOE.
- The LVL products were assumed to be manufactured from 15 veneers, i.e., 45 mm thick, and tested on edge.

4.2.2.2 Numerical model and investigated construction strategies

The numerical model follows the steps below to estimate the characteristic MOE of a LVL of a specific construction strategy:

1. Fifteen veneers are randomly selected from the appropriate fitted distributions presented in Section 4.3.1.3.
2. A LVL product is assumed to be manufactured from these 15 veneers and the MOE of the resulting LVL is calculated as the average of the 15 veneers.
3. The process in items 1. and 2. is repeated 30 times to create 30 LVL corresponding to the minimum number of LVL in AS/NZS 4063.2 (2010) needed to calculate the characteristic MOE of the product.
4. The characteristic MOE of the LVL is calculated following the methodology in the AS/NZS 4063.2 (2010).
5. The methodology in items 1. to 4. is repeated 100 times to understand the characteristic MOE variation between different batches of 30 LVL. The average characteristic MOE out of these 100 simulations is reported in the result section.

The following construction strategies (or scenarios) were run. Scenarios 1 to 3 were run with LVL manufactured either from only southern blue gum veneers or from both southern blue gum and radiata pine veneers (hybrid products). Scenario 4 was run only for the hybrid LVL:

- *Scenario 1*: The veneers are separated into three bins based on their MOE values to manufacture:
  - LVL18 from the first bin with the highest MOE veneers.
  - LVL12 from the second bin with MOE veneers in the middle range.
  - Lower performing LVL from the third bin with the remaining lowest MOE veneers. The characteristic MOE of this product being determined by the veneers not used to manufacture the LVL12 and LVL18.
- *Scenario 2*: The veneers are separated into four bins based on their MOE values to manufacture:
  - LVL21 from the first bin with the highest MOE veneers.
  - LVL18 from the second bin with the second highest MOE veneers.
  - LVL12 from the third bin with the third highest MOE veneers.
  - Lower performing LVL from the fourth bin with the remaining lowest MOE veneers not used to manufacture the other products.

- *Scenario 3*: The veneers are separated into two bins based on their MOE values to manufacture:
    - ➢ LVL15 from the first bin with the highest MOE veneers.
    - ➢ Lower performing LVL from the second bin with the remaining MOE veneers not used to manufactured the LVL15.
- *Scenario 4 (hybrid only)*: The veneers are separated into two bins based on their MOE values to manufacture:
    - ➢ LVL12 from the first bin with the highest MOE veneers.
    - ➢ Lower performing LVL from the second bin with the remaining MOE veneers not used to manufactured the LVL12.

For the southern blue gum only LVL, the scenarios were run with veneers harvested from either Caves, Barker or both sites. For the southern blue gum and radiata pine LVL, the simulations were run (1) having 8 southern blue gum and 7 radiata pine veneers per product, (2) using southern blue gum veneers harvested from both Caves and Barker, and (3) using radiata pine veneers harvested from either Kilsbys (T2) or Snowgums (T1) and Kilsbys (T2) combined. For these hybrid LVL, it is considered that the same percentage of the hardwood and softwood resource is used per LVL type. For instance, if 30% of the highest MOE southern blue gum veneers are used in the manufacture of a LVL18, then also 30% of the highest MOE radiata pine veneers are used in the product. This approach ensures that the veneers of the two resources are used in the same proportion.

Additionally, for all scenarios, the cutoff MOE values to separate the veneers into bins are provided in the results along with the estimated manufactured volume of each LVL type (in %) resulting from each construction strategy.

4.2.3 LVL manufacturing and testing

4.2.3.1 Gluing trials

4.2.3.1.1 General

Clause 2.5 of AS/NZS 4357.0 (2022) notes the requirement that the bonding between veneers of all structural LVL products must be of Type A when tested according to AS/NZS 2098.2 (2012). Type A bonds are necessary for external applications and products exposed to long-term weathering or wet conditions (AS/NZS 2754.1, 2016).

Trials were performed in this section to investigate how various gluing parameters influence the bond quality between veneers, therefore ultimately selecting appropriate gluing parameters for the LVL panels manufactured in Section 4.2.3.2. The influence of the two following parameters on the bond quality was investigated on samples manufactured from veneers of different MOE ranges, with the MOE ranges given in Section 4.2.3.1.3:

- Adhesive spread rate.
- Hot-press pressure.

As southern blue gum was deemed to represent the more challenging species to glue (see Section 2), the gluing trials focussed on southern blue gum LVL. Only a limited number of hybrid (alternating southern blue gum and radiata pine veneers) LVL samples were therefore manufactured. Note that the bond quality of all LVL types, corresponding to the best gluing protocol found in this section, was further verified when testing the LVL panels manufactured in Section 4.2.3.2.

4.2.3.1.2 Adhesive used

The adhesive used in the trial was a phenol-formaldehyde type resin, referred to as CASCOPHEN P6638 and manufactured by Hexion (2024). Following the instructions from the manufacturer, 70.9% weight/total weight of the resin was mixed with 7.7% w/w of wheat flour, 7.7% w/w of Corn Cob Residue (CCR) filler and 13.7% w/w of water, to create the adhesive mix, targeting a viscosity of 3,000 cp at 30ºC.

Table 5 shows the parameters recommended by the manufacturer for the different stages of gluing.

Table 5: Parameters recommended by the manufacturer for the different stages of gluing.

Stage	Parameter value
Spread rate	180-200 gsm
Lay-up time	1 to 3 min
Open assembly time	5 min total
Cold press time	10 min
Cold press pressure	1 MPa
Closed assembly time	30 min
Hot press temperature	135ºC
Hot press pressure	1.3 bar

4.2.3.1.3 Veneers used and conditioning

Twenty-one southern blue gum and two radiata pine 1.3 m long × 1.2 m wide veneer sheets were selected and cut into 310 mm long × 280 mm wide veneer pieces. Based on the MOE distributions presented in Section 4.3.1.3, the southern blue gum veneers were selected to be representative of veneers with low, medium, and high MOE values. The MOE ranges for these veneers are provided in Table 6.

Seven veneer sheets were selected in each MOE range. As the MOE and density values are correlated (Section 4.3.1.4), the veneers also represent different density ranges. The radiata pine veneers were randomly selected.

Table 6: MOE ranges of the southern blue gum veneers selected for the LVL gluing trials.

Label	MOE ranges
Low	8,000 MPa ≤ MOE ≤ 14,000 MPa
Medium	17,000 MPa ≤ MOE ≤ 23,000 MPa
High	26,000 MPa ≤ MOE ≤ 30,000 MPa

The veneer pieces were conditioned at 40ºC and 23% relative humidity in a temperature and humidity chamber. The veneers reached an average moisture content of 4.6%, with the moisture content measured from four samples following the oven-dry methodology in Clause 4 of AS/NZS 1080.1 (2012).

4.2.3.1.4 Test samples and bond quality tests

5-ply LVL samples were manufactured from the veneer pieces following the manufacturing variations given in Table 7. The number of repeats per variation is also provided in the table. In all cases, the four bottom veneers were orientated with the tight side facing down and the top veneer was orientated with the tight side facing up as per common LVL veneer layup. No two veneer pieces cut from the same veneer sheet were glued together, with samples typically manufactured from veneer pieces cut from five different veneer sheets. All samples were left in the hot press for 8 min.

Table 7: Test samples manufactured for the LVL gluing trials.

Test label	Parameter investigated	LVL type	MOE range	Number of repeats	Manufacturing variations
C_G_L	As recommended by manufacturer	Southern blue gum	Low	3	As per Table 5
C_G_M			Medium	3	
C_G_H			High	3	
SR_G_L	Increased spread rate (by 50%)	Southern blue gum	Low	3	As per Table 5 but with a spread rate of 270-300 gsm
SR_G_M			Medium	3	
SR_G_H			High	3	
HP_G_L	Increased hot press pressure (by 54%)	Southern blue gum	Low	3	As per Table 5 but with a hot press pressure of 2 MPa
HP_G_M			Medium	3	
HP_G_H			High	3	
C_H_L	As recommended by manufacturer	Hybrid	Low	1	As per Table 5
C_H_M			Medium	1	
C_H_H			High	1	

A 200 mm long × 100 mm wide test sample was then cut from each 5-ply LVL for bond quality testing. The test samples were first steamed in an autoclave at 200 kPa for a duration of 6 h and then immersed in room temperature water overnight, as per Clause 7.2.2 for Type A bond in AS/NZS 2098.2 (2012). Afterwards, the veneers were separated along their glueline with a chisel following the procedure outlined in Clause 8 in AS/NZS 2098.2 (2012). The bond quality was visually assessed by measuring the percentage area of each glueline covered by wood and given a bond quality score as per Table 1 in AS/NZS 2098.2 (2012). Scores of 0 and 10 reflect 0% to 5% and 96% to 100% of wood failure across the glueline, respectively. A test sample is deemed to pass the bond quality criteria set in AS/NZS 4357.0 (2022) for LVL structural products if (1) the bond quality score of each glueline is at least 2, and (2) the average bond quality score of all gluelines is at least 5.

4.2.3.2 LVL manufacturing

4.2.3.2.1 General

In view of the LVL simulations performed in Section 4.2.2 and the market study component of the project, it was decided to manufacture 11-ply LVL panels (i.e., of a nominal thickness of 33 mm) of five different types, all having a potential market, to quantify their mechanical properties. The LVL products manufactured follow the scenarios provided in Section 4.2.2.2. They consist of:

- Southern blue gum LVL12 and LVL21, i.e., with targeted characteristic MOE of 12,000 MPa and 21,000 MPa, respectively. This follows Scenario 2 in Section 4.2.2.2, and based on the veneer selection detailed later in this section, this would result in using about 60% and 40% of all peeled veneers to manufacture the LVL12 and LVL21, respectively.
- Hybrid LVL12 and LVL18, i.e., with targeted characteristic MOE of 12,000 MPa and 18,000 MPa. This follows Scenario 1 in Section 4.2.2.2, and based on the veneer selection detailed later in this section, this would result in using about 60% and 20% of all peeled veneers to manufacture the LVL12 and LVL18, respectively.
- Hybrid LVL15, i.e., with targeted characteristic MOE of 15,000 MPa. This follows Scenario 3 in Section 4.2.2.2, and based on the veneer selection detailed later in this section, this would result in using about 60% of all peeled veneers to manufacture the product.

For the veneer selection, the veneers of each species were sorted into five bins based on the acoustic MOE of the veneers, each bin containing 20% of all peeled veneers. This mimics a simple way an industrialist could divide the veneers using the veneer MOE value as the grading indicator. From the MOE distribution of the veneers presented in Section 4.3.1.3, the cut-off MOE values for each bin are presented in Table 8. The values in the table are based on combined Caves and Barker veneers for the southern blue gum, and combined T1 and T2 veneers for the radiata pine.

Table 8: MOE cut-off values of each bin for the LVL manufacturing, each bin containing 20% of all peeled veneers.

Bin	Southern blue gum	Radiata pine
Bin 1	MOE ≤ 13,250 MPa	MOE ≤ 7,250 MPa
Bin 2	13,250 MPa < MOE ≤ 16,500 MPa	7,250 MPa < MOE ≤ 8,750 MPa
Bin 3	16,500 MPa < MOE ≤ 19,500 MPa	8,750 MPa < MOE ≤ 10,250 MPa
Bin 4	19,500 MPa < MOE ≤ 23,000 MPa	10,250 MPa < MOE ≤ 12,000 MPa
Bin 5	MOE > 23,000 MPa	MOE > 12,000 MPa

The LVL were then manufactured by randomly selecting veneers from the different bins as per Table 9. The expected characteristic MOE value of the resulting products, obtained from the simulations, is also given in the table. Five LVL panels were manufactured per LVL type, resulting in a total of 25 × 11-ply LVL. For each LVL, the veneers randomly selected from the bins with the highest MOE were positioned on the outside and the veneers selected from the bins with the lowest MOE were positioned on the inside. For the hybrid LVL, the southern blue gum and radiata pine veneers were alternated, with southern blue gum veneers used as the face veneers. For the instance, in reference to Table 9:

- Southern blue gum LVL12 was manufactured from face-to-face veneers as:
  - 2 × southern blue gum from Bin 3 + 2 × southern blue gum from Bin 4 + 3 × southern blue gum from Bin 1 + 2 × southern blue gum from Bin 4 + 2 × southern blue gum from Bin 3.
- Hybrid LVL15 was manufactured from face-to-face veneers as:
  - 1 × southern blue gum from Bin 5 + 1 × radiata pine from Bin 5 + 1 × southern blue gum from Bin 4 + 1 × radiata pine from Bin 4 + 1 × southern blue gum from Bin 3 + 1 × radiata pine from Bin 3 + 1 × southern blue gum from Bin 3 + 1 × radiata pine from Bin 4 + 1 × southern blue gum from Bin 4+ 1 × radiata pine from Bin 5 + 1 × southern blue gum from Bin 5.

Table 9: MOE cut-off values of each bin for the LVL manufacturing, each bin containing 20% of all peeled veneers.

LVL type	Expected characteristic MOE (MPa)	Number of veneers per bin	
		Southern blue gum	Radiata pine
Southern blue gum LVL12	12,975	3×Bin 1 + 4×Bin 2 + 4×Bin 3	--
Southern blue gum LVL21	21,200	5×Bin 4 + 6×Bin 5	--
Hybrid LVL12	12,675	2×Bin 2 + 2×Bin 3 + 2×Bin 4	1×Bin 2 + 2×Bin 3 + 2×Bin 4
Hybrid LVL15	15,300	2×Bin 3 + 2×Bin 4 + 2×Bin 5	1×Bin 3 + 2×Bin 4 + 2×Bin 5
Hybrid LVL18	18,525	6×Bin 5	5×Bin 5

The LVL panels were manufactured in two batches, as explained in Sections 4.2.3.2.2 and 4.2.3.2.3 along with the manufacturing process.

The summarised commercial production notes reflecting the outcomes of this report are provided in the appendix.

4.2.3.2.2 First batch

In the first batch, 275 × 1.3 m long × 1.2 m wide veneers were selected, as per the construction strategies in Table 9, to manufacture the 25 × 11-ply LVL panels. The following manufacturing parameters were followed:

- The veneers were stripped and left in a solar kiln for 3 weeks before manufacturing.
- The same adhesive as in Section 4.2.3.1.2 was used but the CCR filler was replaced by walnut flour at the same w/w content.
- The recommended manufacturing parameters in Table 5 were observed with the following variations:
  - Cold-press time was adjusted to ensure adhesive transfer and glue penetration during this stage (Leggate, et al., 2017).
  - A spread rate of 250 gsm was used.
- For the size of the veneers, the hot press was not able to provide the 2 MPa pressure found in the results section (Section 4.3.3.1) to provide Type A bond for the southern blue gum LVL. A hot press pressure of 1.3 MPa was used instead for all LVL panels.
- The 10 bottom veneers were orientated with the tight side facing down and the top veneer was orientated with the tight side facing up.

Figure 12 shows the various manufacturing stages.

Due to poor weather conditions in the two weeks prior to manufacturing, the veneers left in the solar kiln did not reach a moisture content of 5% and the excess moisture likely resulted in 12 LVL panels out of 25 blowing out when releasing the pressure in the hot-press (Leggate, et al., 2017). These panels were disregarded and remanufactured in the second batch.

Furthermore, to ensure that the bond between veneers of the remaining 13 LVL was strong enough to assess the mechanical properties of each LVL (i.e., that no delamination will develop during mechanical testing), edge and flat bending samples were cut from these LVL panels following the cutting plan presented in Section 4.2.3.3.1. The samples were then conditioned at 20ºC and 65% relative humidity and tested following the procedure outlined in Section 4.2.3.3.2. The LVL panels for which samples showed signs of delamination during mechanical testing were disregarded and remanufactured in the second batch. Four out of the remaining 13 LVL were then remanufactured, leaving a total of 16 LVL remanufactured in the second batch.

4.2.3.2.3 Second batch

The LVL remanufactured in the second batch consisted of all LVL12 (both southern blue gum and hybrid), one southern blue gum LVL21, three hybrid LVL15 and two hybrid LVL18. In this batch, to ensure that a 2 MPa pressure was reached in the hot press for the southern blue gum LVL and provide Type A bond as developed later in Section 3.1.1, the veneers were cut to a width of 0.8 m, resulting in 176 × 1.3 m long × 0.8 m wide veneers selected to remanufacture 16 × 11-ply LVL panels. Compared to the first batch, the following variations were made:

- The veneers were stripped and dried to 5% moisture content in a kiln.
- A hot press pressure of 1.3 MPa and 2 MPa was used for the hybrid and southern blue gum LVL, respectively.

No LVL panels blew out after hot-pressing in this batch.

(c) (d)

Figure 12: Manufacturing stages of the LVL panels, (a) applying adhesive with a double roller glue spreader, (b) LVL being loaded into the cold press, (c) LVL waiting to be hot-pressed during the closed assembly time and (d) LVL being hot-pressed.

4.2.3.3 Mechanical properties and bond quality

4.2.3.3.1 General and cutting plan

Out of each LVL panel manufactured in Section 4.2.3.2, test samples were cut following the cutting plan shown in Figure 13. In total:

- Two 1,100 mm long × 55 mm wide samples were cut for edge bending (Section 4.2.3.3.2).
- Two 700 mm long × 90 mm wide samples were cut for flat bending (Section 4.2.3.3.2).
- Two 210 mm long × 55 mm wide samples were cut for compression (Section 4.2.3.3.3).
- Two 290 mm long × 55 mm wide samples were cut for edge shear (Section 4.2.3.3.4).

- Two 290 mm long × 35 mm wide samples were cut for flat shear (Section 4.2.3.3.4).
- Two 200 mm long × 100 mm wide samples were cut for bond quality (Section 4.2.3.3.5).

Before testing, all samples were conditioned at 20°C and 65% relative humidity, until they reached equilibrium. Moisture content samples were cut from 16 different bending samples to measure the moisture content of the LVL at the time of testing following the oven-dry methodology in AS/NZS 1080.1 (2012).

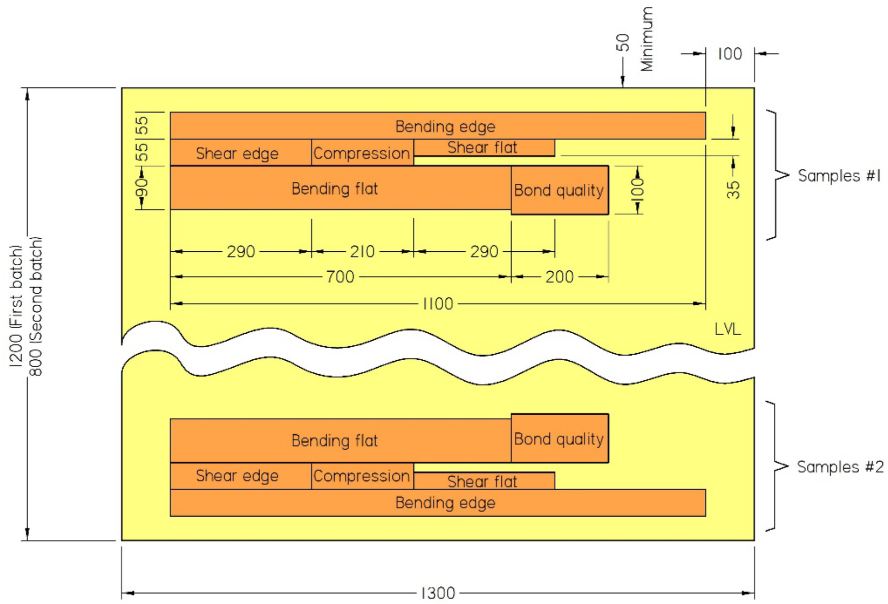


Figure 13: Cutting plan for each LVL to obtain testing samples (units: mm).

4.2.3.3.2 Edge and flat bending

The edge and flat bending LVL samples were tested in four-point bending in accordance with Clauses 9 and 11 of AS/NZS 4357.2 (2006). The span L was equal to 18 times the depth d of the sample, with $d = 55$ mm for edge bending and $d = 33$ mm for flat bending. This resulted in $L = 990$ mm and 594 mm for the edge and flat bending tests, respectively.

The distance between the supports and their nearest load application points, and between the load application points, equalled $L/3$. Steel plates were positioned at the load application point and supports to avoid local crushing of the timber. A Digital Image Correlation (DIC) system was used to measure the vertical displacement δ at mid-span, at the neutral axis and on one side of the samples. The load P was applied by a 100 kN Shimadzu universal testing machine at a stroke rate to reach failure between 2 min and 5 min (AS/NZS 4357.2, 2006). The test set-up is shown in Figure 14.

If failure occurred between the load application points, the bending Modulus of Rupture (MOR) R_b was calculated from the maximum reached load P_{max} as:

$$R_b = \frac{P_{max} L}{bd^2} \qquad (1)$$

where b and d are the measured width and depth of the sample (Figure 14). If failure occurred outside the constant bending moment region and at a distance L_f from the nearest load application point, the bending MOR was calculated as the bending moment at the location of failure (AS/NZS 4063.1, 2010) as,

$$R_b = \frac{P_{max}(L - 3L_f)}{bd^2} \tag{2}$$

The apparent bending Modulus of Elasticity (MOE) E_b was calculated as,

$$E_b = \frac{23}{108}\frac{L^3}{bd^3}K \tag{3}$$

where K is the slope of the linear part of the load P-mid span displacement δ curve, calculated by performing a linear regression between 10% and 40% of the maximum load.

The apparent bending MOE E_b in Eq. (3) was also compared to the MOE of the LVL calculated from the acoustic MOE of the individual veneers, as measured in Section 4.2.1.2.5. This provides an indication on the difference between the static and acoustic MOE for the products.

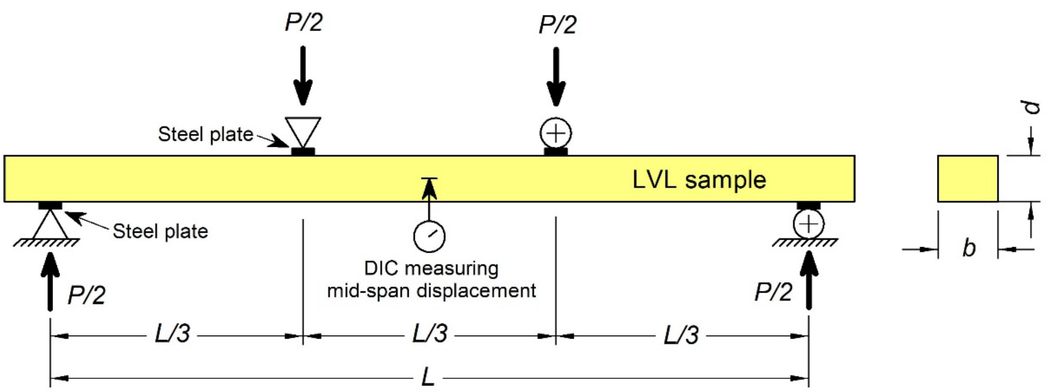
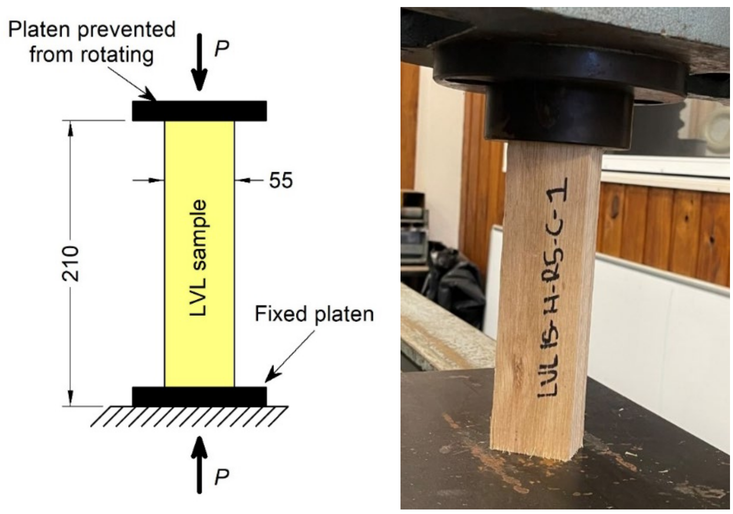


Figure 14: LVL edge and flat bending test set-up.

4.2.3.3.3 Compression parallel to grain

The compression LVL samples were tested in accordance with Clause 15 of AS/NZS 4357.2 (2006), with the length of the test samples about six times the smaller cross-sectional dimension. The end surfaces of the samples were cut plane and parallel to each other, and the specimens were loaded between two fixed platens in a 300 kN Shimadzu universal testing machine at a stroke rate to reach failure between 2 min and 5 min (AS/NZS 4357.2, 2006).



(a) *(b)*

Figure 15: LVL compression test set-up, (a) schematic and (b) photo.

The compressive strength parallel to the grain $R_{c,0}$ was calculated from the maximum reached load P_{max} as:

$$R_{c,0} = \frac{P_{max}}{bd} \tag{4}$$

where b and d are the measured cross-sectional dimensions of the test sample. The test set-up is illustrated in Figure 15.

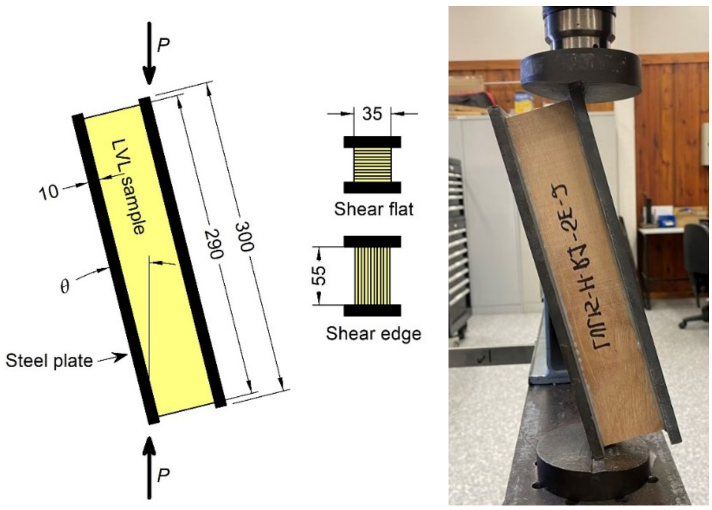
4.2.3.3.4 Edge and flat shear

The LVL edge and flat shear samples were tested in accordance with Clause 16 of AS/NZS 4357.2 (2006). The samples were glued with 2-part epoxy to 300 mm long and 10 mm thick steel plates. The samples were tested in shear, as shown in Figure 16, in a 100 kN Shimadzu universal testing machine at a stroke rate to reach failure between 2 min and 5 min (AS/NZS 4357.2, 2006). In Figure 16 (a), the angle θ between the load direction and the longitudinal axis of the test samples was equal to 14° and 10° for edge and flat shear, respectively. The samples were 10 mm shorter than the 300 mm length recommended in AS/NZS 4357.2 (2006) to ensure that, considering assembly tolerances during gluing, the entire length of LVL samples was always glued to the steel plates.

The shear strength R_s was calculated from the maximum reached load P_{max} as:

$$R_s = \frac{P_{max} cos(\theta)}{Lb} \tag{5}$$

where L is the measured length and b is the measured dimension shown in Figure 16 (b).



(a) (b)

***Figure 16**: LVL edge and flat shear test set-up, (a) schematic and (b) photo of edge shear test.*

4.2.3.3.5 Bond quality

The bond quality was assessed as described in Section 4.2.3.1.4 for Type A bond in AS/NZS 2098.2 (2012) and following the procedure outlined in Clause 8 of AS/NZS 2098.2 (2012). The bond quality results of the panels from the first and second batches are presented separately in the report. The results from the first batch are provided for information only due to the moisture content of the veneers being too high and not enough hot-press pressure applied to the southern blue gum panels as explained in Section 4.2.3.2.2.

4.2.3.3.6 Characteristic values and comparison to commercial products

As the number of tests performed is less than the minimum number of tests required in AS/NZS 4063.2 (2010) to calculate the characteristic properties, characteristic properties are calculated following the approach in the Eurocode which allows for a lower number of tests.

For each of the mechanical property in Sections 4.2.3.3.2 to 4.2.3.3.4, the characteristic design value was calculated following the methodology in Clause 3 of the European standard EN 14358 (2016) based on a number of tests of 10.

These characteristic values were compared to LVL products which are currently or were commercialised and for which the characteristic values are available.

These LVL consist of:

- e-Beam and e-Beam+ (Wesbeam, 2014, Wesbeam, 2023) manufactured by Wesbeam and with characteristic MOE values of 13,200 MPa and 14,000 MPa, respectively.
- hySPAN, hySPAN+ and hyONE (Carter Holt Harvey, 2019, Carter Holt Harvey, 2020) manufactured by CarterHoltHarvey and with characteristic MOE values of 13,200 MPa, 14,000 MPa and 16,000 MPa, respectively.
- LVL13 (NelsonPine, 2021) manufactured by NelsonPine and with a characteristic MOE value of 13,200 MPa.
- LVL-S (Stora Enzo, 2021) manufactured by Stora Enzo and with a characteristic MOE value of 11,600 MPa.

As no commercial LVL product with a characteristic MOE greater than 16,000 MPa was found, the characteristic values of the tested LVL were also compared to the ones of sawn timber grades F27 and F34 in Appendix H of AS 1720.1 (2010), i.e., with characteristic MOE values of 18,500 MPa and 21,500 MPa, respectively.

4.3 Results

4.3.1 Log processing, rotary peeled veneers and recoveries

Out of the 366 billets merchandised, 339 were processed following the geometry limitations outlined in Section 4.2.1.1 and imposed to the billets. This corresponded to (1) 81, 78 and 65 billets ID 1, 2 and 3, respectively, for southern blue gum and (2) 40, 40 and 35 billets ID 1, 2 and 3, respectively, for radiata pine.

These billets resulted in 674, 933, 188 and 369 full veneer sheets recovered from Caves, Barker, Snowgums (T1) and Kilsbys (T2), respectively, i.e., totalling 2.81 kms of veneers.

4.3.1.1 Billet measurements

The average measurements taken on the billets to be peeled are provided in Table 10 and Table 11 for the southern blue gum and radiata pine resources, respectively. The measurements are provided by site and targeted DBHOB. The CoV for each measurement is provided in brackets next to the average value.

For southern blue gum and the largest targeted diameter (i.e., DBHOB between 23.6 cm and 31.8 cm), the trees harvested from Barker have an average measured diameter about 15% greater than Caves. Approximating the average DBHOB of the selected trees to the average value of *LEDOB* and *SEDOB* of billet ID 1 (i.e., corresponding to a diameter over bark at about the same height as the breast height), the selected trees typically have on average a DBHOB close to the upper value of the targeted range of each diameter group. This resulted in larger trees than expected delivered and processed at the Salisbury Research Facility.

Table 10: Average billet measurements (with CoV in % provided in brackets) for southern blue gum.

		Caves		Barker		
Billet ID	**Value**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**Targeted DBHOB greater than 40.0 cm(3)**
1	*SEDOB* (cm)(4)	23.3 (6.3)	27.2 (7.5)	23 (12.0)	31.5 (10.7)	--
	LEDOB (cm)(4)	23.2 (27.9)	30.0 (7.2)	21.7 (43.2)	34.8 (10.2)	35.1 (N/A)
	SEDUB (cm)(4)	21.4 (7.0)	24.6 (7.5)	20.8 (12.4)	28.8 (11.7)	30.3 (1.4)
	LEDUB (cm)(4)	22.7 (8.0)	27.2 (7.9)	22.5 (11.9)	31.5 (12.0)	32.3 (3.9)
	Ovality(5)	1.07 (9.1)	1.05 (2.4)	1.06 (3.1)	1.05 (3.3)	1.01 (0.9)
	S_B(6) (mm)	11.3 (35.6)	14.1 (45.4)	16.8 (56.0)	16.9 (47.0)	12.5 (28.3)
	RD_B (cm)	20.8 (7.1)	24.2 (8.9)	20.8 (14.1)	28.18 (15.1)	29.7 (2.4)
2	*SEDOB* (cm)(4)	21.1 (7.6)	24.8 (8.8)	21.5 (12.5)	28.0 (14.9)	30.3 (N/A)
	LEDOB (cm)(4)	19.1 (43.0)	26.7 (7.3)	21.1 (32.8)	26.5 (38.3)	31.9 (N/A)
	SEDUB (cm)(4)	20.0 (6.4)	23.2 (8.3)	20.2 (10.5)	27.3 (13.0)	28.8 (1.3)
	LEDUB (cm)(4)	20.8 (6.7)	23.9 (7.3)	20.9 (11.4)	27.9 (12.5)	29.6 (0.5)
	Ovality(5)	1.06 (2.4)	1.05 (2.1)	1.07 (3.5)	1.04 (2.0)	1.05 (1.2)
	S_B(6) (mm)	16.1 (60.0)	13.8 (38.9)	14.4 (53.0)	11.1 (37.5)	17.5 (101)
	RD_B (cm)	19.5 (5.7)	22.6 (8.5)	19.7 (11.1)	26.7 (13.4)	28.1 (0.3)
3	*SEDOB* (cm)(4)	20.0 (5.6)	23.8 (8.5)	19.5 (6.1)	26.1 (12.9)	--
	LEDOB (cm)(4)	21.0 (5.8)	24.1 (8.2)	30.4 (113)	26.8 (12.6)	--
	SEDUB (cm)(4)	19.2 (5.2)	21.7 (7.9)	19.2 (7.5)	25.5 (13.5)	26.0 (N/A)
	LEDUB (cm)(4)	20.0 (5.6)	22.4 (7.2)	20.0 (6.9)	26.5 (13.4)	27.3 (N/A)
	Ovality(5)	1.07 (2.5)	1.05 (2.9)	1.07 (2.4)	1.04 (2.1)	1.02 (N/A)
	S_B(6) (mm)	15.8 (50.0)	17.1 (49.8)	13.3 (48.0)	11.7 (53.0)	10.0 (N/A)
	RD_B (cm)	18.9 (8.7)	21.0 (9.6)	18.6 (8.0)	25.1 (12.9)	25.8 (N/A)

(1): Logs 31 to 50.
(2): Logs 1 to 20.
(3): Logs C and D.
(4): Contrary to SEDUB and LEDUB, the SEDOB and LEDOB were not able to be measured for all billets due to bark being removed during harvesting. This resulted in the average OB and UB values reflecting a different number of billets and consequently not always directly comparable.
(5): Calculated as the ratio LSEDUB/SSEDUB.
(6): Over the nominal billet length of 1.3 m.

4.3.1.2 Veneer visual grade distributions

Table 12 to Table 15 detail for Caves, Barker, Snowgums (T1) and Kilsbys (T2), the distributions of the visual grades of the veneers per billet ID and log targeted DBHOB. The information is also plotted for further visualisation in Figure 17 per billet ID, all DBHOB together.

D-grades dominate the feedstock and represent about 75%, 68% and 90% of the southern blue gum, radiata pine T1 and T2 veneers, respectively. On average 17% to 23% of the southern blue gum veneers were F-grade and therefore failed to meet a visual grade and would have limited use in the manufacturing process. The percentage of F-grade veneers is high for the radiata pine T1 feedstock, reaching 32%, but significantly lower and equal to 9.5% for radiata pine T2 veneers. While for Caves, the percentage of F-grade veneers increased with the height of the billet in the tree (billet ID), such correlation was not found for Barker, Snowgums (T1) and Kilsbys (T2). For the southern blue gum, the percentage of A-, B-, C-grades is low, with a maximum of 6.9% encountered for B-grade veneers peeled from trees harvested at Barker. No A-, B-, C-grades were recovered from the radiata pine logs.

Table 11: Average billet measurements (with CoV in % provided in brackets) for radiata pine.

Billet ID	Value	Snowgums (T1) Targeted DBHOB between 15 and 20 cm[(1)]	Kilsbys (T2) Targeted DBHOB between 20 and 25 cm[(2)]
1	*SEDOB* (cm)[(3)]	19.4 (4.7)	24.5 (5.8)
	LEDOB (cm)[(3)]	19.8 (24.4)	26.3 (5.9)
	SEDUB (cm)[(3)]	18.7 (5.4)	23.3 (5.1)
	LEDUB (cm)[(3)]	19.7 (6.5)	24.5 (5.4)
	Ovality[(4)]	1.04 (2.7)	1.05 (2.5)
	S_B[(5)] (mm)	11.3 (37.8)	12.3 (40.8)
	RD_B (cm)	17.7 (5.4)	22.7 (5.0)
2	*SEDOB* (cm)[(3)]	17.8 (5.2)	22.5 (4.9)
	LEDOB (cm)[(3)]	18.6 (6.0)	23.0 (5.3)
	SEDUB (cm)[(3)]	17.1 (5.4)	21.9 (5.6)
	LEDUB (cm)[(3)]	17.9 (5.5)	22.5 (4.4)
	Ovality[(4)]	1.03 (1.7)	1.04 (2.1)
	S_B[(5)] (mm)	10.5 (34.2)	11.3 (32.4)
	RD_B (cm)	16.8 (5.1)	21.0 (5.4)
3	*SEDOB* (cm)[(3)]	16.4 (4.1)	21.2 (5.6)
	LEDOB (cm)[(3)]	17.3 (3.8)	21.6 (5.0)
	SEDUB (cm)[(3)]	15.8 (4.0)	20.5 (5.2)
	LEDUB (cm)[(3)]	16.7 (3.6)	20.9 (5.0)
	Ovality[(4)]	1.03 (2.2)	1.03 (1.9)
	S_B[(5)] (mm)	12.0 (44.0)	12.3 (36.2)
	RD_B (cm)	15.3 (4.0)	19.7 (4.9)

(1): T1 logs 1 to 20.
(2): T2 logs 1 to 20.
(3): Contrary to SEDUB and LEDUB, the SEDOB and LEDOB were not able to be measured for all billets due to bark being removed during harvesting. This resulted in the average OB and UB values reflecting a different number of billets and consequently not always directly comparable.
(4): Calculated as the ratio LSEDUB/SSEDUB.
(5): Over the nominal billet length of 1.3 m.

Table 12: Distributions of visual grade for Caves (southern blue gum), detailed per targeted DBHOB and billet ID.

Diameter	Billet ID	Percentage of grade (%) A	B	C	D	F
All targeted DBHOB	All	0.0	1.2	0.3	75.6	23.0
	1	0.0	1.8	0.7	80.4	17.0
	2	0.0	1.3	0.0	78.3	20.4
	3	0.0	0.0	0.0	66.3	33.7
Targeted DBHOB between 17.0 and 23.6 cm	All	0.0	1.8	0.0	72.5	25.7
	1	0.0	4.3	0.0	81.2	14.5
	2	0.0	0.0	0.0	63.9	36.1
	3	0.0	0.0	0.0	69.4	30.6
Targeted DBHOB between 23.6 and 31.8 cm	All	0.0	0.8	0.5	77.7	21.1
	1	0.0	0.0	1.3	79.9	18.8
	2	0.0	2.2	0.0	85.5	12.3
	3	0.0	0.0	0.0	64.5	35.5

The findings above are consistent with the literature review which showed that for hardwood plantations, D-grade veneers typically dominate the feedstock. Therefore, as outlined in the literature review and confirmed in this section, appearance veneer-based products cannot be manufactured from the resources of interest in this project.

The percentage of D-grade and F-grade veneers does not appear to be significantly correlated with the DBHOB or the billet ID.

As it impacts the recovery values, the high percentage of F-grade veneers for the radiata pine T1 would need to be considered by a manufacturer if T1 logs were to be peeled. Recoveries rates for this resource are provided in Section 4.3.1.5 for further decision-making information.

Table 13: Distributions of visual grade for Barker (southern blue gum), detailed per targeted DBHOB and billet ID.

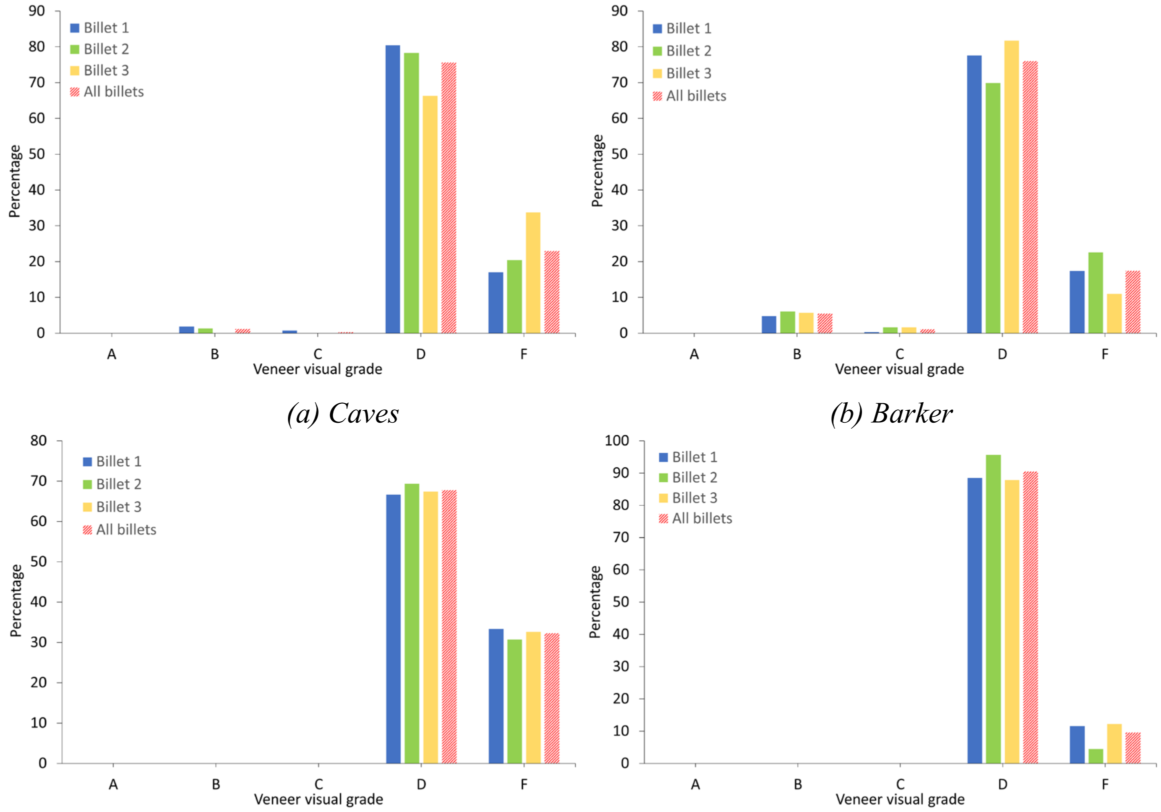
		Percentage of grade (%)				
Diameter	**Billet ID**	**A**	**B**	**C**	**D**	**F**
All targeted DBHOB	All	0.0	5.4	1.1	76.0	17.4
	1	0.0	4.8	0.3	77.6	17.4
	2	0.0	6.0	1.6	69.8	22.5
	3	0.0	5.7	1.6	81.7	11.0
Targeted DBHOB between 17.0 and 23.6 cm	All	0.0	6.9	0.3	74.4	18.3
	1	0.0	8.5	0.0	79.5	12.0
	2	0.0	5.3	0.0	67.4	27.4
	3	0.0	6.5	1.3	75.3	16.9
Targeted DBHOB between 23.6 and 31.8 cm	All	0.0	5.0	1.5	76.1	17.5
	1	0.0	3.1	0.4	75.4	21.1
	2	0.0	6.7	2.4	69.9	21.1
	3	0.0	5.3	1.8	84.6	8.3

Table 14: Distributions of visual grade for Snowgums (T1) (radiata pine), detailed per billet ID.

		Percentage of grade (%)				
Diameter	**Billet ID**	**A**	**B**	**C**	**D**	**F**
Targeted DBHOB between 15 and 20 cm	All	0.0	0.0	0.0	67.8	32.2
	1	0.0	0.0	0.0	66.7	33.3
	2	0.0	0.0	0.0	69.3	30.7
	3	0.0	0.0	0.0	67.4	32.6

Table 15: Distributions of visual grade for Kilsbys (T2) (radiata pine), detailed per billet ID.

		Percentage of grade (%)				
Diameter	**Billet ID**	**A**	**B**	**C**	**D**	**F**
Targeted DBHOB between 20 and 25 cm	All	0.0	0.0	0.0	90.5	9.5
	1	0.0	0.0	0.0	88.5	11.5
	2	0.0	0.0	0.0	95.6	4.4
	3	0.0	0.0	0.0	87.8	12.2



(a) Caves (b) Barker

(c) Snowgums (T1) (d) Kilsbys (T2)

Figure 17: Distributions of visual grades for all peeled veneers for (a) Caves (southern blue gum), (b) Barker (southern blue gum), (c) Snowgums (T1 - radiata pine) and (d) Kilsbys (T2 - radiata pine).

In reference to Section 4.2.1.2.4, Figure 18 and Figure 19 plot the distributions of the most noticeable characteristics downgrading the veneers to D- and F-grades, respectively. The figures provide the data for all sites, all DBHOB together. For all resources, unsound knots were found to be the most noticeable characteristic that downgraded the veneers to a D-grade. For the southern blue gum, either the presence of wane, kino pockets or the aggregate dimension of characteristics along a 300 mm line drawn across the grain (referred to as cumulative defects herein) downgraded the veneers to a F-grade (AS/NZS 2269.0, 2012). For the radiata pine, F-grade veneers mainly resulted due to the aggregate dimension of characteristics.

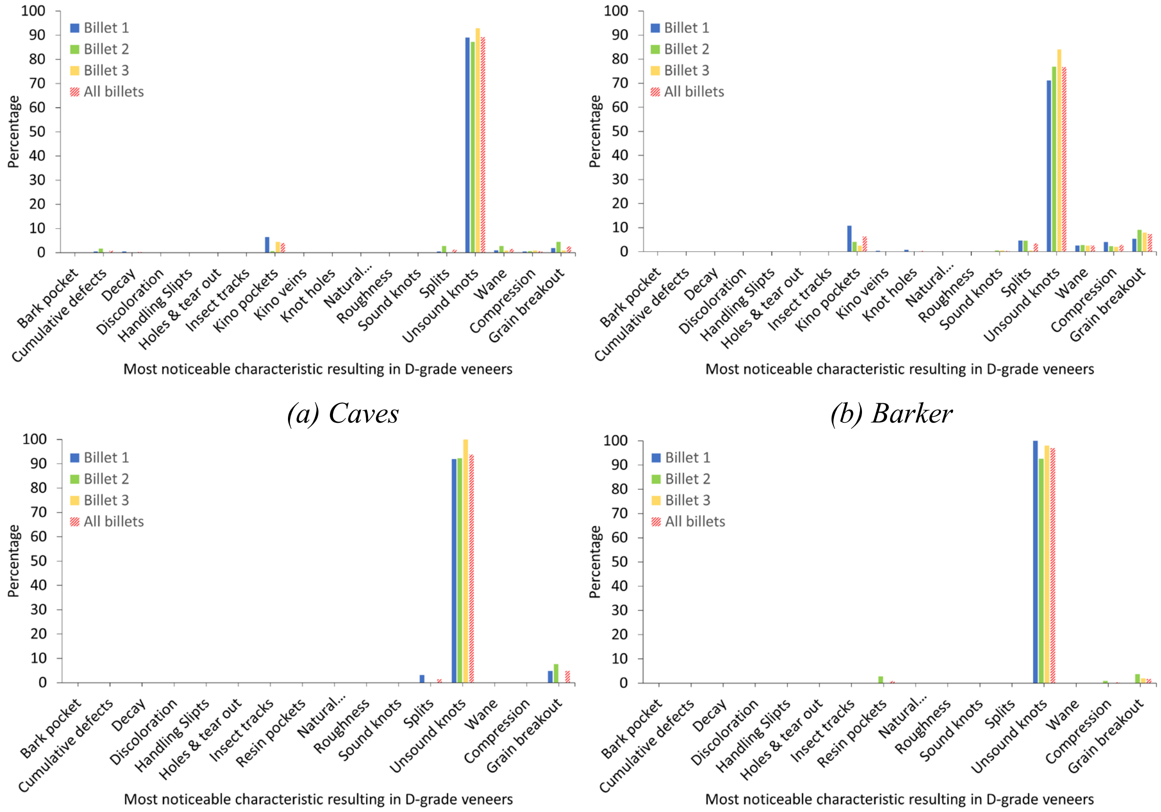
4.3.1.3 Veneer MOE distributions

Table 16 and Table 17 summarise the average MOE of the full veneer sheets recovered per site, targeted DBHOB and billet ID for the southern blue gum and radiata pine resources, respectively. The CoV is provided in brackets next to each average MOE.

The CDF of the MOE are also plotted in Figure 20 to appreciate the distribution of the MOE within the harvested resources.

The average MOE for the peeled veneers is equal to:

- 15,690 MPa for Caves.
- 20,119 MPa for Barker.
- 8,131 MPa for Snowgums (T1).
- 10,502 MPa for Kilsbys (T2).



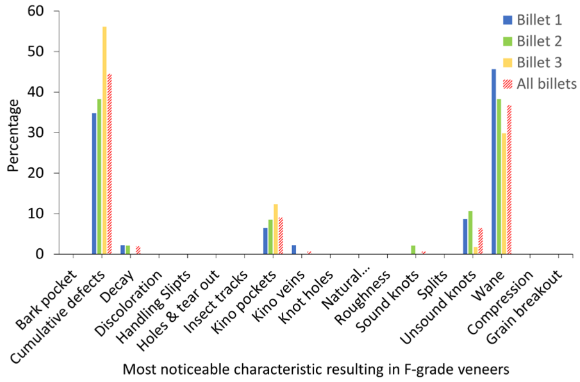
(a) Caves *(b) Barker*

(c) Snowgums (T1) *(d) Kilsbys (T2)*

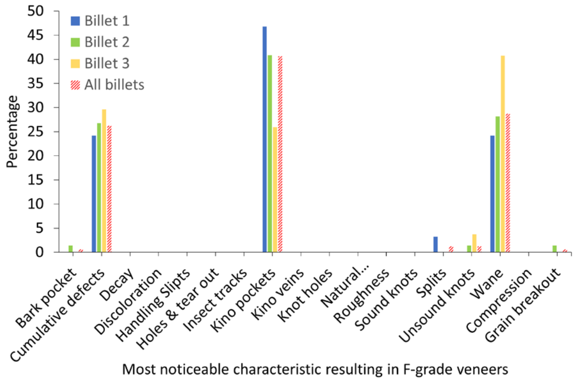
***Figure 18**: Distributions of the most noticeable characteristic determining the D-grade of all peeled veneers for (a) Caves (southern blue gum), (b) Barker (southern blue gum), (c) Snowgums (T1 - radiata pine) and (d) Kilsbys (T2 - radiata pine).*

When compared to Caves, Barker showed higher MOE veneers and less differences in terms of MOE between veneers peeled from logs of different DBHOB. The average MOE of Caves is consistent with the average veneer MOE of 15,896 MPa, with a CoV of 30.8%, found by McGavin, et al. (2015a) after peeling 13-16-year-old fibre-managed southern blue gum logs of 30.6 cm average DBHOB. The One-way ANOVA analyses showed that for the southern blue gum:

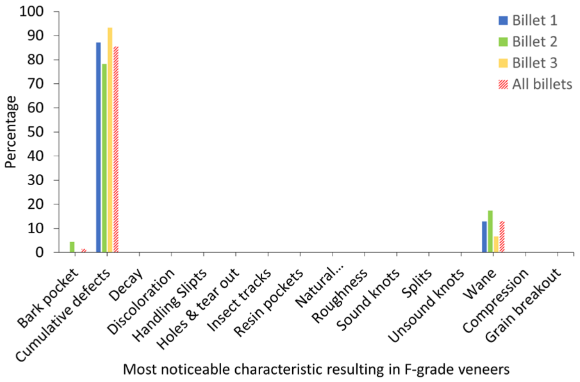
- For both Caves and Barker, there was a statistically significant difference between billet IDs' MOE means ($F(2,659) = 11.91$, $p = 8.2\times10^{-6}$ for Caves, and $F(2,843) = 20.48$, $p = 2.1\times10^{-9}$ for Barker). This difference is principally due to billet ID 1 yielding an average MOE about 9% lower than billet IDs 2 and 3 for Caves, and between 7% and 17% lower for Barker.
- For Caves, there was a statistically significant difference between the MOE means of the two different diameter groups ($F(1,628) = 59.24$, $p = 5.4\times10^{-14}$), with the smaller diameter logs resulting in an average MOE about 16% higher than the larger diameter logs. However, for Barker, there were no statistically significant differences between MOE means of all different diameter groups, including larger logs C and D, ($F(2,915) = 2.987$, $p = 0.0509$).
- There was a statistically significant difference between MOE means of the two different sites ($F(1,1716) = 33.31$, $p = 9.3\times10^{-9}$), with Barker yielding veneers with an average MOE 1.28 times higher than Caves, as seen in Table 16 and highlighted above.



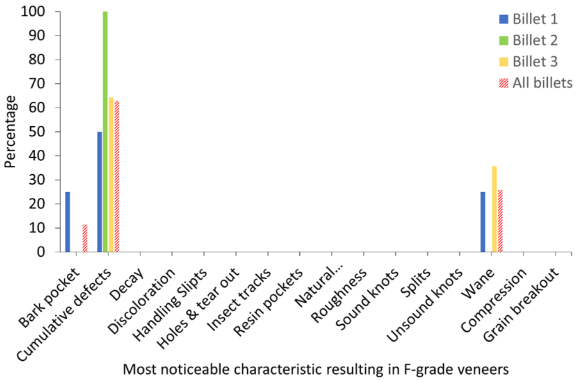
(a) Caves



(b) Barker



(c) Snowgums (T1)



(d) Kilsbys (T2)

***Figure 19**: Distributions of the most noticeable characteristic determining the F-grade of all peeled veneers for (a) Caves (southern blue gum), (b) Barker (southern blue gum), (c) Snowgums (T1 - radiata pine) and (d) Kilsbys (T2 - radiata pine).*

***Table 16**: Average MOE of full veneer sheets (with CoV in % provided in brackets) for southern blue gum.*

	Average MOE (MPa)						
	Caves			Barker			
Billet ID	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB (all logs)(3)**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB below 31.8 cm(3)**	**Targeted DBHOB greater than 40.0 cm(4)**
All	17,126 (22.1)	14,724 (26.5)	15,690 (25.6)	19,435 (27.0)	20,425 (29.5)	20,119 (28.9)	19,563 (24.1)
1	16,842 (22.0)	13,519 (23.4)	14,816 (25.1)	17,946 (27.1)	19,201 (30.1)	18,807 (29.4)	19,403 (23.7)
2	17,548 (23.0)	15,635 (27.5)	16,492 (25.7)	19,124 (26.4)	20,545 (30.4)	20,110 (29.5)	19,808 (25.1)
3	17,243 (21.4)	15,323 (25.7)	16,024 (24.6)	22,063 (23.6)	21,899 (25.8)	21,946 (25.2)	19,413 (24.9)

(1): Logs 31 to 50.
(2): Logs 1 to 20.
(3): Logs 1 to 20 and 31 to 50.
(4): Logs C and D.

For the radiata pine, one-way ANOVA analyses showed that:

- For both the 1st and 2nd thinning, there was no statistically significant differences between MOE means of all different billet IDs ($F(2,178) = 2.638$, $p = 0.074$ Snowgums (T1) and $F(2,361) = 0.349$, $p = 0.705$ for Kilsbys (T2)). The radiata pine showed more consistent material properties along the length of the logs than the southern blue gum.
- There was a statistically significant difference between the MOE means of the two different sites ($F(1,555) = 102.3$, $p = 3.47\times10^{-22}$) with the T2 logs showing an average MOE 29% higher than the T1 logs.

Table 17: Average MOE of full veneer sheets (with CoV in % provided in brackets) for radiata pine.

	Average MOE (MPa)	
	Snowgums (T1)	Kilsbys (T2)
Billet ID	Targeted DBHOB between 15 and 20 cm(1)	Targeted DBHOB between 20 and 25 cm(2)
All	8,131 (26.0)	10,502 (27.0)
1	7,970 (27.2)	10,433 (29.8)
2	8,661 (26)	10,691 (27.3)
3	7,819 (21)	10,409 (23.1)

(1): T1 logs 1 to 20.
(2): T2 logs 1 to 20.

For modelling purposes, Table 18 provides the Weibull parameters that best fit the MOE distributions shown in Figure 20. The parameters of the Weibull distributions are provided per site and by combining sites of the same species. All billet ID and targeted diameters were considered together.

Table 18: Shape (α), scale (β) and location (γ) Weibull parameters that best fit the MOE distributions of the veneer sheets.

			Weibull parameters		
Site(s)	Billet ID	Targeted diameter	*α*	*β (MPa)*	*γ (MPa)*
Caves	All	Between 17 and 31.8 cm	2.3626	10,044	6,795.4
Barker	All	Between 17 and 31.8 cm	3.1826	19,229	2,911.2
Caves + Barker	All	Between 17 and 31.8 cm	2.7638	16,026	3,939.3
Snowgums (T1)	All	Between 15 and 20 cm	2.0447	4,644.3	4,015.1
Kilsbys (T2)	All	Between 20 and 25 cm	3.7243	10,285	1,233.6
Snowgums (T1) + Kilsbys (T2)	All	Between 15 and 25 cm	2.3361	6,997.4	3,505.4

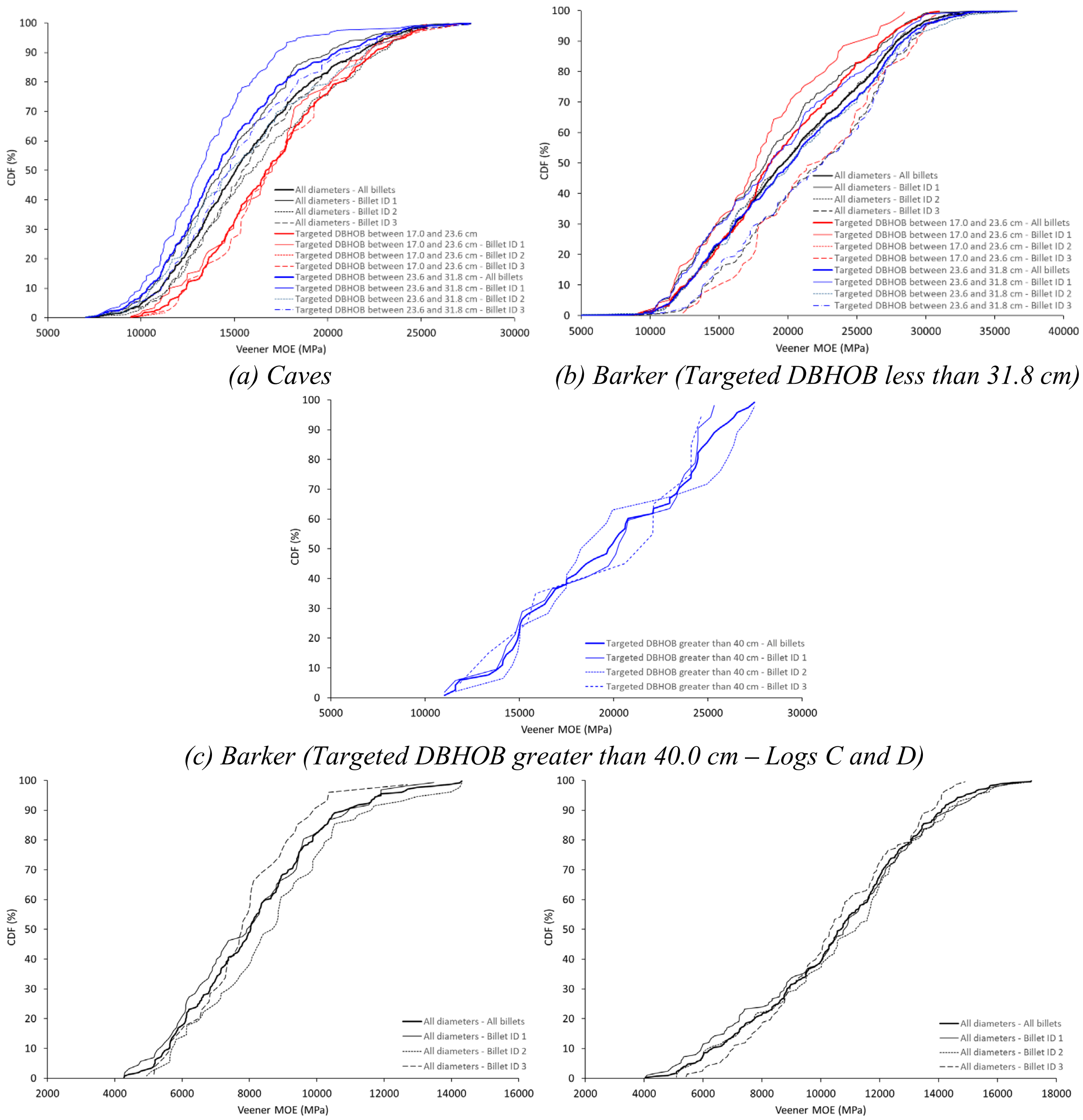
Additionally, Figure 21 plots the distribution of the acoustic MOE (E_{sd}) versus the position r of the veneer along the radius of the tree for each site, with all diameters and billet IDs plotted together. For each site, a linear regression line is plotted in the figure, along with the line equation and the R-square factor of the regression.

For southern blue gum, at the same radial position, Barker provides veneers with a MOE about 26% higher than Caves. For radiata pine, at the same radial position, the MOE for the T1 and T2 veneers are similar, with the T2 veneers only showing an average increase in MOE of 4% when compared to T1.

4.3.1.4 *Veneer density distributions*

Table 19 and Table 20 summarise the average density of the full veneer sheets per site, targeted DBHOB and billet ID for the southern blue gum and radiata pine resources, respectively. The CoV is provided in brackets next to each average MOE.

Similarly to the previous section, the CDF of the measured densities are also plotted in Figure 22 to appreciate the distribution of the measured values within the harvested resources.



(a) Caves *(b) Barker (Targeted DBHOB less than 31.8 cm)*

(c) Barker (Targeted DBHOB greater than 40.0 cm – Logs C and D)

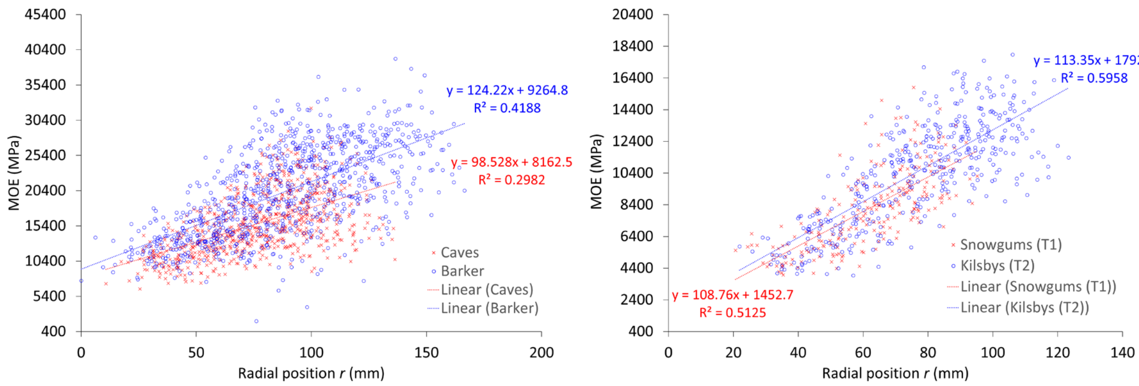
(d) Snowgums (T1) *(e) Kilsbys (T2)*

***Figure 20**: CDF of the full veneer sheet MOE for (a) Caves (southern blue gum), (b) Barker (southern blue gum and targeted DBHOB less than 31.8 cm), (c) Barker (southern blue gum and targeted DBHOB greater than 40 cm), (d) Snowgums (T1 - radiata pine) and (e) Kilsbys (T2 - radiata pine).*

The average density for the peeled veneers is equal to 748 kg/m^3, 779 kg/m^3, 469 kg/m^3 and 483 kg/m^3 for Caves, Barker, Snowgums (T1) and Kilsbys (T2), respectively. Similarly to the

MOE, Barker showed more density consistency between veneers peeled from logs of different DBHOB. The One-way ANOVA analyses showed that for the two species:

- For both Caves and Barker, there was a statistically significant difference between billet ID density means ($F(2,669) = 11.35$, $p = 1.4\times10^{-5}$ for Caves and $F(2,861) = 8.91$, $p = 1.5\times10^{-4}$ for Barker). Similar statistically significant differences were found between the density of the different radiata pine billet ID ($F(2,186) = 7.027$, $p = 1.1\times10^{-3}$ for Snowgums (T1) and $F(2,366) = 8.757$, $p = 1.9\times10^{-4}$ for Kilsbys (T2)). This difference is principally due to the density increasing and decreasing with the height of the logs for the southern blue gum and radiata pine, respectively, as can be seen in Table 19 and Table 20.
- For the southern blue gum, there was a statistically significant difference between the density means of the two different diameter groups ($F(1,429) = 10.117$, $p = 1.6\times10^{-3}$ for Caves and $F(1,635) = 4.308$, $p = 0.038$ for Barker). The average density increased with the targeted DBHOB.
- There was a statistically significant difference between the density means of the two different southern blue gum sites ($F(1,1534) = 53.58$, $p = 4.0\times10^{-13}$), with Barker yielding veneers with higher density.



(a) Southern blue gum *(b) Radiata pine*

***Figure 21**: Veneer MOE (E_{sd}) versus radial position (r) across the tree for (a) southern blue gum and (b) radiata pine.*

***Table 19**: Average density of the full veneer sheets (with CoV in % provided in brackets) for southern blue gum.*

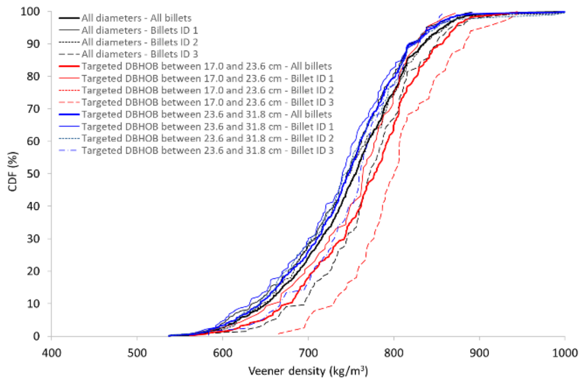
	Average density (kg/m³)						
	Caves			Barker			
Billet ID	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB (all logs)(3)**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB below 31.8 cm(3)**	**Targeted DBHOB greater than 40.0 cm(4)**
All	748 (9.6)	769 (9.1)	741 (9.6)	779 (11.1)	784 (10.4)	780 (11.3)	772 (7.8)
1	738 (9.5)	752 (8.8)	733 (9.8)	766 (11.6)	766 (10.6)	770 (12.1)	765 (8.9)
2	746 (10.0)	759 (9.7)	741 (10.3)	780 (10.7)	794 (9.9)	779 (11.0)	777 (5.9)
3	771 (8.2)	802 (7.4)	753 (7.9)	797 (10.4)	801 (10.4)	795 (10.4)	777 (7.3)

(1): Logs 31 to 50.
(2): Logs 1 to 20.
(3): Logs 1 to 20 and 31 to 50.
(4): Logs C and D.

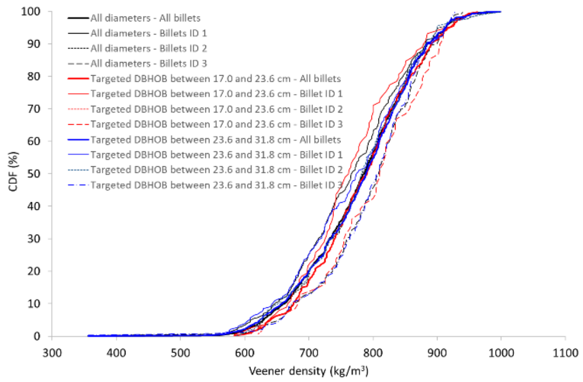
Table 20: Average density of the full veneer sheets (with CoV in % provided in brackets) for radiata pine.

	Average density (kg/m³)	
	Snowgums (T1)	**Kilsbys (T2)**
Billet ID	**Targeted DBHOB between 15 and 20 cm[(1)]**	**Targeted DBHOB between 20 and 25 cm[(2)]**
All	469 (8.5)	483 (10.7)
1	480 (8.7)	496 (11.3)
2	466 (8.6)	478 (10.9)
3	453 (6.4)	470 (8.3)

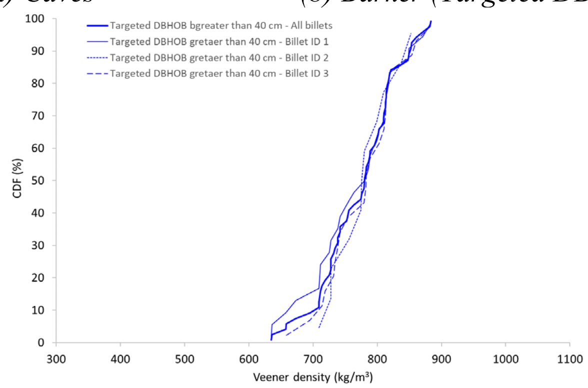
[(1)]: T1 logs 1 to 20.
[(2)]: T2 logs 1 to 20.



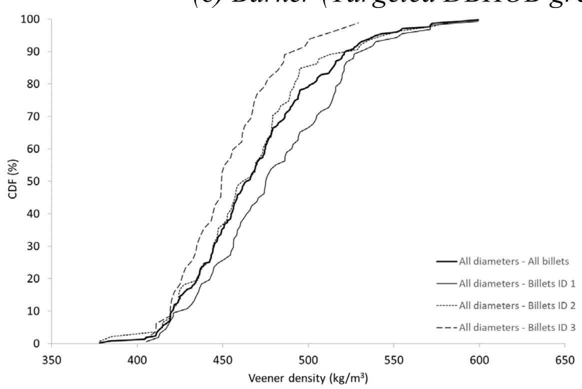
(a) Caves



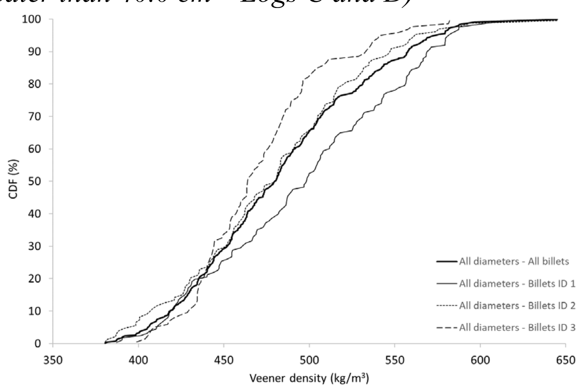
(b) Barker (Targeted DBHOB less than 31.8 cm)



(c) Barker (Targeted DBHOB greater than 40.0 cm – Logs C and D)



(d) Snowgums (T1)

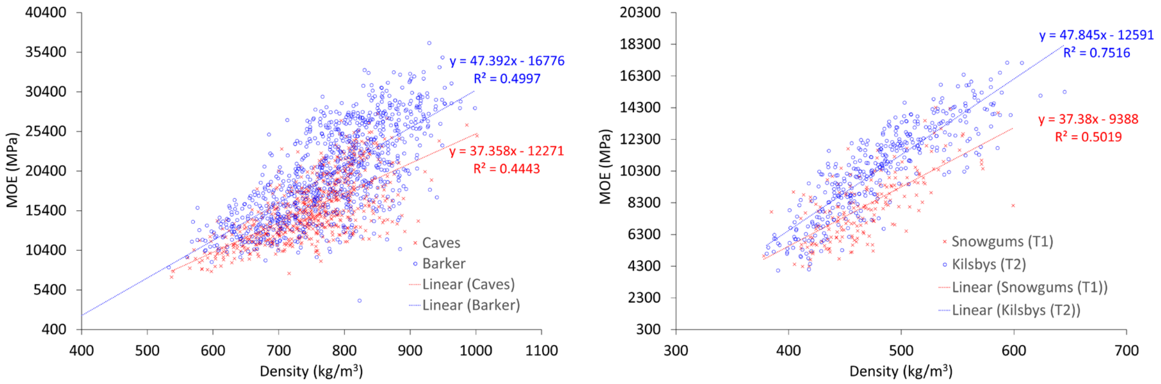


(e) Kilsbys (T2)

***Figure 22**: CDF of the full veneer sheet density for (a) Caves (southern blue gum), (b) Barker (southern blue gum and targeted DBHOB less than 31.8 cm), (c) Barker (southern blue gum and targeted DBHOB greater than 40 cm), (d) Snowgums (T1 - radiata pine) and (e) Kilsbys (T2 - radiata pine).*

Figure 23 plots the distribution of the acoustic MOE (E_{sd}) versus the density (d_{sd}) for each site, with all diameters and billet IDs plotted together. For each site, a linear regression line is plotted in the figure, along with the line equation and the R-square factor of the regression.

For southern blue gum, for the same density, Barker provides veneers with a higher MOE than Caves. For the radiata pine, for the same density, the MOE of the T2 veneers is higher than the T1 veneers.



(a) Southern blue gum *(b) Radiata pine*

***Figure 23**: Veneer MOE (E_{sd}) versus radial position Veneer density (d_{sd}) versus radial position (r) across the tree for (a) southern blue gum and (b) radiata pine.*

4.3.1.5 Veneer recoveries

Table 21 and Table 22 summarise the green veneer recoveries per site, targeted DBHOB and billet ID for the southern blue gum and radiata pine resources, respectively. GNR ranges between 70% to 78% for the southern blue gum and T2 logs but is less than 70% for the T1 logs. The green veneer recoveries of the southern blue gum are consistent with the value of 77% in McGavin et al. (2015a) in which 13-16-year-old fibre-managed southern blue gum logs were processed.

The position of the billets along the log does not influence the green recovery, with similar recovery values for all billet ID. Similarly, no differences can be found between the green recoveries of the different targeted diameter groups.

***Table 21**: Green veneer recovery (GNR) for southern blue gum.*

	GNR (%)						
	Caves			**Barker**			
Billet ID	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB (all logs)(3)**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**All targeted DBHOB below 31.8 cm(3)**	**Targeted DBHOB greater than 40.0 cm(4)**
All	74	75	75	73	73	76	78
1	74	74	74	73	73	74	77
2	75	77	76	75	75	78	78
3	74	76	75	71	71	74	78

(1): Logs 31 to 50.
(2): Logs 1 to 20.
(3): Logs 1 to 20 and 31 to 50.
(4): Logs C and D.

The gross veneer recoveries (GSR) are presented in Table 23 and Table 24 for southern blue gum and radiata pine, respectively. GSR is about 50% for the southern blue gum resources which compares to 57% in McGavin et al. (2015a). Regarding radiata pine, GSR is 42% for the T1 logs, against 60% for the T2 logs. This difference is principally explained by the high percentage of F-grades encountered for the T1 logs (see Section 4.3.1.2).

Table 22: Green veneer recovery (GNR) for radiata pine.

	***GNR* (%)**	
	Snowgums (T1)	**Kilsbys (T2)**
Billet ID	**Targeted DBHOB between 15 and 20 cm**[(1)]	**Targeted DBHOB between 20 and 25 cm**[(2)]
All	67	71
1	65	74
2	71	70
3	64	71

[(1)]: T1 logs 1 to 20.
[(2)]: T2 logs 1 to 20.

Table 23: Gross veneer recovery (GSR) for southern blue gum.

	***GSR* (%)**						
	Caves			**Barker**			
Billet ID	**Targeted DBHOB between 17.0 and 23.6 cm**[(1)]	**Targeted DBHOB between 23.6 and 31.8 cm**[(2)]	**All targeted DBHOB (all logs)**[(3)]	**Targeted DBHOB between 17.0 and 23.6 cm**[(1)]	**Targeted DBHOB between 23.6 and 31.8 cm**[(2)]	**All targeted DBHOB below 31.8 cm**[(3)]	**Targeted DBHOB greater than 40.0 cm**[(4)]
All	47	50	49	50	54	52	[(5)]
1	53	51	52	54	53	53	[(5)]
2	41	57	51	43	52	49	[(5)]
3	43	43	43	45	58	55	[(5)]

[(1)]: Logs 31 to 50.
[(2)]: Logs 1 to 20.
[(3)]: Logs 1 to 20 and 31 to 50.
[(4)]: Logs C and D.
[(5)]: Not enough data for accurate calculations.

Table 24: Gross veneer recovery (GSR) for radiata pine.

	***GSR* (%)**	
	Snowgums (T1)	**Kilsbys (T2)**
Billet ID	**Targeted DBHOB between 15 and 20 cm**[(1)]	**Targeted DBHOB between 20 and 25 cm**[(2)]
All	42	60
1	40	58
2	46	63
3	40	59

[(1)]: T1 logs 1 to 20.
[(2)]: T2 logs 1 to 20.

Finally, the net (*NR*) and graded (NR_A to NR_D) veneer recoveries are presented in Table 25 and Table 26. The recovery values reflect the values found for GSR and the percentages of each visual grade reported in see Section 4.3.1.2. Principally visual D-grade veneers are recovered, reaching more than 50% for the T2 logs.

Table 25: Net (NR) and graded (NRA to NRD) veneer recoveries for southern blue gum.

Billet ID	Caves					Barker				
	All targeted DBHOB (all logs)(1)					All targeted DBHOB below 31.8 cm(1)				
	NR (%)	*NR_A* (%)	*NR_B* (%)	*NR_C* (%)	*NR_D* (%)	*NR* (%)	*NR_A* (%)	*NR_B* (%)	*NR_C* (%)	*NR_D* (%)
All	43	0	1	<1	42	46	0	2	1	43
1	45	0	1	<1	44	47	0	2	<1	45
2	45	0	1	0	44	44	0	3	1	40
3	38	0	0	0	38	49	0	3	1	45

(1): Logs 1 to 20 and 31 to 50.

Table 26: Net (NR) and graded (NRA to NRD) veneer recoveries for radiata pine.

Billet ID	Snowgums (T1)					Kilsbys (T2)				
	Targeted DBHOB between 15 and 20 cm(1)					Targeted DBHOB between 20 and 25 cm(2)				
	NR (%)	*NR_A* (%)	*NR_B* (%)	*NR_C* (%)	*NR_D* (%)	*NR* (%)	*NR_A* (%)	*NR_B* (%)	*NR_C* (%)	*NR_D* (%)
All	37	0	0	0	37	53	0	0	0	53
1	35	0	0	0	35	52	0	0	0	52
2	41	0	0	0	41	56	0	0	0	56
3	36	0	0	0	36	53	0	0	0	53

(1): T1 logs 1 to 20.
(2): T2 logs 1 to 20.

4.3.2 Potential LVL products out of the resources (numerical simulations)

Table 27 and Table 28 present the results from the numerical simulations for the southern blue gum only and hybrid LVL scenarios, respectively. The tables show the percentage of each targeted LVL type which is expected to be manufactured from the resources. The cutoff MOE values for each bin in which the veneers will be segregated to are also presented in the tables.

The following comments can be drawn from the southern blue gum only LVL in Table 27:

- The southern blue gum resources offer enough high MOE veneers to mainly manufacture high performance LVL.
- Using 99% of the veneers recovered from Barker would allow the manufacturing of LVL18 as a unique product.
- Similarly, using 100% of the veneers recovered from both Caves and Barker would allow the manufacturing of a unique LVL15, with the characteristic MOE of the resulting LVL being 8% higher than what would be required for LVL15.
- 64% and 35% of the veneers recovered from Caves can be used to manufacture LVL12 and LVL18, respectively.
- If a manufacturer targets to be using the highest MOE veneers to manufacture LVL21, then no to little LVL18 would be able to be manufactured. LVL12 would complement the LVL21. For instance, using the veneers from both Caves and Barker, 42% and 58% of the veneers can be used to manufacture LVL21 and LVL12, respectively.

Table 27: Numerical simulation results for southern blue gum only LVL.

Scenario	Resources/Sites	Targeted products	Characteristic MOE over 100 simulations (MPa)	Volume (%)	Bin MOE cutoff values (MPa)	
					Low (≥)	High (<)
1	Caves	LVL18	18,000	35	17,100	--
		LVL12	12,000	64	8,200	17,100
		Remaining	7,000	1	--	8,200
	Barker	LVL18	18,000	99	7,100	--
		LVL12	N/A	0	--	--
		Remaining	5,450	1	--	7,100
	Caves + Barker	LVL18	18,000	79	13,500	--
		LVL12	12,000	2	13,200	13,500
		Remaining	9,500	20	--	13,200
2	Caves	LVL21	21,000	10	21,200	--
		LVL18	18,000	11	19,000	21,200
		LVL12	12,700	79	--	19,000
		Remaining	N/A	0	--	--
	Barker	LVL21	21,000	65	17,600	--
		LVL18	N/A	0	--	--
		LVL12	12,350	34	--	17,600
		Remaining	N/A	0	--	--
	Caves + Barker	LVL21	21,000	42	19,100	--
		LVL18	N/A	0	--	--
		LVL12	12,800	58	--	19,100
		Remaining	N/A	0	--	--
3	Caves	LVL15	15,000	84	11,600	--
		Remaining	9,100	16	--	11,600
	Barker	LVL15	17,950	100	--	--
		Remaining	N/A	0	--	--
	Caves + Barker	LVL15	16,200	100	--	--
		Remaining	N/A	0	--	--

Regarding the hybrid LVL presented in Table 28, the following comments can be made:

- The hybrid LVL is well suited to manufacture large volumes of LVL12 (as the commodity product), while still enabling lower volumes of high performance LVL to be manufactured. For instance, 23% and 64% of all southern blue gum and radiata pine veneers can be used to manufacture LVL18 and LVL12, respectively, leaving 13% of the lower MOE veneers unallocated. To limit wastage, 5%, 9%, and 80% of all southern blue gum and radiata pine veneers can be used to manufacture LVL21, LVL18 and LVL12, respectively, only leaving 5% of the veneer unallocated.
- All veneers can be used in the manufacturing of a unique LVL12, with the characteristic MOE of the resulting LVL being more than 6% higher than what would be required for LVL12.
- Manufacturing LVL15 as a unique product would result in utilising between 63% and 69% of all veneers. Using the 31% to 37% of the remaining veneers to manufacture another LVL would result in a product with a low characteristic MOE of about 8,500-9,000 MPa.

Table 28: Numerical simulations results for southern blue gum and radiata pine (Hybrid) LVL.

Scenario	Resources/Sites	Targeted products	Characteristic MOE over 100 simulations (MPa)	Volume (%)	Bin MOE cutoff values (MPa)			
					Southern blue gum		Radiata pine	
					Low (≥)	High (<)	Low (≥)	High (<)
1	Caves + Barker / Snowgums (T1) + Kilsbys (T2)	LVL18	18,000	23	22,300	--	11,725	--
		LVL12	12,200	64	11,800	22,300	6,525	11,725
		Remaining	6,950	13	-	11,800	--	6,525
	Caves + Barker / Kilsbys (T2)	LVL18	18,000	26	21,800	--	12,380	--
		LVL12	12,000	66	10,600	21,800	6,600	12,380
		Remaining	6,450	8	--	10,600	--	6,600
2	Caves + Barker / Snowgums (T1) + Kilsbys (T2)	LVL21	21,000	5	27,500	--	14,550	--
		LVL18	18,000	9	24,300	27,500	12,790	14,550
		LVL12	12,000	80	9,500	24,300	5,500	12,790
		Remaining	5,870	5	--	9,500	--	5,500
	Caves + Barker / Kilsbys (T2)	LVL21	21,000	6	27,400	--	17,880	--
		LVL18	18,000	11	23,700	27,400	13,250	17,880
		LVL12	12,000	82	7,500	23,700	4,600	13,250
		Remaining	4,750	2	--	7,500	--	4,600
3	Caves + Barker / Snowgums (T1) + Kilsbys (T2)	LVL15	15,000	63	16,100	--	8,550	--
		Remaining	8,850	37	--	16,100	--	8,550
	Caves + Barker / Kilsbys (T2)	LVL15	15,000	69	15,100	--	10,000	--
		Remaining	8,700	31	--	15,100	--	10,000
4	Caves + Barker / Snowgums (T1) + Kilsbys (T2)	LVL12	12,700	100	--	--	--	--
		Remaining	N/A	0	--	--	--	--
	Caves + Barker / Kilsbys (T2)	LVL12	13,100	100	--	--	--	--
		Remaining	N/A	0	--	--	--	--

4.3.3 LVL manufacturing and testing

4.3.3.1 Gluing trials

Table 29 shows the minimum and average bond quality scores for the test samples manufactured during the LVL gluing trials in Section 4.2.3.1. The table indicates that for the southern blue gum LVL, using the parameters recommended by the adhesive manufacturer resulted in all samples failing the bond quality requirements for LVL structural products set in AS/NZS 4357.0 (2022) and AS/NZS 2098.2 (2012). Increasing the adhesive spread rate by 50% did not improve the bond quality. However, increasing the hot press pressure by 54% (i.e., to 2 MPa) resulted in all samples passing the bond quality requirements. This improvement is likely attributed to the high stiffness of the southern blue gum veneers and the presence of collapse during drying which required a higher pressure to provide sufficient contact between veneers during the hot press stage.

Regarding the limited number of hybrid test samples, all passed the bond quality requirements in AS/NZS 4357.0 (2022) when the parameters recommended by the manufacturer were followed.

The above results are further confirmed in Section 4.3.3.2.2 where the outcomes of the bond quality tests of the manufactured LVL panels are presented.

Table 29: Bond quality results of the LVL gluing trials.

Description	Test label	Test ID	Minimum bond quality score	Average bond quality score	Result
Southern blue gum LVL and parameters as recommended by manufacturer	C_G_L	1	0	2.0	Fail
		2	2	3.0	Fail
		3	0	4.0	Fail
	C_G_M	1	2	3.3	Fail
		2	2	3.3	Fail
		3	2	3.5	Fail
	C_G_H	1	2	2.8	Fail
		2	0	1.3	Fail
		3	1	1.8	Fail
Southern blue gum LVL and spread rate increased by 50%	SR_G_L	1	1	1.8	Fail
		2	1	1.8	Fail
		3	0	2.8	Fail
	SR_G_M	1	1	1.8	Fail
		2	1	2.8	Fail
		3	0	2.3	Fail
	SR_G_H	1	1	3.3	Fail
		2	3	4.8	Fail
		3	2	3.8	Fail
Southern blue gum LVL and hot press pressure increased by 54%	HP_G_L	1	2	5.3	Pass
		2	5	7.3	Pass
		3	4	6.3	Pass
	HP_G_M	1	5	6.5	Pass
		2	6	7.0	Pass
		3	5	6.8	Pass
	HP_G_H	1	5	5.3	Pass
		2	6	6.5	Pass
		3	6	7.5	Pass
Hybrid LVL and parameters as recommended by manufacturer	C_H_L	1	4	5.3	Pass
	C_H_M	1	7	8.3	Pass
	C_H_H	1	6	7.5	Pass

4.3.3.2 Mechanical properties and bond quality

4.3.3.2.1 Mechanical properties and comparison to commercial products

Table 30 and Table 31 present the average and characteristic mechanical properties, respectively, for the manufactured and tested LVL panels. The CoV of the 10 tests per mechanical property is also provided in brackets below the average value in Table 30. Note that the low characteristic value for flat shear of southern blue gum LVL21 is driven by the low shear strength encountered for one of the five panels.

This panel was manufactured in the first batch and the shear strength reflects the manufacturing obstacles encountered in the manufacturing of this batch, as explained in Section 4.2.3.2.2. Not considering this panel, the characteristic value would be of 4.1 MPa. The moisture content of the tested LVL samples was measured at 12.1% with a CoV of 9.7%.

Table 30: Average mechanical properties of the manufactured and tested LVL (CoV in % given in brackets).

LVL type	MOE (MPa)		Strength (MPa)				
	Edge bending	Flat bending	Edge bending	Flat bending	Com-pression	Edge shear	Flat shear
Southern blue gum LVL12	14,652 (5.1)	18,510 (5.4)	97.1 (5.7)	115.2 (5.1)	64.0 (4.6)	7.8 (5.7)	6.1 (15.9)
Southern blue gum LVL21	20,802 (6.1)	22,583 (8.8)	121.4 (8.0)	135.1 (9.3)	78.6 (6.7)	8.4 (8.1)	5.1 (24.9)
Hybrid LVL12	14,157 (3.1)	17,725 (5.7)	88.8 (8.1)	108.5 (9.8)	56.5 (5.4)	8.8 (8.6)	5.7 (16.0)
Hybrid LVL15	15,846 (6.9)	18,289 (16.8)	96.4 (9.4)	111.7 (14.6)	62.4 (6.7)	8.2 (10.0)	5.8 (14.5)
Hybrid LVL18	18,595 (5.4)	21,216 (15.4)	107.0 (11.5)	125.3 (12.5)	69.1 (3.7)	8.2 (10.8)	6.1 (12.9)

Table 31: Characteristic mechanical properties of the manufactured and tested LVL.

LVL type	MOE (MPa)		Strength (MPa)				
	Edge bending	Flat bending	Edge bending	Flat bending	Com-pression	Edge shear	Flat shear
Southern blue gum LVL12	14,485	18,289	86.3	103.5	57.5	6.9	4.1
Southern blue gum LVL21	20,520	22,143	102.7	111.4	68.6	7.1	2.5
Hybrid LVL12	14,000	17,503	74.2	86.6	50.3	7.3	3.9
Hybrid LVL15	15,602	17,605	79.0	80.5	54.0	6.6	4.2
Hybrid LVL18	18,372	20,489	84.0	96.7	62.2	6.5	4.6

Table 32 provides the reported characteristic values of commercial LVL products. For equivalent edge bending characteristic MOE, comparing Table 31 and Table 32 indicates that the manufactured and tested LVL typically have similar or higher characteristics strength values than the commercial LVL and F grade sawn timber. This provides evidence that the southern blue gum and radiata pine resources analysed as part of this project can result in LVL products which can directly compete with commercial products.

Table 32: Characteristic mechanical properties of selected commercial LVL and sawn timber F grades.

Product	MOE (MPa)		Strength (MPa)				
	Edge bending	Flat bending	Edge bending	Flat bending	Com-pression	Edge Shear(1)	Flat shear(1)
e-beam	13,200	--	50.0	--	47.0	5.0	--
e-beam+	14,000	--	62.0	--	47.0	5.3	--
HySPAN	13,200	--	50.0	42.0	42.0	4.6	3.5
hySPAN+	14,000	--	52.0	--	48.0	4.6	--
hyONE	16,000	--	65.0	52.0	48.0	4.6	3.2
LVL13	13,200	--	48.0	--	38.0	5.3	--
LVL-S	11,600	--	44.0	50.0	35.0	4.2	2.3
F27 (Sawn)	18,500	--	67.0	--	51.0	5.1	--
F34 (Sawn)	21,500	--	84.0	--	63.0	6.1	--

(1) Reported from beam shear tests

For comparison purposes, Figure 24 plots the static apparent bending MOE E_b (Eq. (3)) versus the MOE of the LVL panels calculated from the acoustic MOE of the individual veneers (as measured in Section 4.2.1.2.5). The figure shows that on average the acoustic MOE overestimated the apparent MOE by 9.3%. This value validates the 10% reduction factor between the acoustic MOE and static MOE used in the simulations presented in Section 4.2.2.

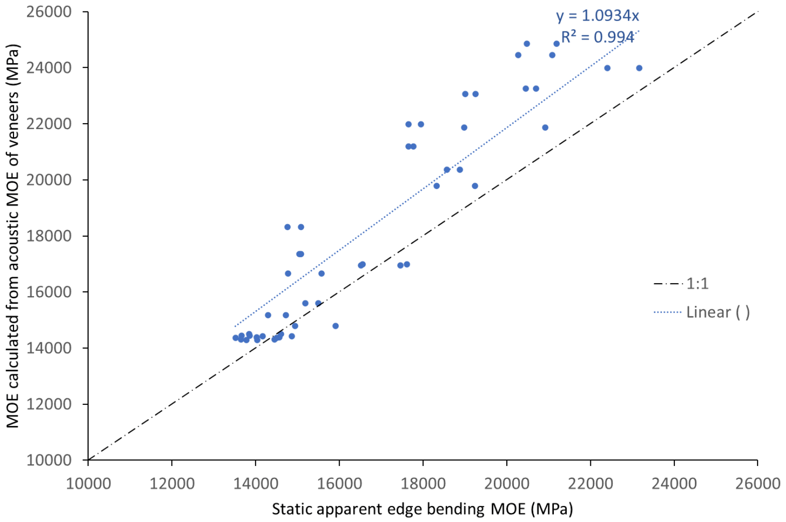


Figure 24: Relationship between static apparent edge bending MOE and MOE calculated from acoustic MOE of individual veneers.

4.3.3.2.2 Bond quality

Table 33 presents the results of the bond quality tests of the 9 LVL panels manufactured in the first batch and kept to assess the mechanical properties reported in the previous section. The manufacturing obstacles encountered in the manufacturing (Section 4.2.3.2.2) are reflected in the table with all hybrid LVL panels failing the bond quality requirements for Type A bond in AS/NZS 2098.2 (2012). However, most southern blue gum LVL21 samples passed the bond quality requirements.

Table 33: Bond quality results of the LVL panels manufactured in the first batch and kept to assess the mechanical properties.

LVL Type	Panel ID	Sample 1			Sample 2		
		Minimum bond quality score	Average bond quality score	Results	Minimum bond quality score	Average bond quality score	Results
Southern blue gum LVL21	1	4	5.4	Pass	4	5.7	Pass
	2	3	4.6	Pass	3	5.2	Pass
	3	4	5.2	Pass	4	5.8	Pass
	5	4	5.2	Pass	2	4.7	Fail
Hybrid LVL15	3	2	4.9	Fail	1	4.3	Fail
	4	1	4.1	Fail	1	4.6	Fail
Hybrid LVL18	2	1	4.0	Fail	1	3.6	Fail
	3	3	4.6	Fail	2	4.7	Fail
	5	1	2.7	Fail	1	4.4	Fail
	4	7	8.8	Pass	6	8.1	Pass

On the other hand, Table 34 presents the results of the bond quality tests for the panels manufactured in the second batch. All panels passed the bond quality requirements for Type A bond in AS/NZS 2098.2 (2012) outlining that LVL structural products can be manufactured out of the resources with phenol-formaldehyde type resin and the correct protocol followed.

Table 34: Bond quality results of the LVL panels manufactured in the second batch.

LVL Type	Panel ID	Minimum bond quality score	Average bond quality score	Results	Minimum bond quality score	Average bond quality score	Results
Southern blue gum LVL12	1	7	7.9	Pass	5	7.5	Pass
	2	7	8.8	Pass	6	8.0	Pass
	3	3	5.9	Pass	6	7.9	Pass
	4	5	8.4	Pass	5	8.3	Pass
	5	4	7.2	Pass	5	7.6	Pass
Southern blue gum LVL21	4	5	7.3	Pass	4	6.6	Pass
Hybrid LVL12	1	5	6.9	Pass	5	7.6	Pass
	2	5	7.6	Pass	6	7.6	Pass
	3	2	6.4	Pass	2	5.3	Pass
	4	6	7.5	Pass	5	6.8	Pass
	5	6	6.8	Pass	4	6.9	Pass
Hybrid LVL15	1	4	7.3	Pass	5	6.8	Pass
	2	3	6.1	Pass	3	6.6	Pass
	5	6	7.3	Pass	6	7.5	Pass
Hybrid LVL18	1	5	8.2	Pass	7	8.1	Pass

4.4 Concluding remarks

The section presented (1) the processing of the southern blue gum and radiata pine logs into veneers, (2) the characterisation of the veneers, (3) scenarios of potential LVL, with associated volumes, which can be manufactured from the studied resources, and (4) the test results of LVL manufactured from the peeled veneers. In total 339 billets were rotary peeled, resulting in 2,164 veneer sheets.

The key findings of the section can be summarised as follows:

- As expected from the literature review (Section 2), visual D-grade veneers dominated the feedstock, both for southern blue gum and radiata pine, limiting the manufacturing of appearance veneered-based products.
- On average 17% to 23% of the southern blue gum veneers failed to meet a visual grade and would have limited use in the manufacturing process. This percentage is higher for the radiata pine T1 feedstock, reaching 32%, but significantly lower and equal to 9.5% for radiata pine T2 veneers.
- No visual A-, B-, C-grades were recovered from the radiata pine logs and only very small quantities of these grades were recovered from the southern blue gum logs.
- The average MOE for the peeled veneers was equal to 15,690 MPa, 20,119 MPa, 8,131 MPa and 10,502 MPa for the 15-year-old southern blue gum, 19-year-old southern blue gum, T1 radiata pine and T2 radiata pine logs, respectively.
- At the same radial position in the trees, the 19-year-old southern blue gum logs provided veneers with a MOE about 26% higher on average than the 15-year-old southern blue

gum logs. For radiata pine, at the same radial position, the MOE for the T1 and T2 veneers are similar on average (less than 4% difference).

- The gross veneer recovery for the southern blue gum was about 50%. Regarding radiata pine, gross veneer recovery was 42% for the T1 logs, against 60% for the T2 logs. This difference was principally explained by the high percentage of visual F-grade veneers encountered for the T1 logs which impacts on the viability of the resource to be processed. The net veneer recovery ranged from 43 % to 46% for the southern blue gum veneers and from 37% (T1) to 53% (T2) for the radiata pine veneers. All above values are consistent with the literature.
- The southern blue gum resources offer enough high MOE veneers to mainly manufacture high performance LVL (LVL15 and above), with low volumes of commodity LVL12.
- The hybrid LVL is well suited to manufacture large volumes of the commodity LVL12, while still enabling lower volumes of high performance LVL (LVL15, LVL18 or LVL21) to be manufactured.
- Using a phenol-formaldehyde type resin, Type A bond were achieved (1) between southern blue gum veneers by increasing the hot press pressure to 2 MPa, and (2) between alternating southern blue gum and radiata pine veneers by following the adhesive manufacturer's recommendations.
- At similar characteristic MOE, the manufactured and tested LVL had similar or higher characteristic strength values than commercially available LVL, and F27 and F34 grades sawn timber.
- High stiffness (with a characteristic MOE greater than 20,000 MPa) and high strength (with a characteristic edge bending strength greater than 120 MPa) LVL were successfully manufactured.

5 Sawing: Log processing, sawn board properties, recoveries and associated GLT

5.1 Foreword

1/3 of the logs harvested in Section 3 were sawn in this section into boards. The boards were then used to manufacture and test southern blue gum and hybrid GLT. This section details and presents:

- The methodology followed to process the logs into sawn boards.
- The measurements taken on the billets and green boards.
- The measurements taken on the dried boards, including imperfections before and after planing, MOE and density distributions, mechanical properties, and distributions of characteristics relevant to GLT manufacturing.
- The board recovery rates calculated for different transformation processes.
- The numerical simulations performed to understand which GLT products, and in which proportion, could be manufactured from the southern blue gum and radiata pine resources.
- The gluing trials performed on boards and finger joints to understand how well the species can be glued in a GLT manufacturing context.
- The GLT types manufactured and tested in this section.
- The characteristic properties of the tested GLT and the corresponding GL grades in the AS 1720.1 (2010).

5.2 Methodology

5.2.1 Log processing and green sawn boards measurements

5.2.1.1 Log preparation and processing into sawn boards

For each southern blue gum site, logs numbered 21 to 30 and 51 to 60, and for each radiata pine site, logs numbered 21 to 30 were merchandised into two sawing billets as shown in Figure 25. Additional logs A and B harvested from Barker (see Section 3.2.1.1) were also merchandised into sawing billets. The logs were merchandised a maximum of 24 hours before sawing. The same numbering system as for the billets in Section 4.2.1.1 was followed, with each billet numbered as the site ID, followed by the tree ID and finally the billet ID.

25 mm thick disks were cut out of the logs on each end of the billets to perform the measurements outlined in Section 5.2.1.2.1. Disk numbering followed the billet numbering by adding “1”, “2” or “3” to the billet ID to distinguish between the three disks cut (Figure 25).

Billets with a SEDOB less than 150 mm or billets with excessive defects were not processed.

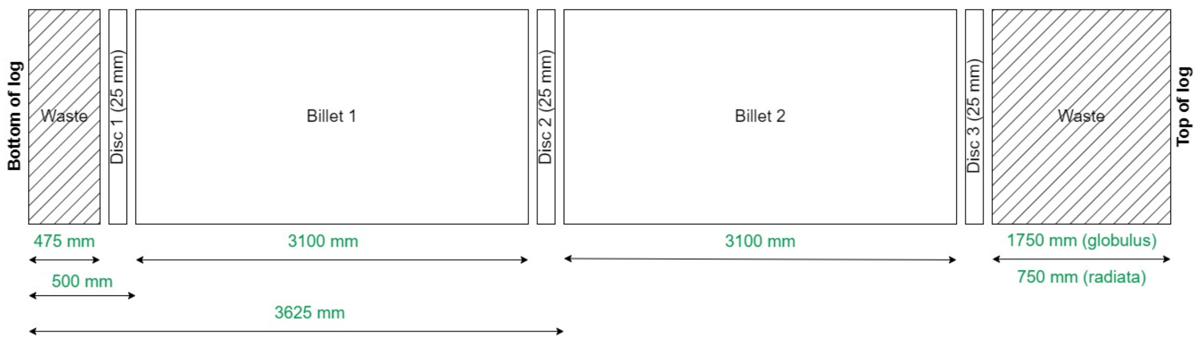


Figure 25: Log merchandising for sawing.

The billets were back sawn using a single Kara master circular saw system with a 6.25 mm kerf, shown in Figure 26, at the Salisbury Research Facility. The sawing patterns aimed at recovering dressed and dried boards of 86 mm × 19 mm, 68 mm × 19 mm and 42 mm × 19 mm. Note that the dressed thickness of 19 mm of the boards does not represent the 35 mm and 45 mm feedstock traditionally preferred in the manufacturing of softwood GLT. However, this thickness was chosen to limit the air-drying time of the southern blue gum boards and obtain boards for both testing and GLT manufacturing within the timeframe of the project.

Figure 26: Single circular saw system used to saw the billets.

Table 35 shows the green dimensions of the sawn boards for the two species considering (1) shrinkage coefficients from green to 12% moisture content of about 12-14% tangentially and 6-7% radially for southern blue gum (The wood database, 2024, WoodSolutions, 2023a), and 5% tangentially and 3% radially for radiata pine (WoodSolutions, 2023b) and (2) extra thickness and width of 6 mm and 10 mm, respectively, for dressing. The sawing patterns applied were based on the SEDOB of the logs and aimed at prioritising the 86 mm wide dressed boards. Examples of followed sawing patterns are presented in Figure 27.

Each board was numbered sequentially in the order it was sawn, by adding the board ID to the billet ID, for instance Board 45-23-2-7 is the seventh board cut from the second billet of tree number 23 harvested from Caves (southern blue gum).

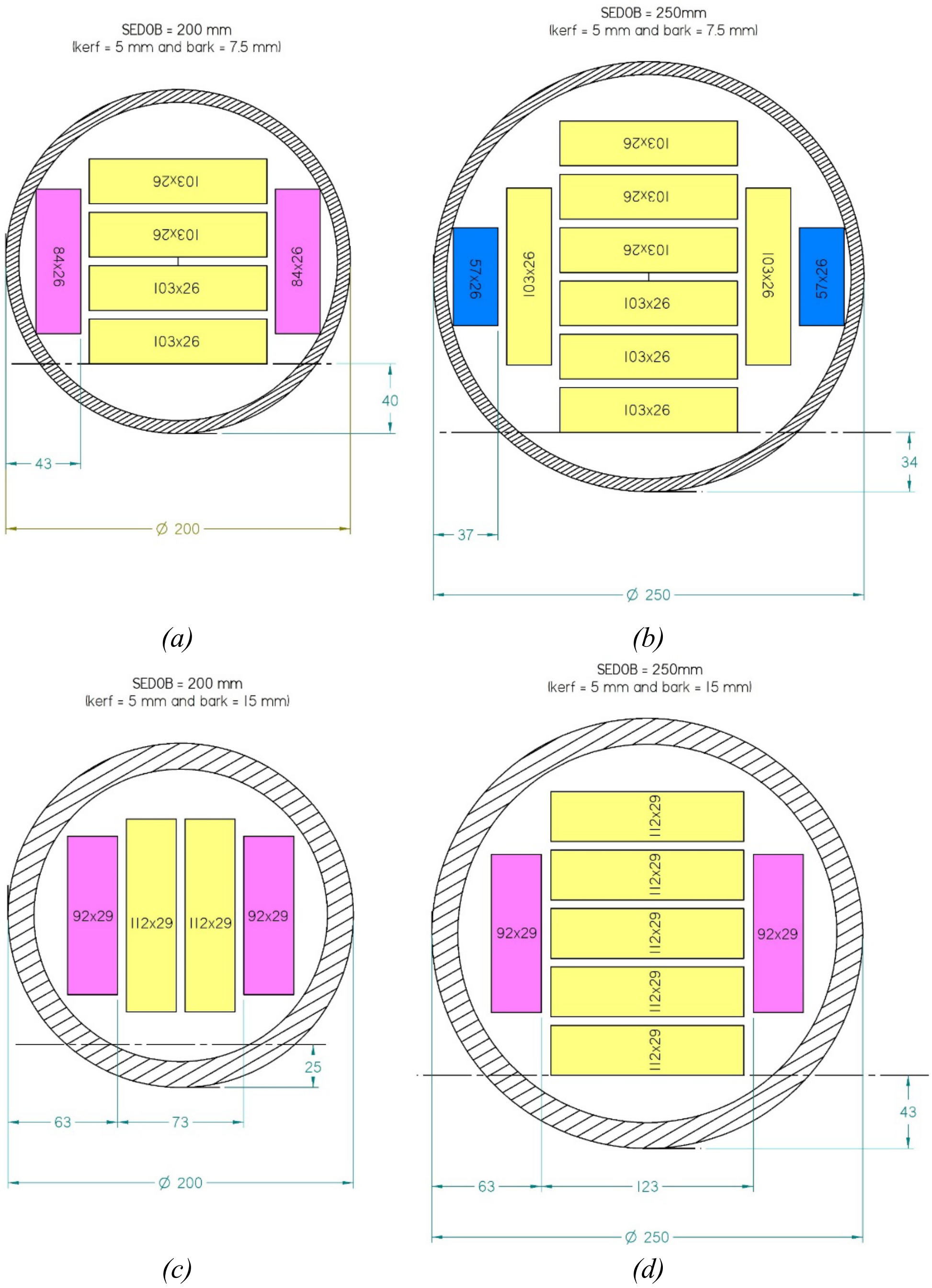


***Figure 27**: Examples of sawing patterns followed for (a) radiata pine billets of SEDOB between 200 mm and 225 mm, (b) radiata pine billets of SEDOB between 250 mm and 275 mm, (c) southern blue gum billets of SEDOB between 200 mm and 225 mm, (d) southern blue gum billets of SEDOB between 250 mm and 275 mm.*

After sawing, the boards were stripped and stacked as shown in Figure 28 (a). The radiata pine boards were then loaded with concrete blocks before being kiln dried over 13 h, following the schedule provided in Table 36, to a targeted moisture content of 12%. The southern blue gum boards were loaded with concrete blocks, wrapped under a hessian mesh, and stored undercover to air dry (Figure 28 (b)) until they reached a moisture content of about 18% to 20%, i.e., for a period of about 6 months. The boards were then transferred into a solar kiln for about one month, until they reached a moisture content of about 14%. Finally, the southern blue gum boards were kiln dried to a target moisture content of 12% with the schedule not recorded by mistake. No steam reconditioning was performed on the southern blue gum boards to tentatively recover collapse (Brennan, et al., 2004, Washusen, 2013).

Table 35: Dressed and green board dimensions.

Aimed dressed dimensions	Green dimensions - Radiata pine	Green dimensions - Southern blue gum
42 mm × 19 mm	57 mm × 26 mm	62 mm × 29 mm
68 mm × 19 mm	84 mm × 26 mm	92 mm × 29 mm
86 mm × 19 mm	103 mm × 26 mm	112 mm × 29 mm

Table 36: Schedule for kiln drying of radiata pine boards.

Air velocity (m/s)	Transition time (min)	Phase time (min)	Dry bulb temperature (°C)	Wet bulb temperature (°C)
3	10	50	60	60
3	10	50	80	80
3	10	50	95	90
7	30	300	120	90
3	10	50	95	95
3	10	50	70	70
3	10	50	50	50
3	10	10	30	25

(a) *(b)*

Figure 28: Southern blue gum boards (a) stripped and stacked after sawing, and (b) air drying.

5.2.1.2 Measurements

5.2.1.2.1 Billet measurements

The same measurements as for the peeled billets in Section 4.2.1.2.1 were taken for each sawn billet, consisting of *SEDOB*, *LEDOB*, *SEDUB*, *LEDUB*, *SSEDUB, LSEDUB*, L_B and S_B.

5.2.1.2.2 Green board measurements

The nominal green width (w_{bg}), thickness (t_{bg}) and length (L_{bg}) of each sawn board was recorded. If geometric characteristics, such as wane and taper, were present in a proportion that was deemed to prevent a board to be dressed to its intended dimensions, then the board would be expected to be cut to different lengths and/or rip to different widths to maximise the recovery during dressing. In such case, the expected nominal green dimensions ($w_{bg} \times t_{bg}$) of the different recovered lengths (L_{bg}) from the board were recorded, with boards less than 900 mm long considered as waste and not recovered.

5.2.2 Dried sawn boards imperfections, characteristics and mechanical properties

5.2.2.1 General

240 southern blue gum and 120 radiata pine dried boards of a nominal length of 3.1 m and aimed to be dressed to cross-sectional dimensions of 86 mm wide × 19 mm thick (Table 35) were randomly selected from the dried sawn boards. The boards were used in this section in the following sequence, aiming at providing information on the suitability of the boards for GLT manufacturing:

- The geometric imperfections (bow, spring, twist and cup), as well as the overall dimensions, of the rough sawn boards were first measured.
- The boards were dressed at TAFE, Acacia Ridge campus, Queensland, using a four-sider Wadkin planer (Figure 29) to a nominal cross-section of 86 mm × 19 mm. Boards before and after planing are showed in Figure 30.
- The geometric imperfections were remeasured to understand by how much these imperfections were reduced after planing. The density and acoustic MOE of the dressed boards were also measured.
- The presence and distribution of characteristics which impact the manufacturing of GLT were recorded for each board.
- Finally, for each species, the boards were divided into three stacks of equivalent MOE distributions for mechanical testing, with the first stack used for tension testing, the second for compression testing and the third for flat bending and shear testing.

(a) (b)

Figure 29: (a) Four-sider Wadkin planer at TAFE and (b) boards being planed.

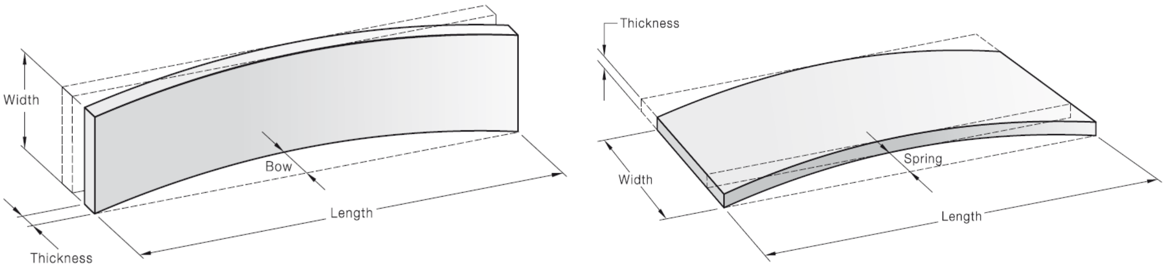
(a) (b)

Figure 30: Radiata pine boards (a) before and (b) after planing.

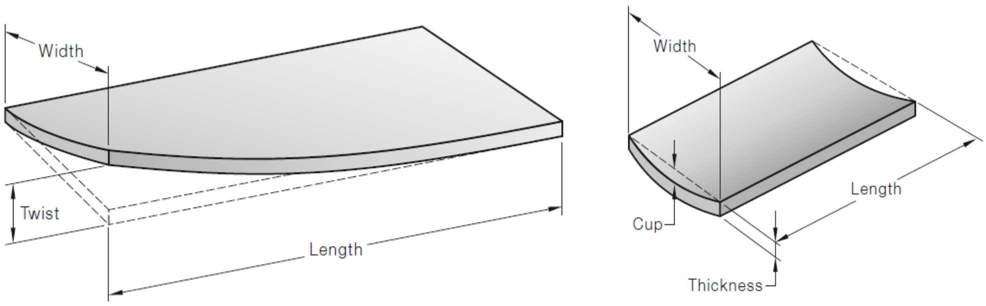
5.2.2.2 Imperfections, density, MOE and other characteristics

5.2.2.2.1 Imperfection measurements

The length, width and thickness of all 360 boards were measured along with the bow, spring, twist and cup (Figure 31) following the methodology in the AS 2082 (2007) before and after planing. The distributions of these imperfections before and after planing were calculated and compared in the report.



(a) Bow (b) Spring



(b) Twist (d) Cup

Figure 31: (a) Bow, (b) spring, (c) twist and (d) cup measurements in AS 2082 (2007).

5.2.2.2.2 Density and MOE

The density of the dressed boards was calculated from the measured dimensions and mass of the boards. The longitudinal acoustic MOE of all 360 dressed boards was measured similarly to the veneers in Section 4.2.1.2.5 by simply supporting the boards on rubber bands and impacting them in their longitudinal direction. The board natural frequency was recorded using a microphone and analysed using the software BING (Brancheriau, et al., 2002, CIRAD, 2012) to obtain the acoustic MOE.

For both species, the distributions of the acoustic MOE and density of the dressed boards are reported in the result section along with the relationship between the two measured properties. To compare how representative the randomly selected boards were from the overall population of sawn boards, the density of the remaining boards aimed to be dressed to 86 mm × 19 mm and 68 mm × 19 mm (Table 35) and used in Section 6 in the manufacture of the GLT beams was also measured. The density distributions of the dressed and all measured boards are also compared in the results section.

To simulate the mechanical properties of GLT beams made from the resources in Section 5.2.4, for each species, the density distribution of the boards was fitted with log-normal distributions. This distribution type was found to best match the data. The CDF *F(x)* of a random variable *x* in terms of the probability p of a log-normal distribution is given as,

$$F(x) = \Phi\left(\frac{\ln(x) - \mu}{\sigma}\right) \tag{6}$$

where Φ is the CDF of the standard normal distribution, σ is the mean and standard deviation of ln(x) and μ is the standard deviation of ln(x). The parameters σ and μ are provided in this report.

5.2.2.2.3 Other characteristics

As developed in the literature review (Section 2), visually grading boards for structural F-grade following AS 2082 (2007) is not appropriate for hardwood plantations as the standard would significantly underestimate the strength of the boards. Moreover, this grading system was developed for boards used for framing, not in the manufacturing of GLT for which strength reducing characteristics can be removed and short lengths of boards, free of such characteristics, finger jointed together to create long lamellas (see Section 6). Additionally, visual grading based on features and desired aesthetic appearance in AS 2796.1 (1999) is also not appropriate for GLT manufacturing, as GLT is a structural product for which appearance is not the primary concern.

Therefore, and as no standard exists to grade boards used in GLT manufacturing, board characteristics deemed to impact the strength, recovery and manufacturing process were quantified and reported in this document. These characteristics were defined from discussions with industry representatives, the utility requirements listed in AS/NZS 1748.1 (2011) and acceptable characteristics provided by Australian manufacturers, such as by ASH (2022b). These characteristics are presented in Table 37 and will help informing on the suitability of the resources for GLT manufacturing based on individual manufacturer's criteria. The requirements for each characteristic in Appendices A and B of AS/NZS 1748.1 (2011) are also listed in the table for information only.

Table 37: Characteristics measured on dressed boards.

Characteristic	Measured for: Southern blue gum	Measured for: Radiata	Value measured	Criteria in Appendices A and B of AS/NZS 1748.1 (2011)
Loose gum veins and ring shakes	✓		Width (mm)	No greater than 3 mm
			Length (mm)	No greater than 1/3 the length of the piece
			Extending from one surface to opposite surface (Y/N)	Not extending from one surface to the opposite surface
Gum pockets	✓		Length (mm)	No greater than the width of the piece
			Extending from one surface to opposite surface (Y/N)	Not extending from one surface to the opposite surface
Resin pockets		✓	Length (mm)	No greater than the width of the piece
			Extending from one surface to opposite surface (Y/N)	Not extending from one surface to the opposite surface
Splits	✓	✓	Length (mm)	Splits not permitted
End splits	✓	✓	Maximum individual length (mm)	no greater than ½ the width of the piece
			Aggregate length (mm)	No greater than the lesser of twice the width of the piece and 200 mm at each end
Pith	✓	✓	Presence of pith at ends of board (Y/N)	Not mentioned
			Presence of pith on faces of board (Y/N)	Not mentioned
			Accumulative length of pith on faces (mm)	Not mentioned
Knots	✓	✓	Maximum tkar for sound knots (on faces only)	Not mentioned
			Maximum tkar for loose/hole knots (on faces only)	Not mentioned
Cross-shakes	✓		Presence of cross-shakes (Y/N)	Cross-shakes not permitted
Wane/want	✓	✓	Maximum width on faces (mm)	No greater than ½ of the width of the face on which it occurs
			Maximum thickness on edges (mm)	No greater than 1/3 of the edge on which it occurs
Undressed parts	✓		Accumulative length of undressed parts on faces (mm)	Not mentioned
			Accumulative length of undressed part on edges (mm)	Not mentioned

Note regarding the following characteristics:

- *Knots*: the knot area ratio at a given location along the length of a board was calculated as the ratio of the sum of the projected area of all knots within a 150 mm long window to the total cross-sectional area of the board. The total knot area ratio (tkar) of the board was taken as the maximum of the knot area ratios along the entire length of the board (Isaksson, 1999). The total knot area ratio is often used as an indicator to characterise the influence of knots on the mechanical properties (Fink, et al., 2014).
- *Undressed parts*: due the level of imperfections encountered in the southern blue gum boards, especially cupping, as presented later in Section 5.3.2.1.1, some of the dressed boards presented areas of rough timber. As surface preparation affects gluing in GLT manufacturing (Leggate, et al., 2022), these areas will affect the bond quality between lamellas. Therefore, the accumulative length of undressed areas, both along the faces and edges, were recorded for the southern blue gum boards only because less distortion was encountered for the radiata pine.

Additional to the characteristics listed in Table 37, for each board, the length of segments with strength reducing characteristics (such as knots, gum veins and gum pockets) less than 10% of the cross-section were recorded. The distribution of these lengths will provide information to a manufacturer wishing to understand how many segments of timber would need to be finger jointed together to produce lamellas with little to no strength reducing characteristics, forming for instance the outer lamellas of GLT beams.

5.2.2.3 Mechanical properties

5.2.2.3.1 General

As mentioned in Section 5.2.2.1, the dressed boards were divided into three stacks of 80 and 40 southern blue gum and radiata pine boards, respectively. The measured acoustic MOE of the boards was used to divide the boards so that the three stacks of the same species had similar MOE distributions. The following was performed:

- The boards in the first stack were tested in tension parallel to grain (Section 5.2.2.3.2).
- The boards in the second stack were tested in compression parallel to grain (Section 5.2.2.3.3).
- The boards in the third stack were used for bending and shear testing. Especially, two 400 mm long flat bending samples (Section 5.2.2.3.4) and two either 200 mm (radiata pine) or 190 mm (southern blue gum) long shear samples (Section 5.2.2.3.5) were cut from each board. The 1.9 m long offcuts from this stack were set aside to manufacture finger joints as detailed in Section 5.2.5.2.

The boards were stored indoor at ambient temperature and relative humidity. Moisture content samples were cut from 19 different boards tested in tension (nine southern blue gum and 10 radiata pine) to estimate the moisture content of the boards at the time of testing following the oven the oven-dry methodology in the AS/NZS 1080.1 (2012).

5.2.2.3.2 Tension parallel to grain

The tension parallel to grain tests were performed in accordance with Clause 2.5 of AS/NZS 4063.1 (2010) but with a reduced span to fit the length of the boards. The ends of the boards were clamped between curved and knurled jaw grips in a custom-built 250 kN testing machine. The curved jaws aimed at minimising stress concentration at clamping and ensuring failure between jaws, not at the jaws. The testing span was 2,025 mm and was 663 mm shorter than the span recommended in AS/NZS 4063.1 (2010). The load P was applied at a constant load rate to reach failure between 2 min and 5 min (AS/NZS 4063.1, 2010). The test set-up is shown in Figure 32.

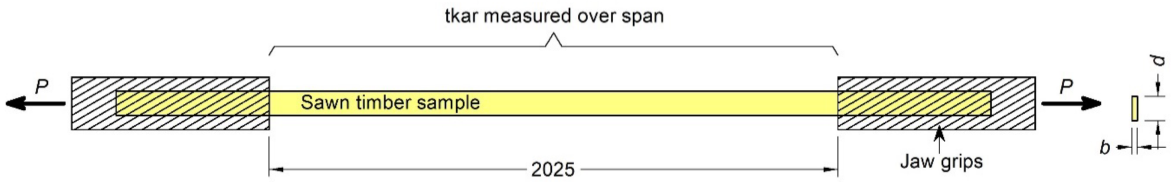
The tensile strength parallel to the grain $R_{t,0}$ was calculated from the maximum reached load P_{max} as:

$$R_{t,0} = \frac{P_{max}}{bd} \tag{7}$$

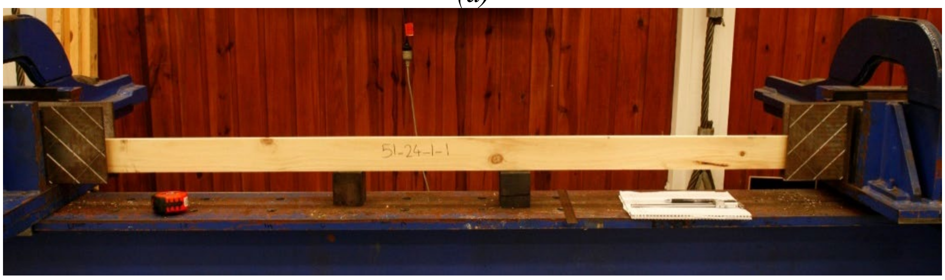
where b and d are the measured width and depth of the sample, respectively.

Note that the testing machine directly applied a load of 16 kN, (i.e., corresponding to a nominal stress of 9.8 MPa) before applying the load at a constant load rate. Some samples, 17 radiata pine and 2 southern blue gum boards, failed before reaching this load of 16 kN. These boards usually had a large cluster of knots, as shown in Figure 33. For these samples, the actual strength $R_{t,0}$ was therefore not accurately measured and was conservatively taken as 1 MPa.

To develop strength predicting equations (see Section 5.2.2.3.6), the tkar over the 2,025 mm span was measured for each sample. The tkar was calculated as explained in Section 5.2.2.2.3 as the maximum knot area ratio along the span of the sample.



(a)



(b)

Figure 32: Board tension parallel to grain test set-up, (a) schematic and (b) photo.

Figure 33: Example of a radiata pine board with a large cluster of knots failing before the minimum load of 16 kN was applied.

5.2.2.3.3 Compression parallel to grain

The compression parallel to grain tests were performed following the alternative method in Clause 2.6 of AS/NZS 4063.1 (2010). Each board was cut into two 1,344 mm long pieces, i.e., forming of total length equal to 2,000 mm + 8 × d as specified in AS/NZS 4063.1 (2010), where d = 86 mm is the nominal depth of the board. Each 1,344 mm long piece was then tested in compression between two fixed platens in a custom-built 250 kN testing machine. The pieces were restrained against lateral buckling with rollers, with the test set-up shown in Figure 34. The load P was applied at a constant load rate to reach failure between 2 min and 5 min (AS/NZS 4063.1, 2010).

The compressive strength parallel to the grain $R_{c,0}$ of each board was calculated as:

$$R_{t,0} = min\left(\frac{P_{max,1}}{b_1 d_1}, \frac{P_{max,2}}{b_2 d_2}\right) \quad (8)$$

where $P_{max,1}$ and $P_{max,2}$ are the maximum loads reached for the first and second 1,344 mm long pieces cut from the board, respectively. Similarly, b_1 and b_2 are the measured widths of the first and second pieces, respectively, and d_1 and d_2 are the measured depths of the first and second pieces, respectively. As for the tests presented in the previous section, the testing machine directly applied a load of 22 kN, (i.e., corresponding to a nominal stress of 13.5 MPa) before applying the load at a constant load rate. One southern blue gum sample failed before reaching this load of 22 kN.

For this sample, $R_{c,0}$ was conservatively taken as 1 MPa.

To develop strength predicting equations in Section 5.2.2.3.6, the tkar was measured over the entire length of each test piece. The tkar of the board was taken as the tkar of the test piece with the minimum strength, therefore corresponding to the piece governing the strength value in Eq. (8).

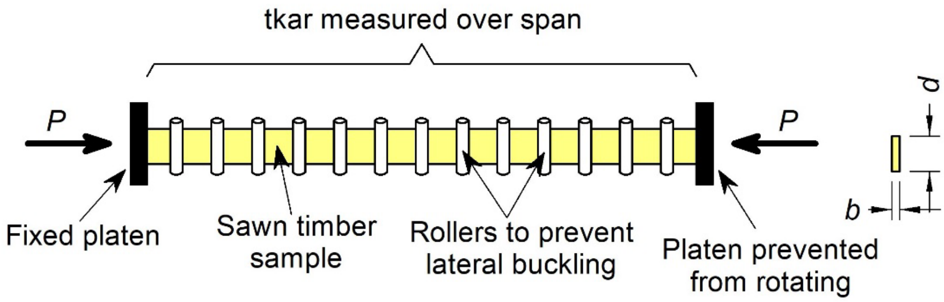


Figure 34: Board compression parallel to grain test set-up.

5.2.2.3.4 Flat bending

The two flat bending samples cut per board were tested in four-point bending according to Clause 2.4 of AS/NZS 4063.1 (2010). The span L was equal to 18 times the nominal thickness of the samples, resulting in $L = 342$ mm. Similar to Section 4.2.3.3.2, the distance between the supports and their nearest load application point, and between the load application points, equalled $L/3$. Steel plates were positioned at the load application points and supports to avoid local crushing of the timber. A DIC system was also used to measure the vertical displacement δ at mid-span and one side of the samples. The samples were tested in a 100 kN Shimadzu universal testing machine at a stroke rate to reach failure between 2 min and 5 min (AS/NZS 4063.1, 2010). The test set-up is similar to the one shown in Figure 14.

The bending MOR R_b and apparent bending MOE E_b were calculated following the procedure outlined in Section 4.2.3.3.2. The apparent static bending MOE E_b was also compared to the acoustic MOE of the boards. Note that due to a manipulation error, the apparent MOE was only recorded for half of the radiata pine bending samples.

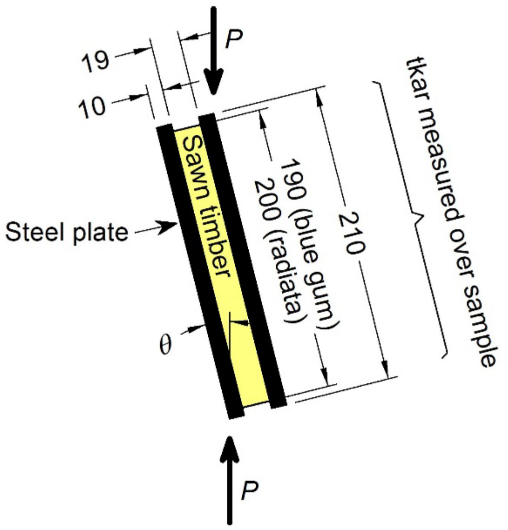
To develop strength predicting equations in Section 5.2.2.3.6, the tkar was measured over the constant bending moment region, i.e., between load application points.

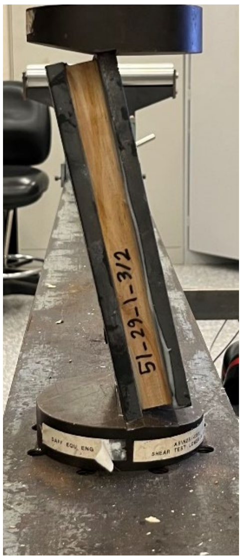
5.2.2.3.5 Shear

The beam shear test set-up in Clause 2.7 of AS/NZS 4063.1 (2010) is not appropriate to determine the flat shear strength of the boards (i.e., in the shear plane that would be loaded in a GLT beam) as the samples are too thin to properly execute this set-up. Therefore, an alternative test method was followed, mimicking the flat shear test set-up in Clause 16 of AS/NZS 4357.2 (2006).

The two samples per board were cut to 200 mm long × 40 mm wide for radiata pine and 190 mm long × 30 mm wide for southern blue gum. The samples were glued with 2-part epoxy to 210 mm long and 10 mm thick steel plates and tested in shear, as shown in Figure 35, in a 100 kN Shimadzu universal testing machine at a stroke rate to reach failure between 2 min and 5 min (AS/NZS 4357.2, 2006). The angle θ between the load direction and the longitudinal axis of the test samples was equal to 10.5°. The different dimensions between the radiata pine and southern blue gum samples were to adapt the sample size to the capacity of the testing machine.

The shear strength R_s was calculated as per Eq. (5).





(a) (b)

***Figure 35**: Board shear test set-up, (a) schematic and (b) photo.*

To develop strength predicting equations in Section 5.2.2.3.6, the tkar was measured over the entire sample length.

5.2.2.3.6 Prediction equations

To develop strength predicting equations to be used in the numerical model predicting the mechanical properties of GLT beams manufactured from the resources (Section 5.2.4), four different equations were fitted to the experimental results in Sections 5.2.2.3.2 to 5.2.2.3.5. The equations were extracted from Gilbert, et al. (2017a) and are using either the acoustic MOE or the density of the boards, with or without the tkar, to predict the strength. The equations are provided hereafter, noting that the first term in all equations (power relationship) represents the strength of the wood itself and the second term in Eqs. (10) and (12) represents a reduction in cross-sectional area due to the presence of the knots. The coefficient γ in Eqs. (10) and (12) denotes the influence of the knots in reducing the strength, and is typically higher in tension than in compression as knots influence the compressive strength more than the tensile strength (Kollmann, 1968).

$$Strength = \alpha \times MOE^{\beta}(1 - \gamma \times tkar) \quad (9)$$

$$Strength = \alpha \times MOE^{\beta} \quad (10)$$

$$Strength = \alpha \times density^{\beta}(1 - \gamma \times tkar) \quad (11)$$

$$Strength = \alpha \times density^{\beta} \quad (12)$$

The coefficients α, β and γ were found by performing a non-linear regression on the test results. The coefficient of determination R^2 of the predictions was also calculated and reported in the result section. Comparing the coefficient of determination between Eqs. (9) and (10), and between Eqs. (11) and (12), allows to quantify by how much considering the knots improves the predictions.

5.2.3 Sawn board recoveries

Two different types of sawn board recoveries were calculated in this report:

- The green sawn board recovery (*GBR*) was calculated as the percentage of log volume converted into usable green boards during the sawing process. *GBR* is given as:

  $$GBR = \left(\frac{\sum_{boards}(t_{bg}w_{bg}L_{bg})}{\sum_{billets}(V_B)}\right) \times 100 \quad (7)$$

  where V_B is the volume of a billet as defined in Eq. (4).

  Note that sawn recoveries are influenced by log geometry, but also processing equipment (McGavin, et al., 2021). Due to non-automated sawing process in the study, the calculated green recoveries would be conservative when compared to computerised mills where logs are scanned and the sawing pattern optimised to individual logs.

- The Net board recovery (NBR) was estimated in the report for the manufactured GLT beams in Section 6. It measures the process efficiency by identifying the saleable GLT products. This includes all losses from the green logs to finish products. It is calculated as,

  $$NBR = GBR \times R_{green\_dry} \times R_{manufacturing} \quad (13)$$

  where *GBR* is the green sawn recovery above, R_{green_dry} reflects the volume lost during the drying process and $R_{manufacturing}$ reflects the volume of material lost during the GLT manufacturing process, including losses due to removing strength reducing characteristics, finger jointing lamellas, dressing the lamellas before gluing and dressing the GLT to final dimensions after gluing.

  R_{green_dry} was estimated for the back sawn boards using (1) shrinkage coefficients from green to 12% moisture content of 14% tangentially and 7% radially for southern blue gum (The wood database, 2024, WoodSolutions, 2023a), and 5% tangentially and 3% radially for radiata pine (WoodSolutions, 2023b), and (2) assuming that 75 mm wide and 25 mm thick dry rough sawn boards would be delivered by the mill to manufacture the 65 mm wide GLT with 19 mm thick lamellas in Section 6, i.e., considering extra thickness and width of 6 mm and 10 mm, respectively, for dressing, as in Section 5.2.1.1.

  Ignoring shrinkage in the longitudinal direction, R_{green_dry} is equal to the ratio of the dry boards cross-sectional area to the green boards cross-sectional area as:

  $$R_{green\_dry} = \frac{w_{bd} \times t_{bd}}{w_{bd} \times (1 - \alpha_T)^{-1} \times t_{bd} \times (1 - \alpha_R)^{-1}} \times 100 \quad (14)$$

where w_{bd} = 75 mm and t_{bd} = 25 mm are the target width and thickness of the dry rough sawn boards, respectively, and α_T and α_R are the tangential and radial shrinkage coefficients from green to 12% moisture content, respectively.

Using the values given above R_{green_dry} = 80% for southern blue gum and 92.2% for radiata pine.

On the other hand, $R_{manufacturing}$ was calculated by still assuming that 75 mm wide and 25 mm thick dry rough sawn boards would be delivered by the mill to manufacture the 65 mm wide GLT with 19 mm thick lamellas in Section 6, as:

$$R_{manufacturing} = \frac{n_{GLT} \times L_{GLT} \times w_{GLT} \times t_{lamellas} \times n_{lamella}}{L_{board} \times 75 \times 25} \times 100 \quad (15)$$

where n_{GLT} is the number of GLT beams manufactured, L_{GLT} = 6.3 m and w_{GLT} = 65 mm are the finish length and width of the manufactured GLT in Section 6, respectively, $t_{lamella}$ = 19 mm is the lamella thickness, $n_{lamella}$ is the number of lamellas per GLT, and L_{board} is the total length of rough sawn boards used in the manufacture of the GLT in Section 6.

Note that, as discussed in Section 6, the grading process used in the manufacture of the GLT beams generated higher wastage values than typically encountered in the day-to-day operation of Warrnambool Timber Industry, especially for the southern blue gum boards. Additionally, the recovery rates for 35 mm and 45 mm thick boards (as traditionally used in commercial GLT) would be lower than the ones reported herein. Therefore, the Net board recovery calculated in this report is indicative.

5.2.4 Potential GLT products out of the resources (numerical simulations)

5.2.4.1 General

The preliminary market analysis (IndustryEdge, 2023) indicated that GL18 and GL13 GLT beams (AS 1720.1, 2010) are the main GLT products to be targeted out of the resources. GL13 represents a commodity product, while GL18 would have applications where high performing products are required, such as above garages (long spans).

Numerical simulations with different manufacturing scenarios are performed in this report to understand the GLT grades, with associated volumes, that could be manufactured from the southern blue gum and radiata pine boards recovered as part of this project. The simulations are explained hereafter and utilise the density distributions of the two resources as the input parameter (Eq. (12)), as the density can be more readily measured by a manufacturer than the acoustic MOE.

The model used to run the simulations applies the principles described for sawn timber and GLT beams in Buchanan (1990) and Foschi, et al. (1980), respectively. These principles were also successfully adapted to LVL beams in Gilbert, et al. (2017b). The model does not require the use of complex finite element analyses (FEA), has rational failure criteria and reflects the actual behaviour of timber structural members for which the bending MOR is higher than the tensile strength (Thelandersson, 2003).

The model estimates the characteristic bending MOE, characteristic bending strength and characteristic shear strength of a GLT beam manufactured from the different manufacturing scenarios explained later in the section. As the density and MOE of the boards were directly measured, and due to the first-principle mechanical model used in calculating the MOE, the confidence of the simulations accurately predicting the characteristic MOE of the GLT beams is high. However, due to uncertainty in the size effect of the resources and the more complex model used for predicting the strength, the confidence of the simulations accurately predicting the characteristic strengths is less. Therefore, the characteristic strength values reported herein must only be seen as indicative of the expected values.

5.2.4.2 Assumptions of the numerical model

The following assumptions were made in the numerical simulations.

- In bending, the Euler-Bernoulli beam theory is used, with plane sections remaining plane.
- In shear, the elastic properties of the lamellas are considered uniform, and the shear stress distribution is assumed to be the one calculated for a rectangular cross-section.
- The influence of the finger joints is ignored and the strength and stiffness of the GLT beams are calculated as if the beams were manufactured from continuous lamellas (i.e., without finger joints).
- The GLT beams are manufactured from standard 35 mm thick lamellas (dressed to 33.3 mm) and have a 300 mm deep × 65 mm wide cross-section, i.e., representative of the reference depth in AS/NZS 1328.1 (1998). The GLT are therefore made up of 9 lamellas.
- The GLT are manufactured from different feedstocks for the inner and outer lamellas, as practiced in industry. In the simulations, it is assumed that the two outer lamellas are from one feedstock and the seven inner lamellas from another one.
- The timber is assumed to have an elastic-perfectly plastic behaviour in compression and be brittle in tension.

5.2.4.3 Numerical model

The numerical model follows the steps below to estimate the characteristic bending MOE, characteristic bending strength and characteristic shear strength of a GLT beam of a specific construction strategy, with the analysed construction strategies provided in Section 5.2.4.4. Only the general procedure is described in this report and more details on the model can be found in Buchanan (1990), Foschi, et al. (1980) and Gilbert, et al. (2017b).

- *Step 1*: Simulate a GLT beam by allocating density and MOE values to each lamella:
    - Randomly allocate a density *d* to each inner and outer lamella from the density fitted distributions provided in Section 5.3.2.1.2 in accordance with the construction strategy (Section 5.2.4.4).
    - Allocate the static MOE to each lamella from (1) the previous density *d*, (2) the predicting equations in Section 5.3.2.1.2 providing the relationship between density and acoustic MOE, (3) the uncertainty in the equations to predict the MOE from the density, and (4) the difference between the static and acoustic MOE, as:

    $$Lamella\ static\ MOE = 0.83 \times a_b \times 1.48 \times 10^{-4} d^{2.11} \quad \text{for southern blue gum boards} \quad (16)$$

    $$Lamella\ static\ MOE = 0.96 \times a_r \times 6.31 \times 10^{-4} d^{2.68} \quad \text{for radiata pine boards} \quad (17)$$

    where the first term in both Eqs. (16) and (17) represents the average measured difference between the static and acoustic MOE (obtained from the bending tests, see Section 5.3.2.2.3), a_b and a_r are random numbers generated from normal distributions (mean = 1.01 and standard deviation = 0.149 for southern blue gum (a_b) and mean = 1.01 and standard deviation = 0.239 for radiata pine (a_r)) reflecting the uncertainty in the predicting equations and the last term represents the predicting equations provided in Section 5.3.2.1.2.

- *Step 2*: Allocate tensile and compressive strength values to each lamella from the test results in Section 5.3.2.2:
  - For each lamella allocate a tensile and compressive strength value from the density value, Eq. (12) and the coefficients provided in Section 5.3.2.2. In Eq. (12), the tkar is arbitrary taken as 10% for all lamellas, mimicking a manufacturer removing the main strength reducing characteristics and finger-jointing the cut boards together (see Section 6). The tkar value can be adjusted for both inner and outer lamellas based on a manufacturer best practice.
  - Multiply each strength value by a random number generated from a normal distribution which reflects the uncertainty in Eq. (12) in predicting the actual strength. The mean and standard deviation of the normal distributions used and calculated from the test data are provided in Table 38.

***Table 38**: Mean and standard deviation of the normal distributions used to reflect the uncertainty in Eq. (12).*

Failure mode	**Southern blue gum**		**Radiata pine**	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**
Tension	1.00	0.383	1.00	0.355
Compression	1.00	0.199	1.00	0.148

- *Step 3*: Allocate a shear strength value to each lamella from the test results in Section 5.3.2.2:
  - As the shear strength was found in Section 5.3.2.2.4 to have little to no correlation with the board density and tkar, for each lamella, the shear strength was randomly generated from a normal distribution with a mean of 12.4 MPa and a standard deviation of 2.27 MPa for the southern blue gum lamellas and a mean of 8.8 MPa and a standard deviation of 1.81 MPa for the radiata pine lamellas (see Section 5.2.2.3.5), i.e., reflecting the test data.
- *Step 4*: Modify the tensile and compressive strength values to consider the size effect and the loading type:
  - The tensile and compressive strength values of each lamella determined in Step 2 were modified to consider the difference in dimensions and loading type between the tested samples in Section 5.2.2.3 and the lamellas used in a GLT beam tested in four-point bending, as prescribed in AS/NZS 4063.1 (2010). This phenomenon is referred to as "size effect". The methodology and modification equations described in Gilbert, et al. (2017b) were used. The size effect factor k_t of 10.0 for glulam in bending and recommended in Lam (2011) was used herein for tension, both parallel and perpendicular to grain, due to bending and tension both being brittle failure modes. As the size effect is more pronounced in tension than compression, the size effect factor in compression was taken as $2 \times k_t$ (see discussion in Gilbert, et al. (2017b) for more details). Therefore, a size effect factor k_c of 20.0 was assumed herein for compression, both parallel and perpendicular to grain.
- *Step 5*: Modify the shear strength values to consider the size effect and the loading type:
  - The size effect in shear is less understood and researched than for tension and compression (De Santis, et al., 2023). A size effect was still assumed to exist herein in shear with the size effect factor taken equal to the one used in tension, as both shear and tension experience brittle failure modes. The shear strength of each

lamella determined in Step 3 was then modified by multiplying it by the following factor b_s:

$$b_s = \left(\frac{L_{sample}}{L_{lamella}}\frac{W_{sample}}{W_{lamella}}\frac{t_{sample}}{t_{lamella}}\right)^{1/k_t} \quad (18)$$

where L_{sample}, W_{sample} and t_{sample} are the length, width and thickness, respectively, of the shear samples tested in Section 5.2.2.3.5. $L_{lamella}$, $W_{lamella}$ and $t_{lamella}$ are the length, width and thickness, respectively, of the lamellas uniformly loaded in shear in a GLT beam tested in shear in accordance to AS/NZS 4063.1 (2010), i.e., over a span of six times the depth.

- *Step 6*: Run the model in bending assuming the GLT beam is tested according to AS/NZS 4063.1 (2010):
  - The bending MOE of the GLT beam was calculated from the static MOE of each lamella using the transformed section method (Jayne, et al., 1982).
  - The bending strength of the GLT beam was calculated by increasing the bending strain and calculating the associated stress distribution following the procedure in Gilbert, et al. (2017b). Failure was assumed when the tensile stress at the bottom lamellas reached the failure criteria defined in Gilbert, et al. (2017b). The failure criteria considers both the strength of the lamellas and the non-unform stress distribution in the lamellas.
- *Step 7*: Run the model in shear assuming the GLT beam is tested according to AS/NZS 4063.1 (2010):
  - The shear strength of the GLT beam was obtained by increasing the shear strain and calculating the shear stress in each lamella from the parabolic shear distribution of a rectangular cross-section (Wilkinson, 2007). Failure developed when the shear stress in one lamella exceeded its shear strength (calculated from Step 5).
- *Step 8*: Repeat Steps 1 to 7 for each construction strategy to obtain the characteristic values.
  - For each construction strategy in Section 5.2.4.4, Steps 1 to 7 were repeated 30 times to obtain the mechanical properties of 30 different randomly generated GLT beams. 30 tests correspond to the minimum number of tests needed in AS/NZS 4063.2 (2010) to calculate the characteristic properties of the product.
  - The characteristic bending MOE, characteristic bending strength and characteristic shear strength of the GLT beams were finally calculated from the 30 simulations following the methodology in AS/NZS 4063.2 (2010).

Steps 1 to 8 are repeated 100 times to understand the variation in characteristic properties between different batches of 30 GLT beams. The average characteristic properties out of these 100 simulations are reported in the results section.

5.2.4.4 Investigated construction strategies

The following construction strategies (or scenarios) were run. Scenarios 1 and 2 were run with GLT manufactured only from southern blue gum boards, while Scenarios 3 and 4 simulate strategies where both southern blue gum and hybrid GLT are manufactured.

- *Scenario 1*: Only one southern blue gum GLT product is manufactured using all available southern blue gum boards:

- The denser boards (22% of the total volume) are used for the outer lamellas, and the remaining boards (78% of the total volume) are used for the inner lamellas.

- *Scenario 2*: Manufacturing two southern blue gum GLT products using all the available southern blue gum boards:
  - The first product is manufactured using the denser boards (40% of total volume), with the denser 22% of these boards used for outer lamellas and the remaining 78% used for inner lamellas.
  - The second product is manufactured using the boards not used in the manufacture of the first product (60% of total volume), with the denser 22% of these boards used for outer lamellas and the remaining 78% used for inner lamellas.
  - In this scenario, for every GLT beam of the first product manufactured, 1.5 GLT beam of the second product would be manufactured.

- *Scenario 3*: Manufacturing one southern blue gum and one hybrid GLT, the two products using all available southern blue gum and radiata pine boards:
  - The first product (southern blue gum only) is manufactured using the denser southern blue gum boards (40% of total volume of the southern blue gum boards), with the denser 22% of these boards used for outer lamellas and the remaining 78% used for inner lamellas. This is the same product as the first product in the previous scenario.
  - The second product (hybrid) is manufactured using the remaining southern blue gum boards (60% of total volume of the southern blue gum boards) as the outer lamellas, and using all radiata pine boards as the inner lamellas.
  - For every 1 m^3 of timber, this scenario will use 0.32 m^3 of southern blue gum and 0.68 m^3 of radiata pine. For every GLT beam of the first product manufactured, 6.75 GLT of the second product would be manufactured.

- *Scenario 4*: Manufacturing one southern blue gum and one hybrid GLT, the two products using all available southern blue gum and radiata pine boards:
  - The first product (southern blue gum only) is manufactured using half of the 36% denser southern blue gum boards as outer lamellas and the remaining 64% less denser boards used for inner lamellas.
  - The second product (hybrid) is manufactured using the other half of the 36% denser southern blue gum boards as outer lamellas, and using all radiata pine boards as the inner lamellas.
  - For every 1 m^3 of timber, this scenario will use 0.61 m^3 of southern blue gum and 0.39 m^3 of radiata pine. For every GLT beam of the first product manufactured, one GLT of the second product would be manufactured.

All scenarios were run with the density distributions obtained from all measured boards and from Caves and Barker combined for southern blue gum, and from Snowgums (T1) and Kilsbys (T2) combined for radiata.

5.2.5 GLT manufacturing and testing

5.2.5.1 Gluing trials

AS/NZS 1328.1 (1998) requires that the glueline integrity for GLT products be made in conformity with method A of Appendix C for qualification tests of new products, for Service Classes 1 through 3 when using a Type 1 adhesive.

Gluing trials were performed in this section to investigate how various parameters influence the glueline integrity of GLT, therefore ultimately providing information on the gluability of the resources for GLT applications. The influence of the following parameters was investigated on samples manufactured from boards of different density ranges, with the density ranges given in the results section (Section 5.3.5.1):

- Adhesive type.
- Gluing pressure.
- Board orientation.
- Surface preparation.

Similarly to the LVL gluing trials, as southern blue gum was deemed to represent the more challenging species to glue (see Section 2), the bonding trials principally focussed on southern blue gum GLT, with a lower number of manufactured and tested hybrid GLT. Also, as the adhesive spread rate was found not to influence the bond quality of the LVL products in Section 4.3.3.2.2, this parameter was not investigated for the GLT bonding trials, and the recommendations either provided by the manufacturer or literature followed.

5.2.5.1.1 Adhesive used

Two different types of adhesives, commonly used in the manufacture of GLT, were trialled. They consisted of a single-component PUR (681.60 manufactured by Jowat adhesives (2019)) as suggested by the literature review and a two-component RF (4:1 ratio of resin (950.82) to hardener (950.85), also manufactured by Jowat adhesives). Adhesives were applied and mixed (when appropriate) as recommended by the manufacturer unless mentioned otherwise.

5.2.5.1.2 Test samples and trials

Four different gluing trials were performed sequentially with the results of the preceding trial used to select the parameters of the next trial.

For each trial, boards were first ripped to a width of 75 mm and crosscut to lengths of 200 mm. The GLT samples were then assembled from five 200 mm lengths, cut from five different boards and dressed to a thickness of 19 mm, forming 5-lamella GLT.

Per trial, the influence of each parameter was investigated on nominally identical samples which were manufactured from lamellas crosscut from the same overall boards, as illustrated in Figure 36.

For the hybrid samples, the three inner lamellas were radiata pine and the outer lamellas were southern blue gum. The boards were conditioned at ambient temperature and humidity before manufacturing and all samples were left in the press for 24 h. In total, 66 GLT samples were manufactured. Figure 37 shows samples out of the press.

The trials are detailed hereafter and summarised in Table 39:

- *Trial 1*: Influence of the gluing pressure and adhesive type.
  - ➢ Four parameters were investigated in the first trial and consisted of adhesive type and gluing pressure: (1) PUR with the manufacturer recommended pressure of 1 MPa, (2) PUR with an increased pressure of 1.6 MPa, (3) RF with the manufacturer recommended pressure of 1.2 MPa and (4) RF with an increased pressure of 2 MPa.
  - ➢ For each of the parameters above, six different samples were manufactured, consisting of six southern blue gum samples of increasing density. The average density of the boards constituting each sample is provided in the results section.

- The boards were planed to a thickness of 19 mm in a thicknesser (Formula SP1 Mini Max) with straight knives a few hours, typically less than 3 h, before gluing.
- The spread rates were as per recommended by the manufacturer: (1) targeted 180 gsm per glueline for PUR and applied on one surface and (2) targeted 360 gsm per glueline for RF and applied on both surfaces.
- The orientation of the boards was random.

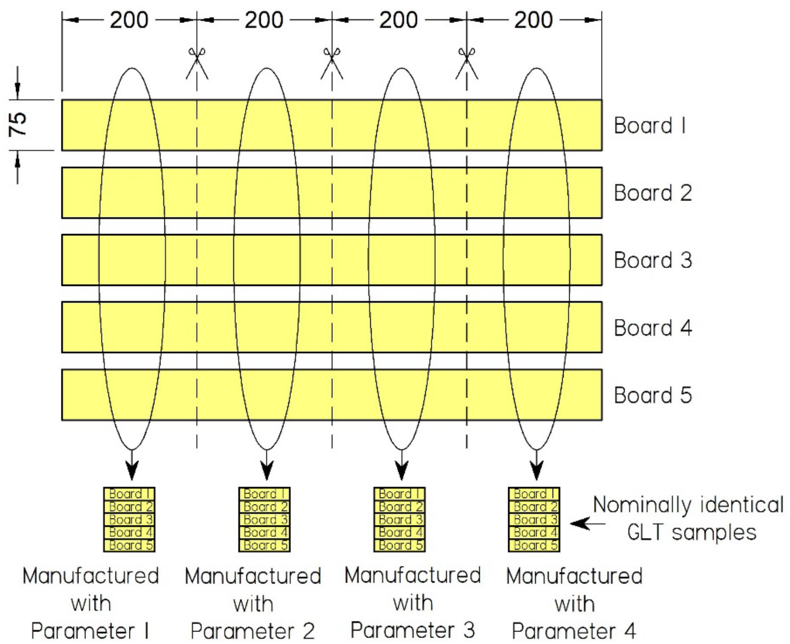


Figure 36: Manufacturing principles to obtain nominally identical GLT samples.

Figure 37: Examples of GLT samples out of the press.

- *Trial 2*: Influence of the lamella orientation and adhesive type.
  - Two parameters were investigated in the second trial consisting of orientating the boards as per Figure 38 and using both PUR and RF. Note that the outer lamellas were orientated opposite to the recommendation in the EN 14080 (2013). Comparing the results between the first and second trials provides an indication if the board orientation influences the glueline integrity.

- For each of the parameters above, 12 different samples were manufactured, consisting of (1) six southern blue gum samples of increasing density and (2) six hybrid samples, also of increasing density for the southern blue gum lamellas. The average density of the boards constituting each sample is provided in the results section.
- The manufacturer recommended spread rate and pressure were used for the two adhesives.
- The boards were planed to a thickness of 19 mm in a thicknesser (Formula SP1 Mini Max) with straight knives a few hours, typically less than 3 h, before gluing.

- *Trial 3*: Influence of the surface preparation (face milling) and adhesive type.
  - Two parameters were investigated in the third trial consisting of face milling the board in a Rotoles (400 D-S, Ledinek Germany), at a cutter speed of 21,000 rpm and a feed speed of 45 m/min, and using both PUR and RF. When compared to planed boards, this surface preparation method was found to improve bonding in Leggate, et al. (2021a). The time between face milling and glue application was less than 5 min.
  - As the first two trials showed that bonding was principally challenging for samples of high density (> 800-850 kg/m^3), six different samples were manufactured for each parameter, consisting of (1) three southern blue gum samples manufactured from random lamellas of density greater than 850 kg/m^3 and (2) three hybrid samples, also with random southern blue gum lamellas of density greater than 850 kg/m^3. The radiata pine lamellas were randomly selected and their density were not measured.
  - The manufacturer recommended pressure was used for the two adhesives and the spread rates were increased as per Table 39 to be consistent with the work in Leggate, et al. (2021a) and Faircloth, et al. (2024) on face milling.
  - The boards were orientated as per Figure 38.

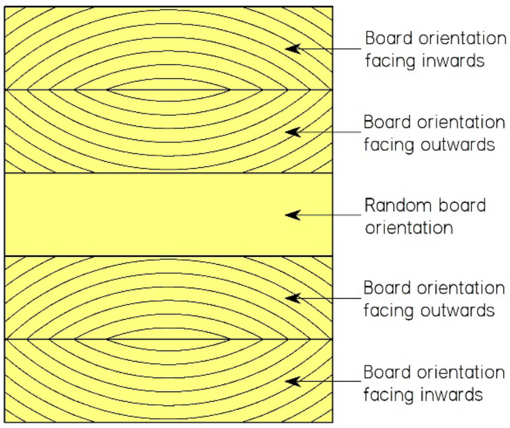


Figure 38: Board orientation for Trials #2 to #4.

- *Trial 4*: Influence of the surface preparation (planing and sanding) and adhesive type.
  - Similar to the third trial, two parameters were investigated in the fourth trial. These parameters consisted of planing to a thickness of 20 mm the boards first in a thicknesser (Formula SP1 Mini Max) followed by sanding (in a SANDYA 16 S) with 40 grit sandpaper (removing 0.5 mm on each side to a final thickness of 19 mm), and using both PUR and RF. In some instances (Leggate, et al., 2021b),

planing followed by sanding has been found to yield comparable if not greater performance than face milling. The time between surface preparation and glue application was less than 5 minutes.

- The trial focused on the challenging density range of > 800-850 kg/m^3. Three southern blue gum samples were manufactured for each adhesive from random lamellas of density greater than 850 kg/m^3.
- The press pressure and glue spread rate were increased as per Table 39 to be consistent with Trial #3 and the literature.
- The boards were orientated as per Figure 38.

5.2.5.1.3 Glueline integrity test method and assessment

After gluing, 5 mm was removed on each side of the manufactured GLT to reduce the width to 65 mm. A 75 mm long test sample, as prescribed in AS/NZS 1328.1 (1998), was then cut from each GLT. The test samples were assessed for glueline integrity according to Method A in Appendix C of AS/NZS 1328.1 (1998). The following procedure and measurements were performed:

- The length of each glueline on the end-grain faces was measured.
- The test samples were immersed in water in a vacuum/pressure cylinder and a 5 min vacuum (at 75 kPa) followed by a 1 h pressure treatment (at 550 kPa) cycle was performed twice.
- Samples were then dried in a kiln at 65ºC and at a relative humidity of 15% with an air velocity of 2.5 m/s for 21.5 h.
- The water immersion and drying processes in the last two dot points were repeated to perform two full treatment cycles.
- The length of open gluelines on the end-grain faces was measured at the end of the two treatment cycles as per AS/NZS 1328.1 (1998). The total and maximum delamination percentages as detailed in Eqs. (19) and (20), respectively, were calculated (AS/NZS 1328.1, 1998):

$$Total\ delamination = 100 \times \frac{l_{tot\_delam}}{l_{tot\_glueline}} \quad (19)$$

and

$$Maximum\ delamination = 100 \times \frac{l_{max\_delam}}{2l_{glueline}} \quad (20)$$

where $l_{total,delam}$ is the length of the total open gluelines (i.e., of all gluelines), $l_{total,glueline}$ is the length of all assessed gluelines measured in the first dot point above, $l_{max,delam}$ is the maximum length of open glueline of all measured gluelines, and $l_{glueline}$ is the length of a single glueline.

- The samples were finally assessed based on the criteria in Clause 2.6.4 of AS/NZS 1328.1 (1998). A sample is deemed to satisfy the glueline integrity criteria if the total delamination is less than 5% (note that if greater than 5% but below 10% a third cycle can be performed) and the maximum delamination is less than 40%.

Table 39: Test samples and test parameters for the GLT gluing trials.

Trial	Test label	Sample type	Density(1)	Lamella orientation	Adhesive	Spread rate (gsm)	Pressure (MPa)	Surface preparation
1	T1_PUR_P1_G1 to G6	Southern blue gum	Low (G1) to High (G6)	Random	PUR	180	1	Planed
	T1_PUR_P2_G1 to G6						1.6	
	T1_RF_P1_G1 to G6				RF	360	1.2	
	T1_RF_P2_G1 to G6						2	
2	T2_PUR_P1_G1 to G6	Southern blue gum	Low (G1) to High (G6)	Figure 38	PUR	180	1	Planed
	T2_RF_P1_G1 to G6				RF	360	1.2	
	T2_PUR_P1_H1 to H6	Hybrid	Low (H1) to High (H6) (southern blue gum board only)		PUR	180	1	
	T2_RF_P1_H1 to H6				RF	360	1.2	
3	T3_PUR_P1_G1 to G3	Southern blue gum	>850 kg/m^3	Figure 38	PUR	250	1	Face milled
	T3_RF_P1_G1 to G3				RF	450	1.2	
	T3_PUR_P1_H1 to H3	Hybrid	>850 kg/m^3 (southern blue gum board only)		PUR	250	1	
	T3_RF_P1_H1 to H3				RF	450	1.2	
4	T4_PUR_P1_G1 to G3	Southern blue gum	>850 kg/m^3	Figure 38	PUR	250	1.2	Planed and sanded
	T4_RF_P1_G1 to G3				RF	450	1.4	

(1) Density of the lamellas provided in results section.

5.2.5.2 Finger jointing trials

AS/NZS 1328.1 (1998) requires that finger joints are manufactured and tested in accordance with AS 5068 (2006). To perceive potential challenges in manufacturing finger joints out of the resources, 72 finger jointed samples were manufactured from the offcuts of the dressed boards tested in Section 5.2.2.

5.2.5.2.1 Adhesives used

The same PUR and RF adhesives detailed in Section 5.2.5.1.1 were used to manufacture the finger joints. The PUR was applied on one side of a joint and at an average spread rate of 575 gsm. The RF was applied on both sides of a joint and at an average spread rate of 615 gsm per glueline. The spread rates were similar to the ones successfully used for finger jointed LVL in Gilbert, et al. (2024).

5.2.5.2.2 Test samples

The samples were manufactured in six groups of 12 samples consisting of five groups of southern blue gum samples of increasing density ranges and one group of radiata pine samples of random densities. The density ranges for the southern blue gum samples correspond to 20 percentile increments on the density distribution presented in Section 5.3.2.1.2 and are presented in Table 40.

To manufacture a sample, 10 mm horizontal finger joints (Figure 39) were cut at both ends of a 420 mm long dressed board. The board was then cut in two, and the two ends finger jointed together in a custom-made press (Figure 40) at a pressure of 8 MPa and 5 MPa for the southern blue gum and radiata pine samples, respectively. The pressure is lower than the one recommended in the EN 15497 (2014) but in the range used in the literature, with the pressure found not to influence the quality of southern blue gum finger jointed boards in Lara-Bocanegra, et al. (2017), as discussed in Section 2. The pressure was held for 5 s and the adhesive was left to cure for at least one week.

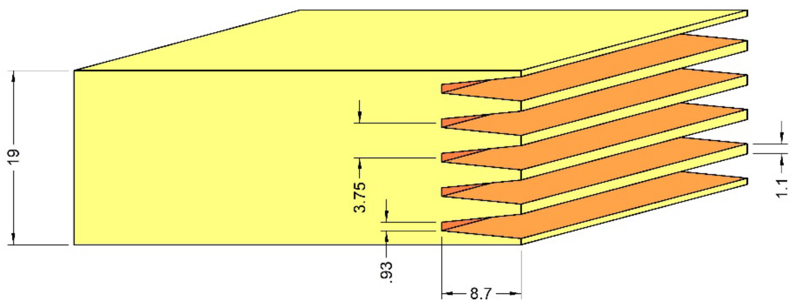


Figure 39: Finger joint geometry (units: mm).

Per group, half of the samples were manufactured with PUR and half with RF, and per adhesive type, three samples were tested “WET”, following the water treatment outlined in Clause 8.3 of AS 5068 (2006), and three samples were tested “DRY” for comparison purpose, i.e., without any water treatment. For the water treatment, the samples were placed in a vacuum/pressure cylinder, weighed down and immersed in water. A vacuum was drawn at 75 kPa for 1.5 hour followed by a pressure of 500 kPa for 1.5 hour. The vacuum-pressure cycle was repeated a second time. All samples were tested in four-point bending and on flat bending following the methodology outlined in Section 4.2.3.3.2. The WET samples were tested within a few hours after the end of the water treatment. In all tests, the finger joint was positioned at mid-span.

Figure 40: Custom-made finger jointing press.

Table 40 summarises the manufactured and tested samples. The moisture content of the dry joints was measured on a total of six samples following the oven-dry methodology in the AS/NZS 1080.1 (2012).

Table 40: Manufactured and tested finger jointed samples.

Test label	Sample type	Density range (kg/m^3)	Adhesive	Treatment	Number of repeats
FJ_PUR_WET_G1	Southern blue gum	< 675	PUR	WET	3
FJ_PUR_DRY_G1				DRY	3
FJ_RF_WET_G1			RF	WET	3
FJ_RF_DRY_G1				DRY	3
FJ_PUR_WET_G2		> 675 and < 730	PUR	WET	3
FJ_PUR_DRY_G2				DRY	3
FJ_RF_WET_G2			RF	WET	3
FJ_RF_DRY_G2				DRY	3
FJ_PUR_WET_G3		> 730 and < 790	PUR	WET	3
FJ_PUR_DRY_G3				DRY	3
FJ_RF_WET_G3			RF	WET	3
FJ_RF_DRY_G3				DRY	3
FJ_PUR_WET_G4		> 790 and < 850	PUR	WET	3
FJ_PUR_DRY_G4				DRY	3
FJ_RF_WET_G4			RF	WET	3
FJ_RF_DRY_G4				DRY	3
FJ_PUR_WET_G5		> 850	PUR	WET	3
FJ_PUR_DRY_G5				DRY	3
FJ_RF_WET_G5			RF	WET	3
FJ_RF_DRY_G5				DRY	3
FJ_PUR_WET_R1	Radiata pine	Any	PUR	WET	3
FJ_PUR_DRY_R1				DRY	3
FJ_RF_WET_R1			RF	WET	3
FJ_RF_DRY_R1				DRY	3

5.2.5.2.3 Assessment

The following values were measured for each tested sample:

- The bending MOR R_b following the procedure outlined in Section 4.2.3.3.2. The bending MOR of the dry samples is compared to the flat bending MOR of the boards without finger joints and of similar density (see Section 5.3.2.2.3).
- The wood failure percentage was visually assessed. A joint satisfies the adhesive bond durability requirements in AS 5068 (2006) if the average and minimum wood failure percent-ages of the wet joints are greater than 40% and 20%, respectively, for hardwood, and 60% and 30%, respectively, for softwood.
- The failure mode of each finger joint was also recorded following Appendix C of AS 5068 (2006). The failure modes are based on the ASTM D4688 (2021) and consist of six different failure modes (numbered from 1 to 6). The higher the failure mode number is, the more mechanically efficient is the finger joint.

5.2.5.3 GLT manufacturing

From the available sawn boards, four southern blue gum and three hybrid 6.3 m long × 209 mm deep × 65 mm wide GLT beams were able to be manufactured at Warrnambool Timber Industry (Dennington, Victoria), each beam composed of 11×19 mm thick lamellas. The manufacture targeted GL17 southern blue gum and GL13 hybrid GLT beams. Each hybrid beam was made of 4 southern blue gum and 7 and radiata pine lamellas. The manufacture of the beams is detailed in Section 6.

5.2.5.4 Mechanical properties and GL grades

Each manufactured GLT beam was cut into one 4.2 m long beam to be tested in bending (Section 5.2.5.4.1) and one 1.8 m long beam to be tested in shear (Section 5.2.5.4.2).

The samples were conditioned at ambient temperature and relative humidity in an enclose area before testing. One moisture content sample was cut from each beam after testing to measure the moisture content at the time of testing following the oven-dry methodology in AS/NZS 1080.1 (2012).

5.2.5.4.1 Bending

The 4.2 m long GLT samples were tested in four-point bending in a 300 kN Shimadzu universal testing machine following the recommendations in Clause 2.4 of AS/NZS 4063.1 (2010). The load was applied at a constant stroke rate to reach failure between 2 min and 5 min. The span L was equal to 18 times the depth of the beam, i.e., L = 3,762 mm. Two laser displacement transducers recorded the displacement at mid-span, on both sides of the beam and at the neutral axis. The mid-span displacement of the beam was taken as the average of the two transducers.

The test set-up is similar to the one for LVL presented in Figure 14 and a GLT beam being tested is shown in Figure 41. For each beam, the bending MOR R_b was calculated with Eqs. (1) and (2) and the bending MOE was calculated with Eq. (3). In the equations, each cross-sectional dimension was taken as the average of two measurements along the length of the beam, at 1/3 and 2/3 of the span. The failure mode was also recorded.

Figure 41: 4.2 m long GLT sample tested in four-point bending.

5.2.5.4.2 Shear

The 1.8 m long GLT samples were tested in three-point bending in a 300 kN Shimadzu testing machine following the recommendations for beam shear in Clause 2.7 of AS/NZS 4063.1 (2010). The load was applied at a constant stroke rate to reach failure between 2 min and 5 min. The span L was equal to 6 times the depth of the beam, i.e., L = 1,254 mm. The test set-up is illustrated in Figure 42 and a photo of a beam being tested is shown in Figure 43. For each beam, the shear strength R_s was calculated as:

$$R_s = \frac{0.75 \times P_{max}}{bd} \tag{21}$$

where P_{max} is the maximum recorded applied load, b and d are the measured width and depth of the sample, respectively, each taken as the average of two measurements along the length of the beam, at 1/3 and 2/3 of the span.

The failure mode was also recorded.

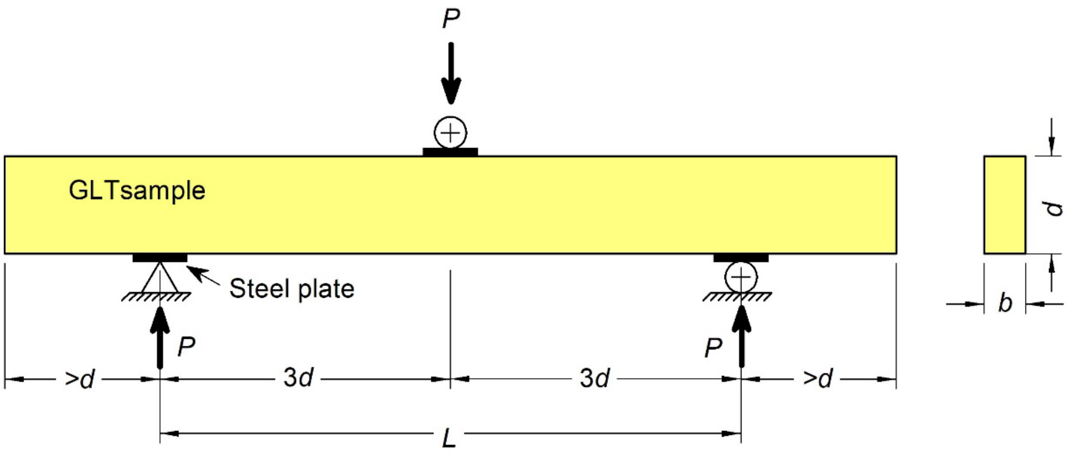


Figure 42: Test set-up for the GLT samples tested in three-point bending.

Figure 43: 1.8 m long GLT sample tested in three-point bending.

5.2.5.4.3 Characteristic values and grades

Similarly to the LVL, for each of the mechanical property in Sections 5.2.5.4.1 and 5.2.5.4.2, the characteristic design value was calculated following the methodology in Clause 3 of the European standard EN 14358 (2016) based on the number of tests of performed.

Each characteristic value is also compared to the minimum characteristic value for the GL grades in the AS 1720.1 (2010), providing an indication if the targeted grades of GL17 for the southern blue gum and GL13 for the hybrid are met.

5.3 Results

5.3.1 Log processing and green sawn boards measurements

Out of the 124 billets merchandised, all were processed into sawn boards. These resulted in 670 and 239 boards sawn from the southern blue gum and radiata pine billets, respectively.

5.3.1.1 Billet measurements

Similar to Section 4.3.1.1, the average measurements taken on the billets to be sawn are provided in Table 41 and Table 42 for the southern blue gum and radiata pine resources, respectively. The measurements are provided by site and targeted DBHOB. The CoV for each measurement is provided in brackets next to the average value. The tables also indicate, same as in Section 4.3.1.1, that the harvested trees have on average larger diameters than the targeted ones.

Table 41: Average billet measurements (with CoV in % provided in brackets) for southern blue gum.

Billet ID	Value	Caves		Barker		
		Targeted DBHOB between 17.0 and 23.6 cm(1)	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**Targeted DBHOB between 17.0 and 23.6 cm(1)**	**Targeted DBHOB between 23.6 and 31.8 cm(2)**	**Targeted DBHOB greater than 40.0 cm(3)**
1	*SEDOB* (cm)(4)	22.5 (9.1)	26.6 (6.2)	21.6 (18.1)	29.5 (9.8)	--
	LEDOB (cm)(4)	25.3 (6.4)	24.0 (53.7)	25.9 (18.1)	33.6 (7.9)	--
	SEDUB (cm)(4)	20.4 (8.8)	24.3 (7.1)	19.4 (19.1)	27.6 (13.3)	34.5 (0.6)
	LEDUB (cm)(4)	22.8 (7.2)	27.2 (9.3)	22.3 (19.5)	30.7 (10.7)	38.6 (6.4)
	Ovality(5)	1.03 (2.2)	1.04 (3.5)	1.05 (4.1)	1.03 (3.0)	1.02 (1.9)
	S_B(6) (mm)	21.3 (47.3)	27.2 (45.6)	24.7 (53.8)	18.6 (41.7)	20.0 (35.4)
2	*SEDOB* (cm)(4)	21.0 (6.9)	24.4 (7.4)	19.7 (21.9)	27.8 (13.8)	34.2 (0.0)
	LEDOB (cm)(4)	22.5 (9.1)	26.6 (6.2)	21.6 (18.1)	29.5 (9.8)	37.3 (N/A)
	SEDUB (cm)(4)	19.3 (7.2)	22.6 (7.3)	18.0 (22.9)	25.7 (15)	32.1 (0.9)
	LEDUB (cm)(4)	20.4 (8.8)	24.3 (7.1)	19.4 (19.1)	27.6 (13.3)	34.5 (0.6)
	Ovality(5)	1.06 (3.8)	1.04 (2.3)	1.02 (6.1)	1.03 (2.6)	1.01 (0.7)
	S_B(6) (mm)	19.4 (43.5)	22.0 (28.7)	25.0 (49.8)	17.5 (43.1)	32.5 (54.4)

(1): Logs 51 to 60, (2): Logs 21 to 30, (3): Logs A and B.
(4): Contrary to SEDUB and LEDUB, the SEDOB and LEDOB were not able to be measured for all billets due to bark being removed during harvesting. This resulted in the average OB and UB values reflecting a different number of billets and consequently not always directly comparable.
(5): Calculated as the ratio LSEDUB/SSEDUB.
(6): Over the nominal billet length of 3.1 m.

Table 42: Average billet measurements (with CoV in % provided in brackets) for radiata pine.

Billet ID	Value	Snowgums (T1)	Kilsbys (T2)
		Targeted DBHOB between 15 and 20 cm(1)	**Targeted DBHOB between 20 and 25 cm(2)**
1	*SEDOB* (cm) (3)	18.5 (8.4)	23.6 (9.0)
	LEDOB (cm) (3)	21.5 (9.7)	27.0 (7.0)
	SEDUB (cm) (3)	18.0 (8.0)	22.9 (10.1)
	LEDUB (cm) (3)	20.2 (8.5)	25.2 (9.3)
	Ovality(4)	0.93 (4.3)	0.95 (5.4)
	S_B(5) (mm)	18.0 (14.3)	13.5 (25)
2	*SEDOB* (cm) (3)	16.4 (7.3)	22.0 (8.4)
	LEDOB (cm) (3)	18.5 (8.4)	23.6 (9.0)
	SEDUB (cm) (3)	15.9 (7.9)	21.1 (9.2)
	LEDUB (cm) (3)	18.0 (8.0)	22.9 (10.1)
	Ovality(4)	0.97 (5.8)	0.97 (8.1)
	S_B(5) (mm)	15.0 (44.4)	15.0 (33.3)

(1): T1 logs 21 to 30, (2): T2 logs 21 to 30.
(3): Contrary to SEDUB and LEDUB, the SEDOB and LEDOB were not able to be measured for all billets due to bark being removed during harvesting. This resulted in the average OB and UB values reflecting a different number of billets and consequently not always directly comparable.
(4): Calculated as the ratio LSEDUB/SSEDUB.
(5): Over the nominal billet length of 3.1 m.

5.3.1.2 Green board measurements

Based on the observations gathered on the green boards, Table 43 and Table 44 show for the southern blue gum and radiata pine logs, respectively, the number and length of boards expected to be recovered from the logs.

Table 43: Expected number of boards to be recovered for southern blue gum.

	Board length			
Green dimensions	**0.9 m to 1.5 m**	**1.5 m to 2.0 m**	**2.0 m to 2.5 m**	**> 2.5 m**
62 mm × 29 mm	26	22	13	43
92 mm × 29 mm	69	21	24	84
112 mm × 29 mm	21	60	61	252

Table 44: Expected number of boards to be recovered for radiata pine.

	Board length			
Green dimensions	**0.9 m to 1.5 m**	**1.5 m to 2.0 m**	**2.0 m to 2.5 m**	**> 2.5 m**
57 mm × 26 mm	4	4	3	13
84 mm × 26 mm	8	6	5	22
103 mm × 26 mm	5	12	8	168

5.3.2 Dried sawn boards imperfections, characteristics and mechanical properties

5.3.2.1 Imperfections, density, MOE and other characteristics

5.3.2.1.1 Imperfections

The average imperfection measurements before and after planing are provided in Table 45 for both species. The distributions of these imperfections are also visualised in Figure 44 and Figure 45 for the southern blue gum and radiata pine boards, respectively.

Planing was efficient in removing the spring and cup imperfections for the blue gum boards, with 72% of the boards having a spring less than or equal to 2 mm, and 82% of the boards having a cup less than or equal to 1 mm. For the two species, after planing, between 40% to 60% of the boards had a bow less than or equal to 2 mm. Bow is less an issue in the manufacturing of GLT than spring and cup as it can be eliminated when pressing the boards to form the GLT.

In general, planing was more efficient in removing the imperfections for the southern blue gum boards than for the radiata pine boards.

Table 45: Average measured imperfections before and after planing the boards

	Bow		Spring		Twist		Cup	
Species	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Southern blue gum	9.4	4.6	10.5	2.3	10.7	2.9	3.6	0.2
Radiata pine	4.2	3.1	3.6	3.0	8.2	4.5	1.0	0.0

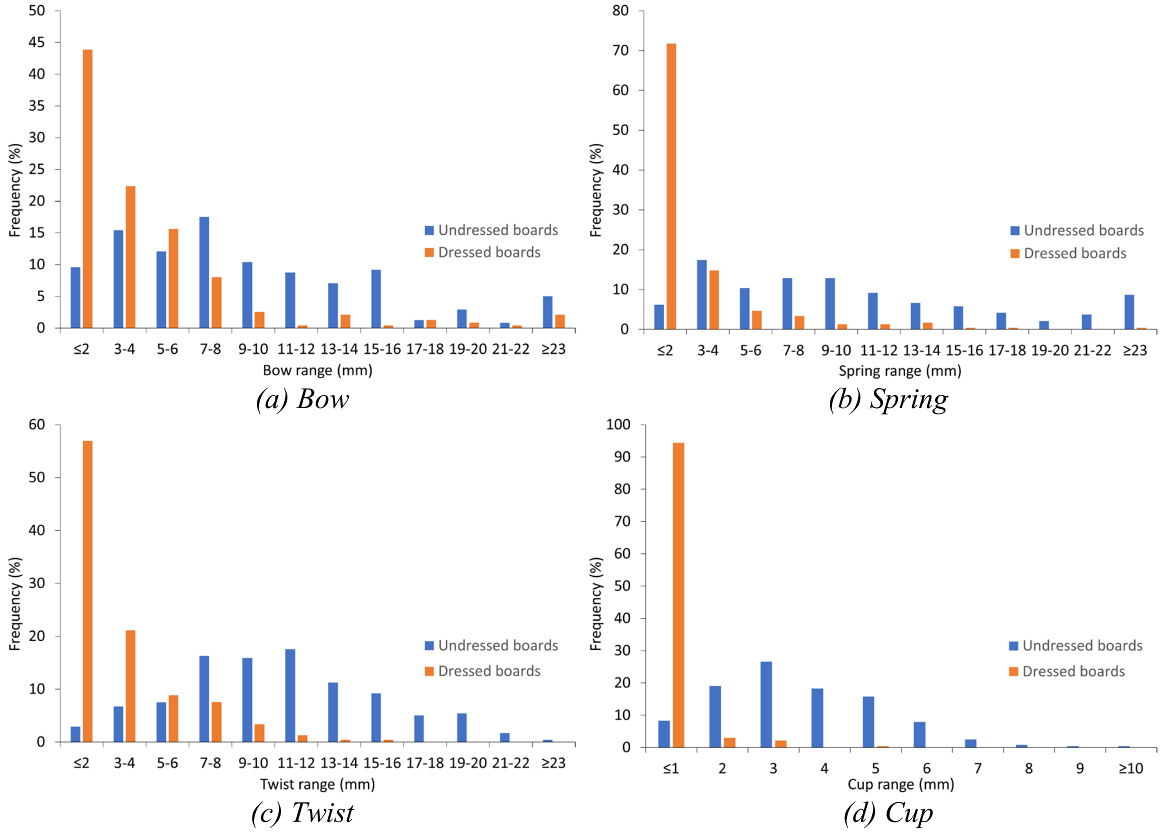


***Figure 44**: Distributions of measured imperfections of the southern blue gum boards (a) bow, (b) spring, (c) twist and (d) cup.*

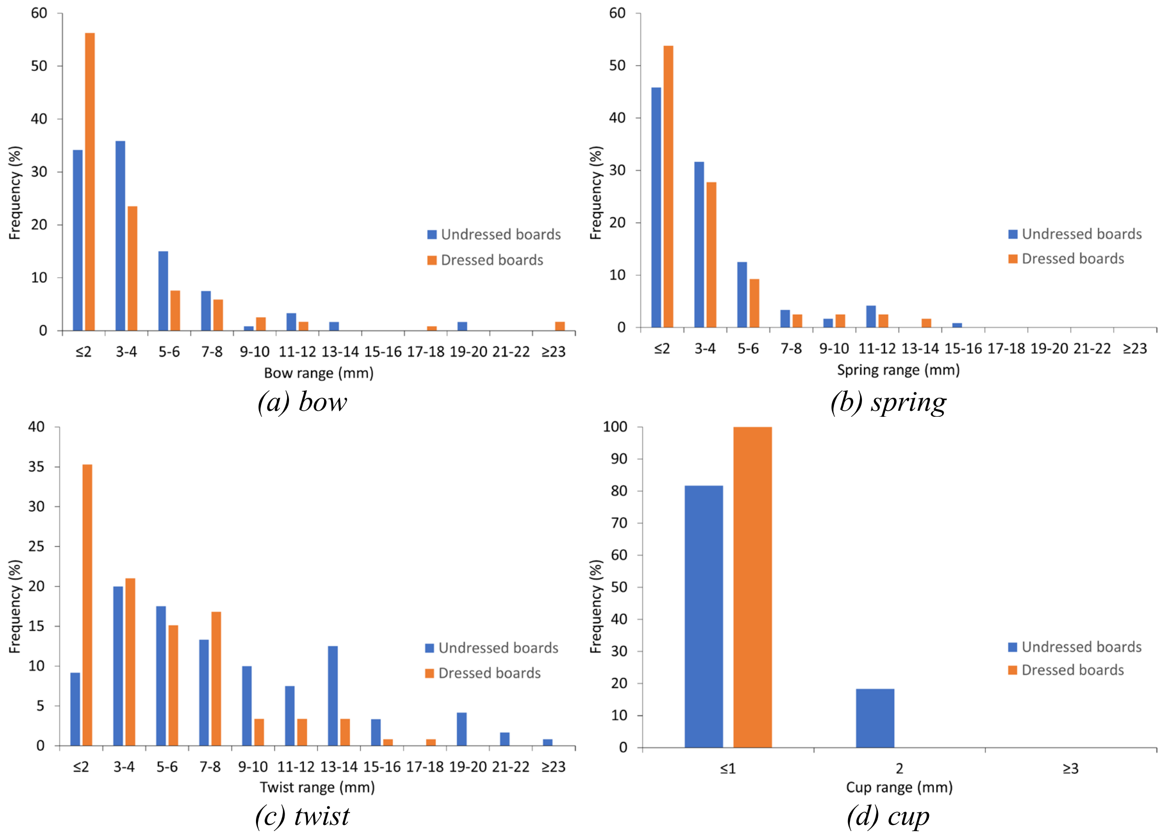
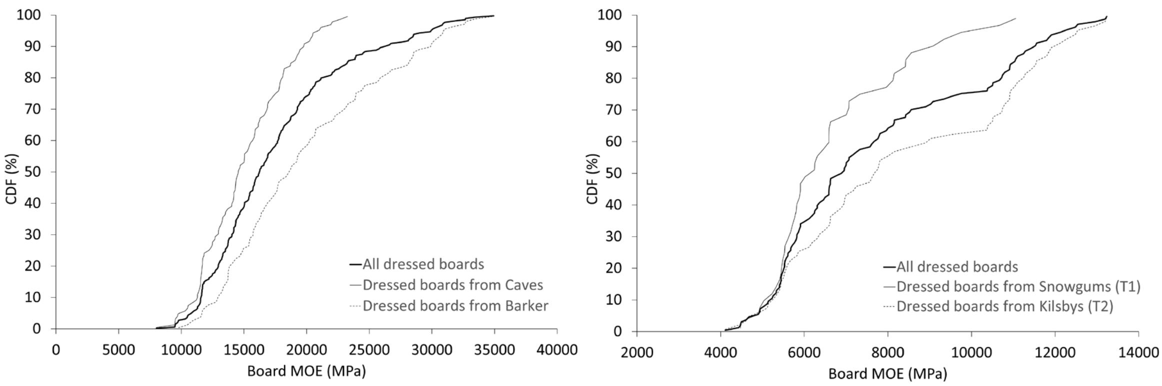


***Figure 45**: Distributions of measured imperfections of the radiata pine boards (a) Bow, (b) Spring, (c) Twist and (d) Cup.*

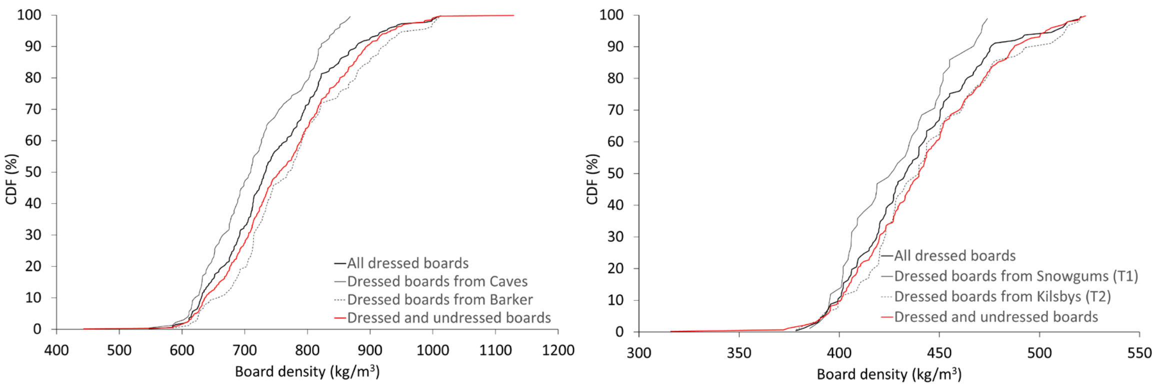
5.3.2.1.2 Density and MOE

Figure 46 and Figure 47 plot the acoustic MOE and density distributions of the dressed boards, respectively. In the two figures, the distributions are also broken down per site. The distributions of the density of all boards sawn (both dressed and undressed) and aimed to be dressed to 86 mm × 19 mm and 68 mm × 19 mm are also presented in Figure 47.



(a) Southern blue gum *(b) Radiata pine*

***Figure 46**: CDF of the board acoustic MOE for (a) southern blue gum and (b) radiata pine.*



(a) Southern blue gum *(b) Radiata pine*

***Figure 47**: CDF of the board density for (a) southern blue gum and (b) radiata pine.*

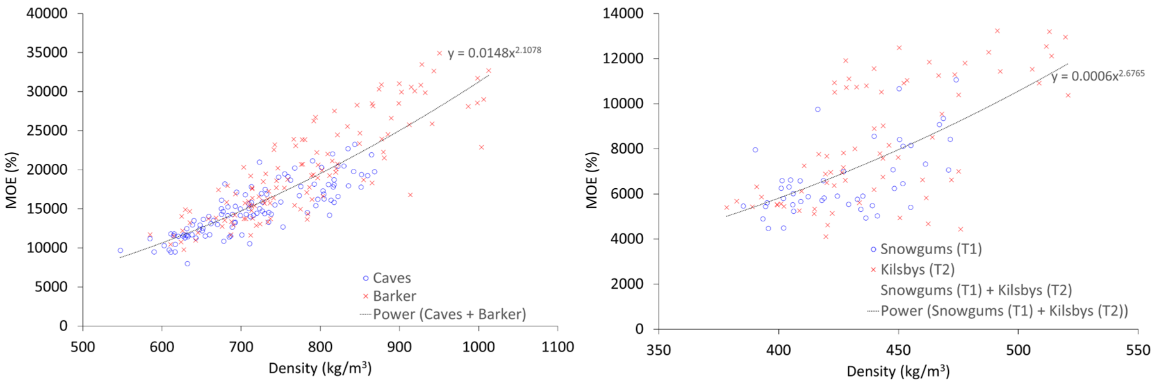
The figures show than similarly to the veneers, the MOE and density of Barker and Snowgums (T1) are higher than Caves and Kilsbys (T2), respectively. 20% of the southern blue gum boards have acoustic MOE and density greater than 21,000 MPa and 850 kg/m^3, respectively. In Figure 47, the density distributions of the boards randomly selected and dressed to assess the properties and characteristics of the sawn resources are representative of all sawn boards. For both species, the difference between the average density of the dressed and all sawn boards is less than 2%.

Table 46 provides the log-normal parameters that best fit the density distributions of the dressed and undressed boards shown in Figure 47.

***Table 46**: Mean and standard deviation of ln(x) of the log-normal distributions that best fit the density distributions of the dressed and undressed boards.*

	Log-normal parameters	
Species	***σ***	***μ***
Southern blue gum	0.12794	0.07845
Radiata pine	6.631	6.087

Figure 48 plots for both species the relationship between the acoustic MOE and density of the boards. Best fit power equations are also shown in the figure.



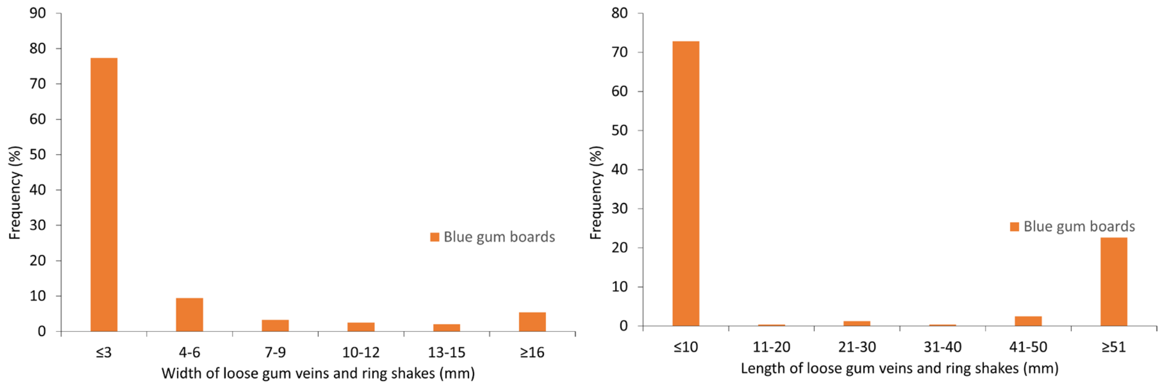
(a) Southern blue gum *(b) Radiata pine*

***Figure 48**: Board acoustic MOE versus board density for (a) southern blue gum and (b) radiata pine.*

5.3.2.1.3 Other characteristics

The other characteristics listed in Table 37 and measured on the dressed boards are presented and discussed as follows:

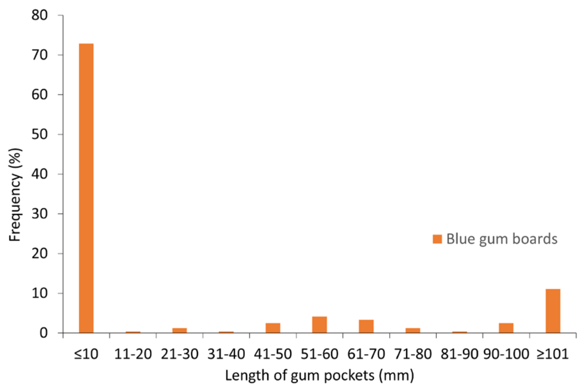
- *Loose gum veins and ring shakes*: The distributions of the width and length of the loose gum veins and ring shakes are reported in Figure 49 for the southern blue gum boards. Seven boards out of the 240 (i.e., 3%) had loose gum veins or ring shakes extending from one surface to the opposite surface. For information, 78% and all boards satisfied the width and length requirements, respectively, in Appendix B of AS/NZS 1748.1 (2011).



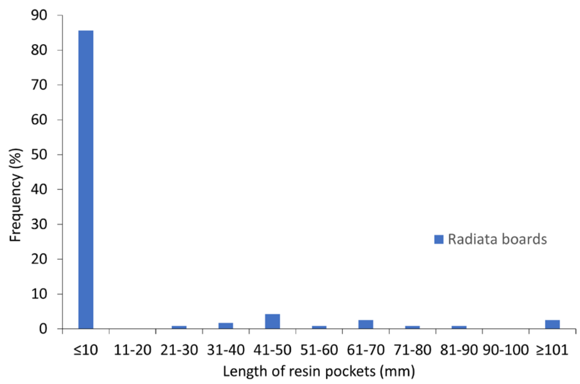
(a) Width *(b) Length*

***Figure 49**: Loose gum veins and ring shakes distributions for all southern blue gum boards, (a) width and (b) length.*

- *Gum and resin pockets*: The distributions of the length of gum (southern blue gum boards) and resin (radiata pine boards) pockets are reported in Figure 50. More than 70% of the boards had gum or resin pockets less than or equal to 10 mm in length. 10% and 4% of the southern blue gum and radiata pine boards, respectively, had pockets extending from one surface to the opposite surface. For information, 86% and 98% of the southern blue gum and radiata pine boards, respectively, satisfied the length requirement in Appendices A and B of AS/NZS 1748.1 (2011).



(a) Gum pockets



(b) Resin pockets

***Figure 50**: Distributions of the length of (a) gum pockets (all southern blue gum boards) and (b) resin pockets (all radiata pine boards).*

- *Splits*: None of the radiata pine boards presented splits while splits were present on 7% of the southern blue gum boards. The length distribution of the splits of the split southern blue gum boards is plotted in Figure 50. About 30% of the split southern blue gum boards had splits less than 100 mm in length.

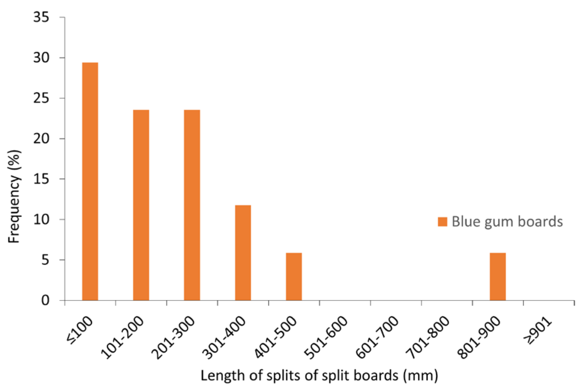
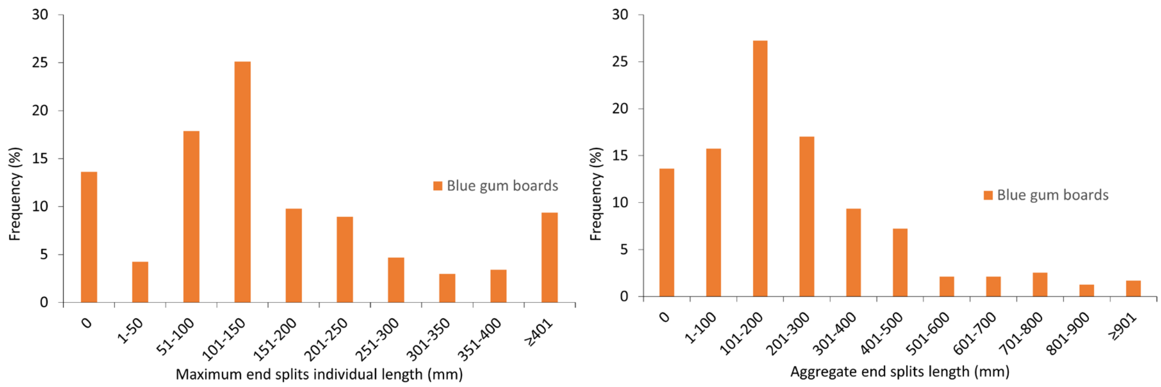


***Figure 51**: Distribution of the length of splits of the split southern blue gum boards.*

- *End splits*: None of the radiata pine boards presented end splits while only 14% of the southern blue gum boards did not present end splits. The maximum individual length and aggregate length distributions of the end splits of all southern blue gum boards are plotted in Figure 52. For information, only 16% and 29% of the southern blue gum boards satisfied the maximum individual length and aggregate length requirements, respectively, in Appendix B of AS/NZS 1748.1 (2011). End splits can be trimmed for GLT manufacturing.



(a) Maximum individual length *(b) Aggregate length*

***Figure 52**: End split distributions for all southern blue gum boards, (a) maximum individual length width and (b) aggregate length.*

- *Pith*: Pith was present at the ends of the boards for 13% and 36% of the southern blue gum and radiata pine boards, respectively. On the other hand, pith was present on the faces of the boards for 26% and 40% of the southern blue gum and radiata pine boards, respectively. Figure 53 plots the accumulative length distributions of pith on the faces of the southern blue gum and radiata pine boards where pith was present. Radiata pine boards showed significantly longer accumulative pith on faces than the southern blue gum boards, likely due to the smaller diameters of the processed radiata pine logs.

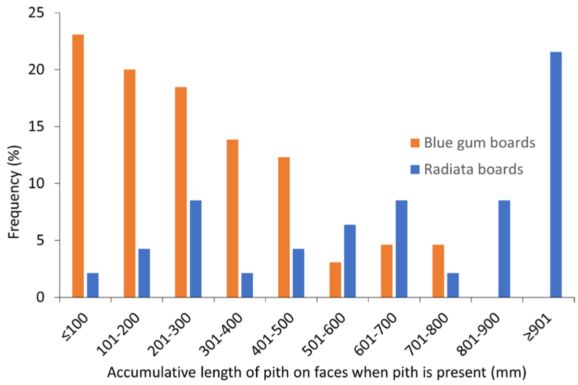
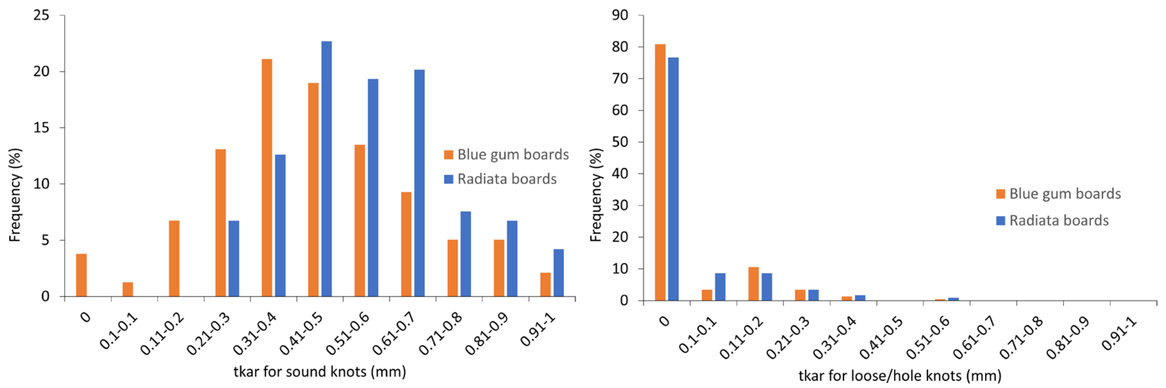


***Figure 53**: Distributions of the accumulative length of pith for southern blue gum and radiata pine boards where pith was present on the faces.*

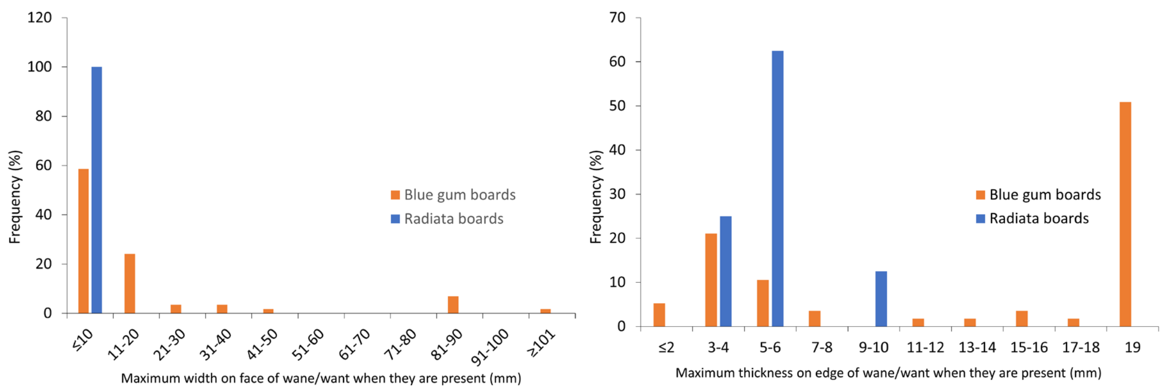
- *Total knot area ratios*: Figure 54 plots the distributions of the tkar for sound and loose knots of all southern blue gum and radiata pine boards. The radiata pine boards presented higher tkar for sound knots, with an average tkar of 0.44 for southern blue gum and 0.63 for radiata pine. None and 5% of the radiata pine and southern blue gum boards, respectively, had a tkar for sound knots less than or equal to 0.1 (i.e., with little to no knots). More than 70% of the boards did not have loose knots or holes.



(a) Sound knots *(b) Loose/hole knots*

Figure 54*: tkar distributions for all southern blue gum and radiata pine boards for (a) sound knots and (b) loose/hole knots.*

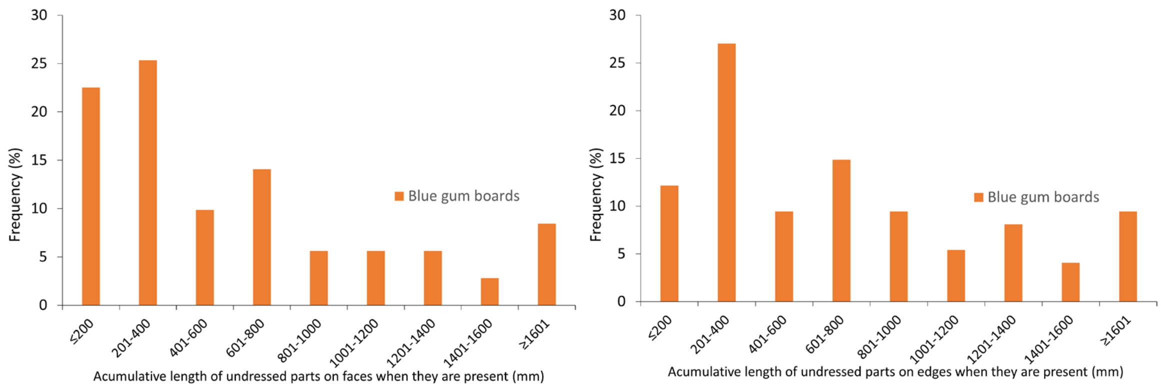
- *Cross-shakes*: 95% of the southern blue gum boards did not have cross-shakes.
- *Wane and want*: Wanes or wants were present on 20% and 7% of the southern blue gum and radiata pine boards, respectively. Figure 55 plots the distributions of the maximum width on face and maximum thickness on edges of the wanes and wants for all the boards where they were present. For information for the boards where wane or want were present, 93% and all of the southern blue gum and radiata pine boards, respectively, satisfied the maximum width on face requirement in Appendices A and B of AS/NZS 1748.1 (2011), while 27% and 87% of the southern blue gum and radiata pine boards, respectively, satisfied the maximum thickness on edges requirement.



(a) Maximum width on faces *(b) Maximum thickness on edges*

Figure 55*: Wane/want distributions for boards where wane/want were present, (a) maximum width on faces and (b) maximum thickness on edges.*

- *Undressed parts*: 30% of the southern blue gum boards showed undressed parts, with an average accumulative length on faces and edges of 627 mm and 752 mm, respectively. The distributions of the length of the undressed parts for the boards where there were present are plotted in Figure 56.



(a) Accumulative length on faces *(b) Maximum thickness on edges*

Figure 56*: Undressed part distributions for boards where undressed parts were present, (a) accumulative length on faces and (b) accumulative maximum thickness on edges.*

- *Length of segments with strength reducing characteristics less than 10%*: The distributions of the length of segments of boards with strength reducing characteristics less than 10% of the cross-section are plotted in Figure 57. The average length of these segments is 614 mm and 550 mm for the southern blue gum and radiata pine boards, respectively

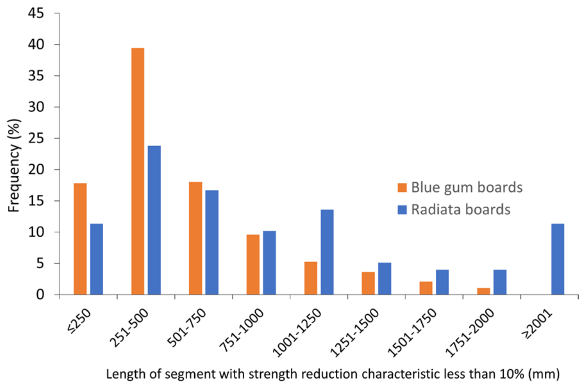


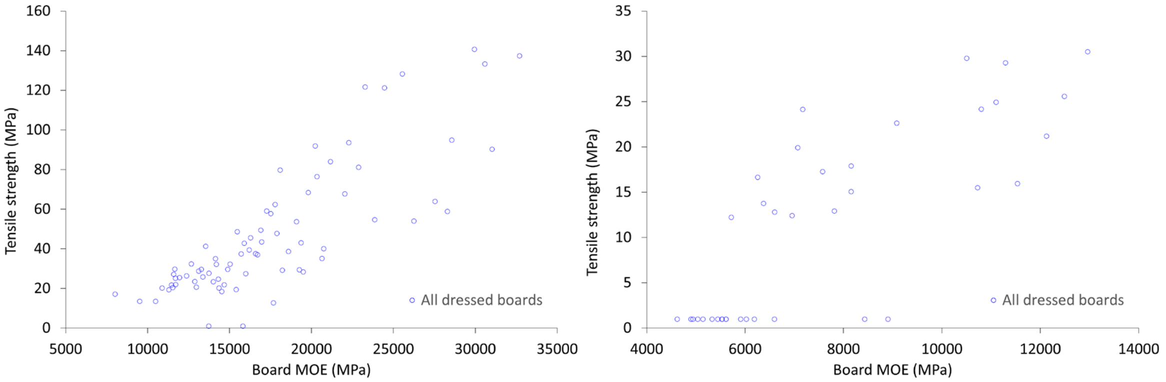
Figure 57*: Length of segments with strength reducing characteristics less than 10% of the cross-section distributions.*

5.3.2.2 Mechanical properties

The moisture content of the tested board samples (both southern blue gum and radiata pine) was measured at 11.7% with a CoV of 7.1%.

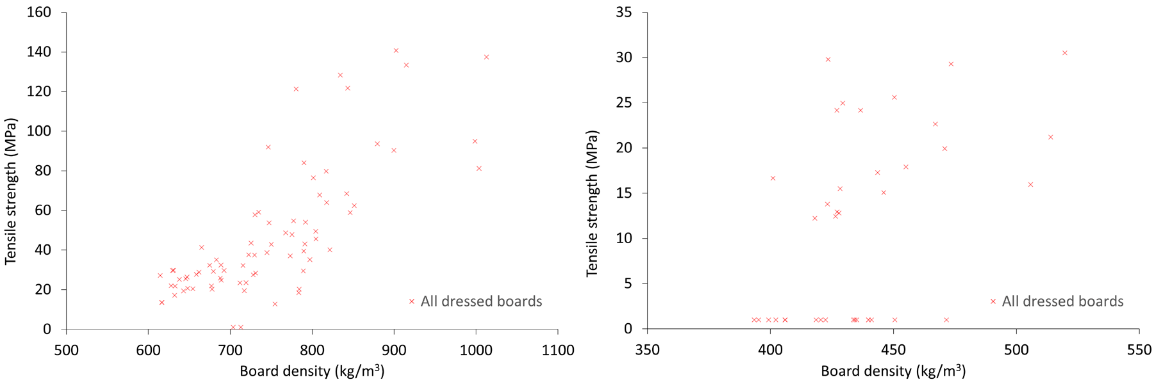
5.3.2.2.1 Tension parallel to grain

For both species, the relationships between the acoustic MOE and the tensile strength, and between the density and the tensile strength of the boards are shown in Figure 58 and Figure 59, respectively. The tensile strength of the radiata pine boards was low and less than 30 MPa, while high MOE southern blue gum boards reached tensile strength greater than 100 MPa.



(a) Southern blue gum *(b) Radiata pine*

Figure 58*: Board acoustic MOE versus tensile strength parallel to grain for (a) southern blue gum and (b) radiata pine.*



(a) Southern blue gum *(b) Radiata pine*

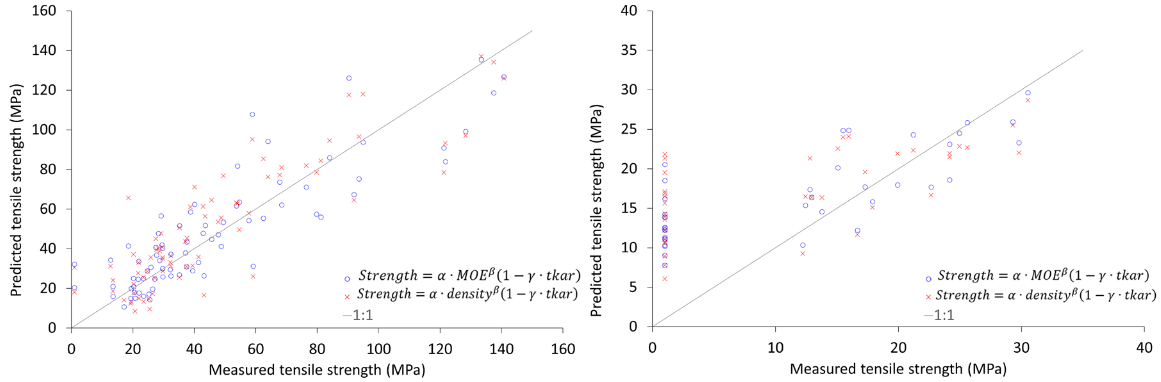
Figure 59*: Board density versus tensile strength parallel to grain for (a) southern blue gum and (b) radiata pine.*

The factors for predicting Eqs. (9) to (12) are provided in Table 47, along with the coefficient of determination for each equation. The accuracy of predicting Eqs. (9) and (11) is also visualised in Figure 60 for both species. Considering the tkar in the equations improved the predictions. Using either the MOE or density as the main input parameter provide similar coefficients of determination, indicating that both parameters can be used to predict the tensile strength. However, the density must be used in conjunction with the tkar to significantly improve the accuracy of the predictions.

Table 47*: Coefficients α, β and γ of predicting equations for board tensile strength parallel to grain and associated coefficients of determination.*

	Southern blue gum				**Radiata pine**[(1)]			
Equation	α	β	γ	R^2	α	β	γ	R^2
$Strength = \alpha \cdot MOE^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (9)	3.93×10^{-4}	1.234	0.666	0.77	1.36×10^{-1}	0.580	0.572	0.58
$Strength = \alpha \cdot MOE^{\beta}$ - Eq. (10)	1.64×10^{-6}	1.750	--	0.69	2.66×10^{-3}	0.979	--	0.54
$Strength = \alpha \cdot density^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (11)	4.58×10^{-7}	2.525	0.836	0.77	2.671	0.404	0.805	0.51
$Strength = \alpha \cdot density^{\beta}$ - Eq. (12)	5.61×10^{-7}	2.742	--	0.58	8.79×10^{-5}	2.018	--	0.16

(1) boards failing at a strength of 1 MPa (see Section 5.2.2.3.2) were not considered in the prediction equations.

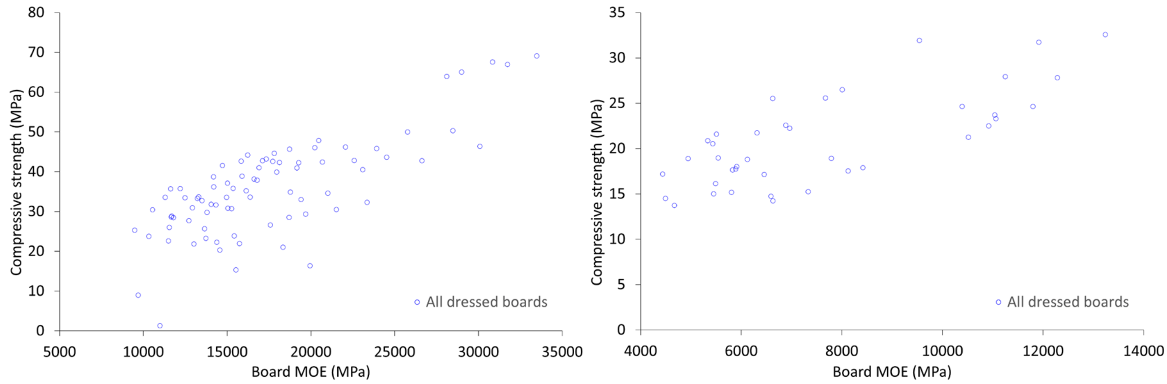


(a) Southern blue gum *(b) Radiata pine*

Figure 60: *Measured versus predicted tensile strength parallel to grain for (a) southern blue gum and (b) radiata pine.*

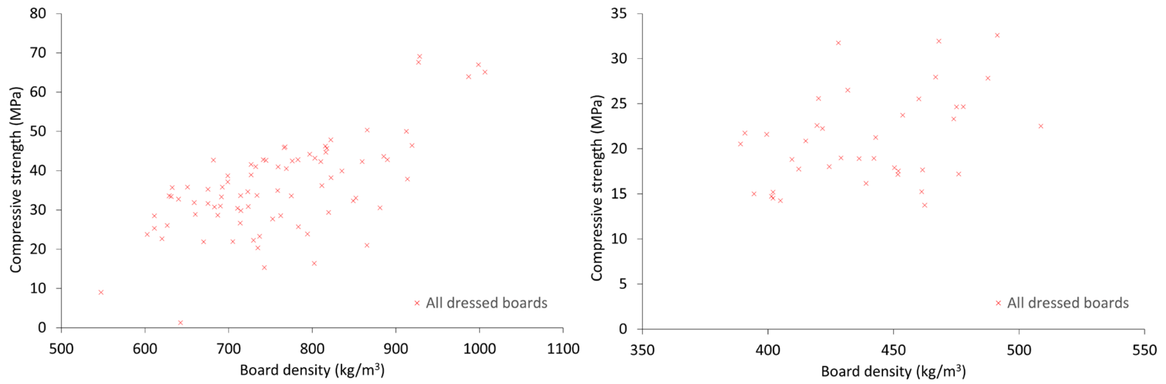
5.3.2.2.2 Compression parallel to grain

Similar to the previous section, the relationships between the acoustic MOE and the compressive strength, and between the density and the compressive strength of the boards are shown in Figure 61 and Figure 62, respectively. The compressive strength of the radiata pine boards ranged between 10 MPa and 30 MPa, while compressive strengths up to 70 MPa were encountered for the southern blue gum boards.



(a) Southern blue gum *(b) Radiata pine*

Figure 61: *Board acoustic MOE versus compressive strength parallel to grain for (a) southern blue gum and (b) radiata pine.*



(a) Southern blue gum *(b) Radiata pine*

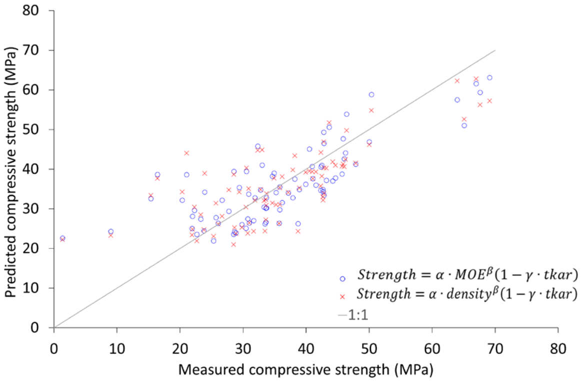
Figure 62: *Board density versus compressive strength parallel to grain for (a) southern blue gum and (b) radiata pine.*

The factors for predicting the compressive strength using Eqs. (9) to (12) are provided in Table 48, along with the coefficient of determination for each equation. The accuracy of predicting

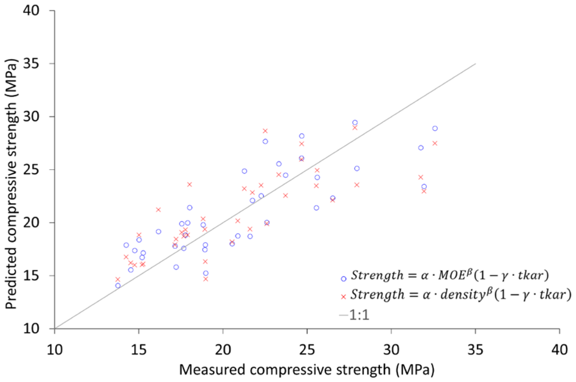
Eqs. (9) and (11) is also visualised in Figure 63 for both species. Similar conclusions to the tensile strength can be drawn for the predicting equations and the compressive strength parallel to grain.

Table 48: Coefficients α, β and γ of predicting equations for board compressive strength parallel to grain and associated coefficients of determination.

	Southern blue gum				Radiata pine			
Equation	***α***	***β***	***γ***	***R²***	***α***	***β***	***γ***	***R²***
$Strength = \alpha \cdot MOE^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (9)	$1.31{\times}10^{-1}$	0.595	0.324	0.61	1.74	0.309	0.407	0.66
$Strength = \alpha \cdot MOE^{\beta}$ - Eq. (10)	$9.97{\times}10^{-3}$	0.839	--	0.57	$1.44{\times}10^{-1}$	0.558	--	0.55
$Strength = \alpha \cdot density^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (11)	$2.65{\times}10^{-2}$	1.128	0.434	0.58	$9.30{\times}10^{-1}$	0.574	0.532	0.59
$Strength = \alpha \cdot density^{\beta}$ - Eq. (12)	$2.22{\times}10^{-4}$	1.801	--	0.46	$1.19{\times}10^{-6}$	2.742	--	0.17



(a) Southern blue gum



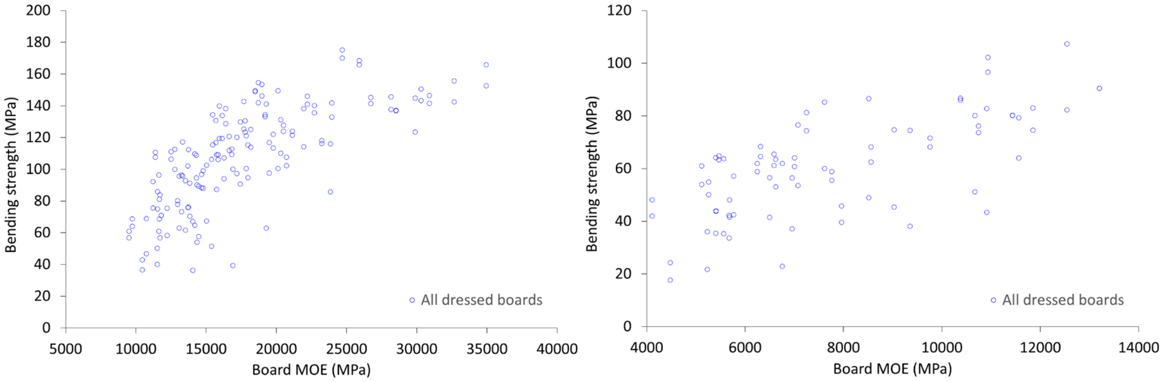
(b) Radiata pine

Figure 63: Measured versus predicted compressive strength parallel to grain for (a) southern blue gum and (b) radiata pine.

5.3.2.2.3 Flat bending

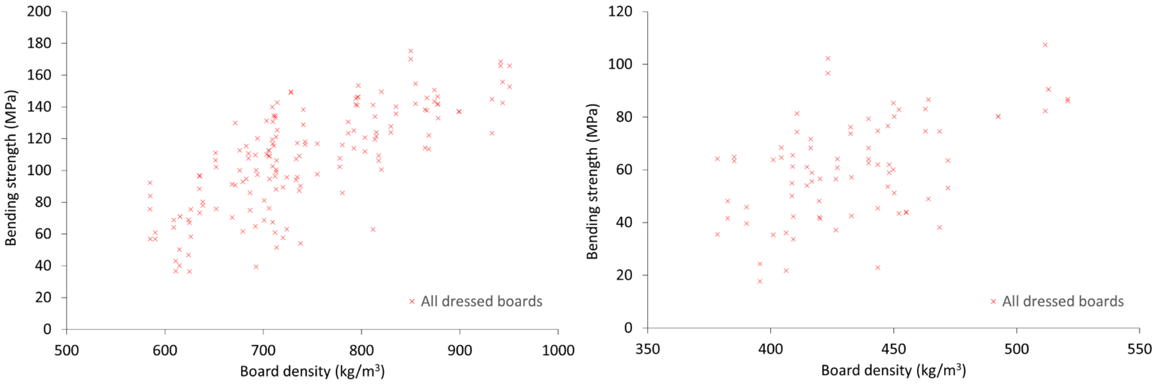
As for the tensile and compressive strengths, the relationships between the acoustic MOE and the bending strength, and between the density and the bending strength of the boards are shown in Figure 64 and Figure 65, respectively. The bending strength of the radiata pine boards ranged between 20 MPa and 100 MPa, while the bending strength of the southern blue gum boards ranged between 40 MPa and 180 MPa.

Additionally, the difference between the measured acoustic and static MOE are plotted in Figure 66. On average the acoustic MOE is 17% and 4% higher than the static MOE for the southern blue gum and radiata pine boards, respectively.



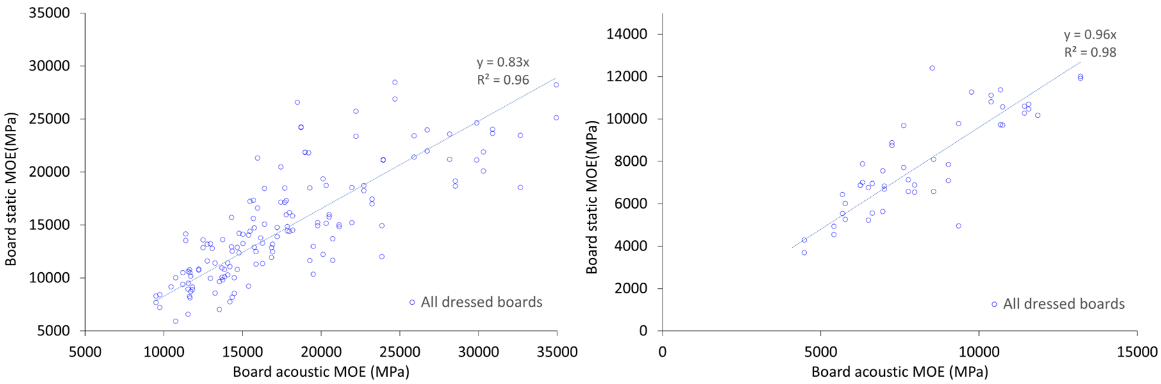
(a) Southern blue gum *(b) Radiata pine*

***Figure 64**: Board acoustic MOE versus bending strength for (a) southern blue gum and (b) radiata pine.*



(a) Southern blue gum *(b) Radiata pine*

***Figure 65**: Board density versus bending strength for (a) southern blue gum and (b) radiata pine.*



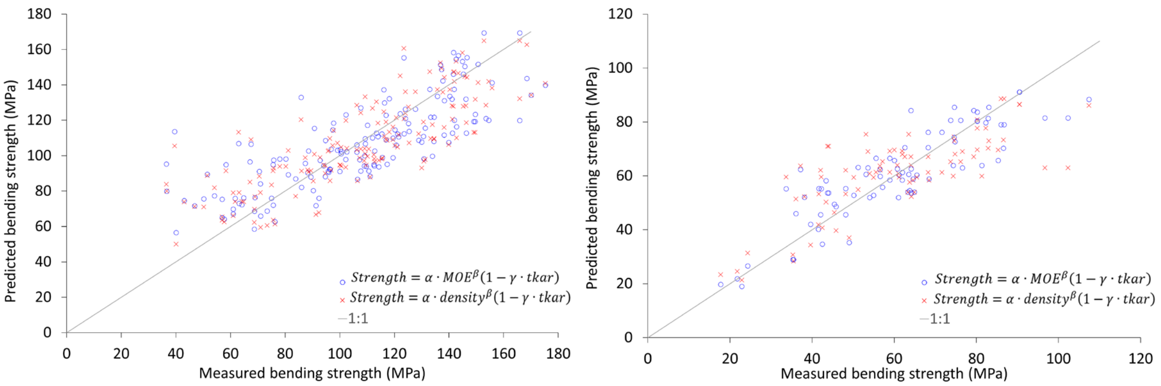
(a) Southern blue gum *(b) Radiata pine*

***Figure 66**: Board acoustic versus static MOE for (a) southern blue gum and (b) radiata pine.*

The factors for predicting the bending strength using Eqs. (9) to (12) are provided in Table 49, along with the coefficient of determination for each equation. The accuracy of predicting Eqs. (9) and (11) is also visualised in Figure 67 for both species. Similar conclusions to the previous sections can be drawn for the predicting equations and the bending strength parallel to grain.

Table 49: Coefficients α, β and γ of predicting equations for board bending strength and associated coefficients of determination.

	Southern blue gum				Radiata pine			
Equation	***α***	***β***	***γ***	***R²***	***α***	***β***	***γ***	***R²***
$Strength = \alpha \cdot MOE^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (9)	5.54×10^{-1}	0.550	0.382	0.62	3.31×10^{-1}	0.592	0.832	0.76
$Strength = \alpha \cdot MOE^{\beta}$ - Eq. (10)	1.47×10^{-1}	0.675	--	0.55	1.26×10^{-1}	0.691	--	0.47
$Strength = \alpha \cdot density^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (11)	1.01×10^{-2}	1.414	0.436	0.66	2.93×10^{-3}	1.649	0.827	0.58
$Strength = \alpha \cdot density^{\beta}$ - Eq. (12)	1.31×10^{-3}	1.710	--	0.54	3.54×10^{-6}	2.742	--	0.27

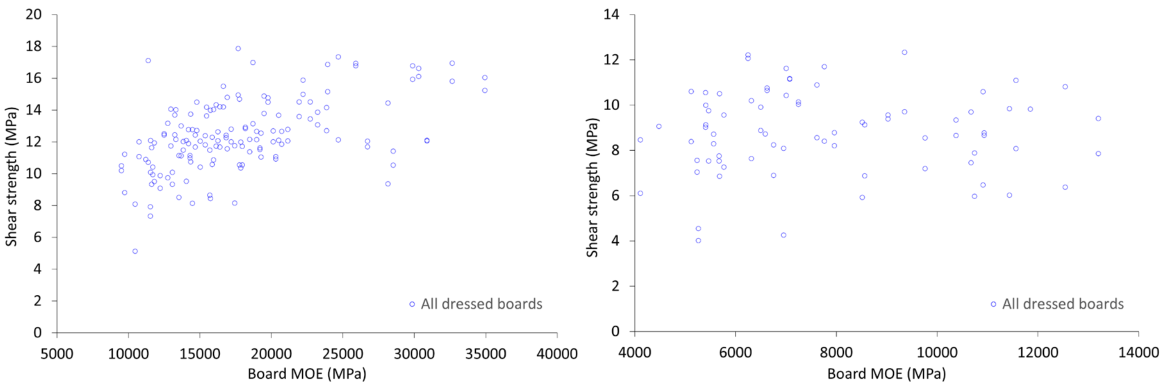


(a) Southern blue gum *(b) Radiata pine*

Figure 67*: Measured versus predicted bending strength for (a) southern blue gum and (b) radiata pine.*

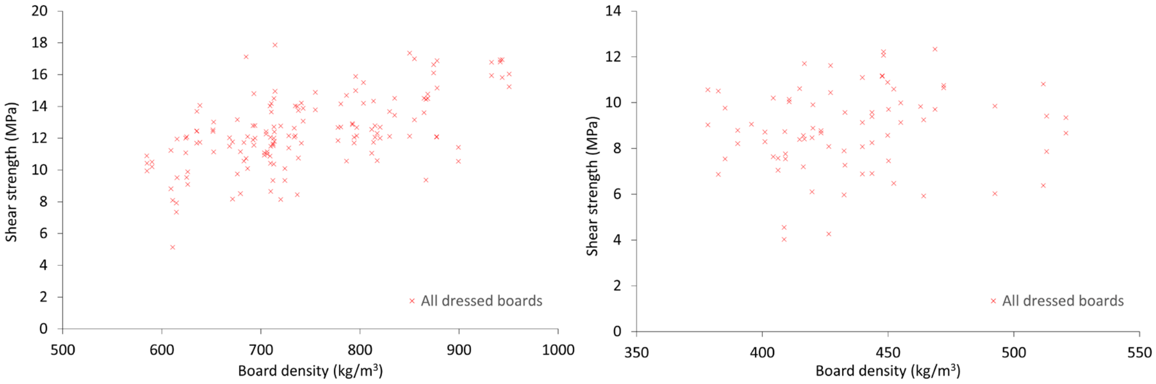
5.3.2.2.4 Shear

Similar the previous sections, the relationships between the acoustic MOE and the shear strength, and between the density and the shear strength of the boards are shown in Figure 68 and Figure 69, respectively. The average shear strength of the radiata pine and southern blue gum boards was 8.8 MPa and 12.4 MPa, respectively.



(a) Southern blue gum *(b) Radiata pine*

Figure 68*: Board acoustic MOE versus shear strength for (a) southern blue gum and (b) radiata pine.*



(a) Southern blue gum *(b) Radiata pine*

Figure 69*: Board density versus shear strength for (a) southern blue gum and (b) radiata pine.*

The factors for predicting the shear strength using Eqs. (9) to (12) are provided in Table 49, along with the coefficient of determination for each equation. The low coefficient of determination for all equations show that the shear strength is not correlated to either the acoustic MOE or the density of the boards. Considering the tkar in the equation did not improve the prediction contrary to the tensile, compressive and bending strengths covered in the previous sections.

Table 50*: Coefficients α, β and γ of predicting equations for board shear strength and associated coefficients of determination.*

	Southern blue gum				Radiata pine			
Equation	***α***	***β***	***γ***	***R^2***	***α***	***β***	***γ***	***R^2***
$Strength = \alpha \cdot MOE^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (9)	6.14×10^{-1}	0.309	0.028	0.29	7.87	0.014	0.093	0.02
$Strength = \alpha \cdot MOE^{\beta}$ - Eq. (10)	5.55×10^{-1}	0.319	--	0.29	6.48	0.034	--	0.00
$Strength = \alpha \cdot density^{\beta}(1 - \gamma \cdot tkar)$ - Eq. (11)	1.26×10^{-2}	1.043	0.027	0.35	1.40	0.305	0.093	0.03
$Strength = \alpha \cdot density^{\beta}$ - Eq. (12)	1.71×10^{-3}	1.346	--	0.35	5.66×10^{-7}	2.73	--	0.01

5.3.3 Sawn board recoveries

5.3.3.1 Green board recoveries (GBR)

Table 51 and Table 52 summarise the green sawn recoveries per site, targeted DBHOB and billet ID for the southern blue gum and radiata pine resources, respectively. Average GBR values are 41% for Caves and 42% for Barker. On average, 47% of the logs were recovered into green boards for Snowgums (T1) and 45% for Kilsbys (T2). These values compare to the GBR values in McGavin, et al. (2021) ranging between 35% to 49% on logs of average SEDUB between 18.7 cm and 30.7 cm. As mentioned in the methodology, the recovery values of the green boards presented herein are lower than what would be expected in a commercial facility where logs are scanned, and the sawing process optimised for individual logs.

Table 51: Green board recovery (GBR) for southern blue gum.

	GBR (%)						
	Caves			Barker			
Billet ID	Targeted DBHOB between 17.0 and 23.6 cm(1)	Targeted DBHOB between 23.6 and 31.8 cm(2)	All targeted DBHOB (all logs)(3)	Targeted DBHOB between 17.0 and 23.6 cm(1)	Targeted DBHOB between 23.6 and 31.8 cm(2)	All targeted DBHOB below 31.8 cm(3)	Targeted DBHOB greater than 40.0 cm(4)
All	43	38	42	35	42	41	--(5)
1	45	35	41	38	41	40	36
2	42	42	42	31	44	41	--(5)

(1): Logs 51 to 60.
(2): Logs 21 to 30.
(3): Logs 21 to 30 and 51 to 60.
(4): Logs A and B.
(5): Not calculated as boards from Log A, billet ID 2 were not kept by mistake.

Table 52: Green board recovery (GBR) for radiata pine.

	GBR (%)	
	Snowgums (T1)	Kilsbys (T2)
Billet ID	Targeted DBHOB between 15 and 20 cm(1)	Targeted DBHOB between 20 and 25 cm(2)
All	47	45
1	46	47
2	49	42

(1): T1 logs 21 to 30.
(2): T2 logs 21 to 30.

5.3.3.2 Net board recoveries (NBR)

Table 53 summarises the *NBR* per species, including the intermediate recovery values used in the calculation, i.e., *GBR*, R_{green_dry} and $R_{manufacturing}$. The recovery values combine both southern blue gum and hybrid GLT beams. Note *NBR* was calculated based on the 641 m and 171 m of southern blue gum and radiata pine boards, respectively, used to manufacture the four southern blue gum and three hybrid 6.3 m long × 209 mm deep × 65 mm wide GLT beams.

NBR was higher for the radiata pine (21.6%) than the southern blue gum (12.0%) boards, partially reflected by the fact that the radiata pine boards were used for the inner lamellas for which larger strength reducing characteristics were tolerated in the grading process when compared to the outer lamellas, therefore generating less waste. Additionally, and as mentioned in Section 6.3.2, the grading process of the southern blue gum boards used in the manufacture of the GLT beams generated higher wastage values than typically encountered in the day-to-day operation of Warrnambool Timber Industry. Both the latter and the former are reflected in the values of $R_{manufacturing}$ of 36.2% for southern blue gum and 50.9% for radiata pine. The *NBR* values are indicative as explained in the methodology section.

Table 53: Net board recovery (NBR) with intermediate recovery values.

	Recovery (%)	
Recovery type	Southern blue gum	Radiata pine
GBR(1)	41.5	46.0
R_{green_dry}	80.0	92.2
$R_{manufacturing}$	36.2	50.9
NBR	12.0	21.6

(1) Obtained from previous subsection.

However, the recovery values compare and agree to reported values between 8% and 19% in the literature for recoveries of Australian hardwood plantations into dried, dressed and graded engineered products, e.g., flooring (Leggate, et al., 2000).

5.3.4 Potential GLT products out of the resources (numerical simulations)

Table 54 summarises the results from the numerical simulations for the southern blue gum and hybrid GLT scenarios. For each 1 m^3 of manufactured GLT per scenario, the table shows the break down volumes per species. Under each characteristic value, the corresponding GL grade in AS 1720.1 (2010) is provided in brackets.

In terms of MOE, GL18 southern blue gum GLT can be manufactured from the southern blue gum resources, with the first product of Scenario #2 having a characteristic MOE more than 2,500 MPa greater than the cut-off for GL18. For Scenario #1, the unique product has a characteristic MOE only 1,045 MPa lower than the cut-off for GL18 and could be lifted by using denser boards as the outer lamellas. Regarding the hybrid products, Scenario #4 produces a southern blue gum GLT with a characteristic MOE close to a GL17 (500 MPa lower) and a hybrid product corresponding to a GL13. Therefore, the simulations indicate that GL18 and GL13 grades, as targeted by the market study, can be achieved out of the resources in terms of characteristic MOE using the right construction strategies.

The simulations also tend to indicate that the strength would be the limiting factor, with the characteristic bending strength typically resulting in a grade below the one obtained from the characteristic MOE. However, as discussed in the methodology, the confidence in the strength values is less than for the MOE and the values are provided as an indication of which characteristic strength could result from the manufactured GLT.

Table 54: Numerical simulation results for southern blue gum and hybrid GLT.

Scenario	Manufacturing strategies	Volume per species for 1 m^3 of GLT (m^3)		Characteristic values over 100 simulations (MPa) with associated GL grades		
		Southern blue gum	**Radiata**	**MOE**	**Bending strength**	**Shear Strength**
1	*Product #1*: One unique southern blue gum GLT using all boards	1	0	17,455 (GL17)	34.8 (GL13)	5.5 (GL18)
2	*Product #1*: One southern blue gum GLT using the 40% denser boards	0.4	0	21,036 (GL18)	44.0 (GL17)	5.5 (GL18)
	Product #2: One southern blue gum GLT using the remaining boards (60%)	0.6	0	13,435 (GL13)	26.2 (GL12)	5.5 (GL18)
3	*Product #1*: One southern blue gum GLT using the 40% denser boards	0.13	0	21,036 (GL18)	44.0 (GL17)	5.5 (GL18)
	Product #2: One hybrid GLT using the remaining southern blue gum boards (60%) and all radiata pine boards	0.19	0.68	10,087 (GL10)	18.6 (<GL8)	3.7 (GL10)
4	*Product #1*: One southern blue gum GLT using half the 36% denser boards as outer lamellas	0.5	0	16,208 (GL13)	35.9 (GL13)	5.5 (GL18)
	Product #2: One hybrid GLT using the other half of the 36% denser southern blue gum boards as outer lamellas and all radiata pine boards	0.11	0.39	13,736 (GL13)	27.5 (GL12)	3.7 (GL10)

5.3.5 GLT manufacturing and testing

5.3.5.1 Gluing trials

Table 55 summarises the outcomes of glueline integrity tests of the first trial detailed in Section 5.2.5.1. Per sample, the average measured density of the lamellas is also provided in the table. RF performed better than PUR, but both adhesives failed to satisfy the glueline integrity requirements in AS/NZS 1328.1 (1998) for the high-density samples, typically greater than 800-850 kg/m^3. These results are consistent with the ones presented in the literature in Section 2.4.2.3. No significant difference was found between the different applied pressures.

Table 55: Glueline integrity test results for the first gluing trial.

Description	Test label	Average southern blue gum lamella density (kg/m^3)	Total delamination (%)	Maximum delamination (%)	Results
Southern blue gum GLT with PUR at recommended pressure	T1_PUR_P1_G1	595	16.0	20.8	Fail
	T1_PUR_P1_G2	677	0.0	0.0	Pass
	T1_PUR_P1_G3	757	12.5	28.5	Fail
	T1_PUR_P1_G4	812	32.1	50.0	Fail
	T1_PUR_P1_G5	838	70.6	50.0	Fail
	T1_PUR_P1_G6	892	90.8	50.0	Fail
Southern blue gum GLT with PUR at increased pressure	T1_PUR_P2_G1	595	8.3(1)	11.5	Pass
	T1_PUR_P2_G2	677	8.3(1)	19.2	Pass
	T1_PUR_P2_G3	757	26.5	38.5	Fail
	T1_PUR_P2_G4	812	75.0	50.0	Fail
	T1_PUR_P2_G5	838	75.0	50.0	Fail
	T1_PUR_P2_G6	892	94.0	50.0	Fail
Southern blue gum GLT with RF at recommended pressure	T1_RF_P1_G1	595	1.0	3.8	Pass
	T1_RF_P1_G2	677	2.1	8.5	Pass
	T1_RF_P1_G3	757	0.0	0.0	Pass
	T1_RF_P1_G4	812	2.5	10.0	Pass
	T1_RF_P1_G5	838	19.6	24.6	Fail
	T1_RF_P1_G6	892	25.8	41.5	Fail
Southern blue gum GLT with RF at increased pressure	T1_RF_P2_G1	595	3.1	7.7	Pass
	T1_RF_P2_G2	677	6.2(1)	13.1	Pass
	T1_RF_P2_G3	757	0.0	0.0	Pass
	T1_RF_P2_G4	812	21.0	33.1	Fail
	T1_RF_P2_G5	838	23.3	30.8	Fail
	T1_RF_P2_G6	892	27.7	33.1	Fail

(1) Third water immersion and drying cycle performed.

The glueline integrity results for the second trial are summarised in Table 56, along with the average measured density of the lamellas per sample. Similar results to the first trial were encountered in the second trial with the RF performing better than PUR, and both adhesives failing to satisfy the glueline integrity requirements in the AS/NZS 1328.1 (1998) for the high-density samples, and this for both southern blue gum and hybrid GLT samples. The board orientation was not found to impact on the glueline integrity.

Table 56: Glueline integrity test results for the second gluing trial.

Description	Test label	Average southern blue gum lamella density (kg/m³)	Average radiata pine lamella density (kg/m³)	Total delamination (%)	Maximum delamination (%)	Results
Southern blue gum GLT with PUR at recommended pressure and orientated boards	T2_PUR_P1_G1	638	--	7.1(1)	18.5	Pass
	T2_PUR_P1_G2	712	--	3.3	8.5	Pass
	T2_PUR_P1_G3	794	--	29.0	46.2	Fail
	T2_PUR_P1_G4	849	--	72.1	50.0	Fail
	T2_PUR_P1_G5	865	--	80.8	50.0	Fail
	T2_PUR_P1_G6	893	--	67.3	50.0	Fail
Southern blue gum GLT with RF at recommended pressure and orientated boards	T2_RF_P1_G1	638	--	0.6	2.3	Pass
	T2_RF_P1_G2	712	--	4.4	10.0	Pass
	T2_RF_P1_G3	794	--	3.1	10.0	Pass
	T2_RF_P1_G4	849	--	5.6(1)	10.0	Pass
	T2_RF_P1_G5	865	--	23.7	24.6	Fail
	T2_RF_P1_G6	893	--	31.2	50.0	Fail
Hybrid GLT with PUR at recommended pressure and orientated boards	T2_PUR_P1_H1	630	400	1.0	3.8	Pass
	T2_PUR_P1_H2	715	415	7.3(1)	13.1	Pass
	T2_PUR_P1_H3	800	433	2.1	8.5	Pass
	T2_PUR_P1_H4	846	453	3.7	9.2	Pass
	T2_PUR_P1_H5	869	465	24.4	32.3	Fail
	T2_PUR_P1_H6	932	490	30.4	30.8	Fail
Hybrid GLT with RF at recommended pressure and orientated boards	T2_RF_P1_H1	630	400	0.6	2.3	Pass
	T2_RF_P1_H2	715	415	0.0	0.0	Pass
	T2_RF_P1_H3	800	433	2.1	3.1	Pass
	T2_RF_P1_H4	846	453	2.5	10.0	Pass
	T2_RF_P1_H5	869	465	0.0	0.0	Pass
	T2_RF_P1_H6	932	490	13.5	34.6	Fail

(1) Third water immersion and drying cycle performed.

The glueline integrity results for the third trial (with high density samples only) are now summarised in Table 57. The face milling improved the glueline integrity scores, especially for the hybrid samples which all passed the requirements in the AS/NZS 1328.1 (1998) for the two investigated adhesives. However, all southern blue gum GLT samples glued with PUR did not pass the glueline integrity criteria. Two out of the three southern blue gum GLT samples glued with RF passed the glueline integrity criteria, compared to none for this density range in the previous two trials, outlining the benefit of face milling the lamellas compared to planing..

Table 57: Glueline integrity test results for the third gluing trial.

Description	**Test label**	**Average southern blue gum lamella density (kg/m³)(2)**	**Average radiata pine lamella density (kg/m³)**	**Total dela-mination (%)**	**Maximum dela-mi-nation (%)**	**Results**
Southern blue gum GLT with PUR at recommended pressure and face milling	T3_PUR_P1_G1	> 850	--	44.4	50.0	Fail
	T3_PUR_P1_G2	> 850	--	28.1	31.5	Fail
	T3_PUR_P1_G3	> 850	--	56.3	50.0	Fail
Southern blue gum GLT with RF at recommended pressure and face milling	T3_RF_P1_G1	> 850	--	9.8(1)	15.4	Pass
	T3_RF_P1_G2	> 850	--	9.8(1)	10.8	Pass
	T3_RF_P1_G3	> 850	--	41.0	50.0	Fail
Hybrid GLT with PUR at recommended pressure and face milling	T3_PUR_P1_H1	> 850	(3)	0.0	0.0	Pass
	T3_PUR_P1_H2	> 850	(3)	0.6	2.3	Pass
	T3_PUR_P1_H3	> 850	(3)	1.5	6.2	Pass
Hybrid GLT with RF at recommended pressure and face milling	T3_RF_P1_H1	> 850	(3)	0.0	0.0	Pass
	T3_RF_P1_H2	> 850	(3)	0.0	0.0	Pass
	T3_RF_P1_H3	> 850	(3)	1.2	4.6	Pass

(1) Third water immersion and drying cycle performed.
(2) Southern blue gum boards of density greater than 850 kg/m³ were used for all GLT samples but the exact composition of individual sample was not tracked.
(3) Radiata pine boards were randomly selected, and their density was not recorded.

Finally, the glueline integrity results for the fourth trial (with high density samples only) are summarised in Table 58. The planing followed by sanding improved the glueline integrity scores for both adhesives when compared to their counterparts from the third trial (Table 57). All of the GLT samples glued with RF passed the glueline integrity criteria outlined in AS/NZS 1328.1 (1998), all with better scores than in the third trial. However, all GLT samples glued with PUR did not pass, but the scores improved compared to the third trial.

Table 58: Glueline integrity test results for the fourth gluing trial.

Description	**Test label**	**Average southern blue gum lamella density (kg/m³)(1)**	**Average radiata pine lamella density (kg/m³)**	**Total dela-mination (%)**	**Maximum dela-mination (%)**	**Results**
Southern blue gum GLT with PUR and planed/ sanded	T4_PUR_P1_G1	> 850	--	27.1	44.6	Fail
	T4_PUR_P1_G2	> 850	--	34.4	38.5	Fail
	T4_PUR_P1_G3	> 850	--	22.1	46.2	Fail
Southern blue gum GLT with RF and planed/ sanded	T4_RF_P1_G1	> 850	--	1.3	5.4	Pass
	T4_RF_P1_G2	> 850	--	0.0	0.0	Pass
	T4_RF_P1_G3	> 850	--	2.5	10.0	Pass

(1) Southern blue gum boards of density greater than 850 kg/m³ were used for all GLT samples but the exact composition of individual sample was not tracked.

In summary, RF performed better than PUR and is recommended from the above trials in the manufacturing of southern blue gum GLT. Planing the boards was found not to be adequate for southern blue gum lamellas of density greater than 800-850 kg/m^3, and while face milling produced some improvements, was still unsuccessful in achieving sufficient glueline integrity to pass the requirements in AS/NZS 1328.1 (1998). Sanding post-planing produced reductions in measured delamination values for both adhesive types with the RF adhesive passing the glueline integrity requirements. This surface preparation method is recommended but needs to be further confirmed on a higher number of samples.

5.3.5.2 Finger jointing trials

Table 55 summarises the test results of the finger jointed samples. The wood failure percentages are compared to the adhesive bond durability requirements in AS 5068 (2006). The CoV of the three tests performed per investigated configuration is also provided in brackets next to the average value for the bending MOR and failure mode. Additionally, the bending MOR of the southern blue gum finger jointed samples are compared in Figure 70 to the bending MOR of the southern blue gum boards reported in Section 5.3.2.2.3. The middle density value of each density group for the finger jointed samples is used in the figure. The moisture content of the dry finger jointed samples was measured at 11.2% with a CoV of 10.5%.

Table 59: Test results of the manufactured and tested finger joints (CoV in % given in brackets).

Description	Test label	Average bending MOR (MPa)	Average failure mode	Average wood failure (%)	Minimum wood failure (%)	Wood failure result
Wet southern blue gum samples with PUR	FJ_PUR_WET_G1	27.4 (27.9%)	1 (0.0)	1.7	0	Fail
	FJ_PUR_WET_G2	30.6 (17%)	1 (0.0)	0.0	0	Fail
	FJ_PUR_WET_G3	31.7 (11.3%)	1 (0.0)	0.0	0	Fail
	FJ_PUR_WET_G4	35.6 (14.5%)	1 (0.0)	0.0	0	Fail
	FJ_PUR_WET_G5	27.5 (8.8%)	1 (0.0)	0.0	0	Fail
Dry southern blue gum samples with PUR	FJ_PUR_DRY_G1	56.2 (7%)	3 (0.0)	40.0	25	N/A
	FJ_PUR_DRY_G2	42.9 (4.9%)	1.3 (43.3)	6.7	0	N/A
	FJ_PUR_DRY_G3	59.1 (15.8%)	2 (50.0)	28.3	0	N/A
	FJ_PUR_DRY_G4	58.1 (18.4%)	1.3 (43.3)	6.7	0	N/A
	FJ_PUR_DRY_G5	66.1 (14.7%)	1.3 (43.3)	5.0	0	N/A
Wet southern blue gum samples with RF	FJ_RF_WET_G1	34.2 (17.8%)	1 (0.0)	0.0	0	Fail
	FJ_RF_WET_G2	37.2 (6.8%)	1 (0.0)	1.7	0	Fail
	FJ_RF_WET_G3	40.6 (20.3%)	1 (0.0)	0.0	0	Fail
	FJ_RF_WET_G4	24.1 (18.2%)	1 (0.0)	0.0	0	Fail
	FJ_RF_WET_G5	41.4 (40%)	1 (0.0)	0.0	0	Fail
Dry southern blue gum samples with RF	FJ_RF_DRY_G1	44.7 (5.9%)	1.7 (34.6)	8.3	0	N/A
	FJ_RF_DRY_G2	49.5 (18.9%)	1.3 (43.3)	13.3	10	N/A
	FJ_RF_DRY_G3	51.2 (24.9%)	1 (0.0)	3.3	0	N/A
	FJ_RF_DRY_G4	47.9 (32.9%)	1.3 (43.3)	6.7	0	N/A
	FJ_RF_DRY_G5	42.4 (34.5%)	1 (0.0)	0.0	0	N/A
All radiata pine samples	FJ_PUR_WET_R1	19.9 (9.9%)	2 (50.0)	46.7	15	Fail
	FJ_PUR_DRY_R1	43.1 (27.3%)	5 (20.0)	98.3	95	N/A
	FJ_RF_WET_R1	20.8 (7.8%)	3 (0.0)	71.7	65	Pass
	FJ_RF_DRY_R1	27.7 (14.2%)	4.3 (13.3)	96.7	90	N/A

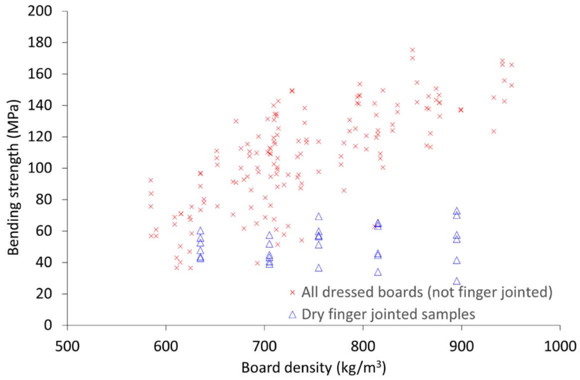


Figure 70: Board density versus bending strength for the southern blue gum boards and finger jointed samples.

All southern blue gum samples failed the bond durability requirements in AS 5068 (2006), with low wood failure percentages for both PUR and RF. This result is in accordance with the literature which showed low wood failure percentage (especially for high density boards) for southern blue gum finger jointed boards, even when tested dry (González-Prieto, et al., 2022, Lara-Bocanegra, et al., 2017). Additionally, as seen in Figure 70, the bending MOR of the finger jointed samples does not increase with the density as it is the case for the southern blue gum boards. For the high-density samples, the bending MOR of the finger jointed samples was more than twice less than the bending MOR of the boards. These reflects some adhesion challenges also outlined in the failure modes and the wood failure percentages of the dry and wet finger jointed samples. However, strength values closer to the unjointed boards were found in the literature for finger jointed blue gum boards (González-Prieto, et al., 2022, Lara-Bocanegra, et al., 2017). Additional tests are recommended to understand which parameters must be varied to obtained satisfactory results for the southern blue gum boards and pass the requirements set in AS 5068 (2006) for adhesive bond durability.

Additionally, it is worth mentioning that Faircloth, et al. (2023) evaluated a series of hardwoods (spotted gum – *Corymbia citriodora*, and Darwin stringybark – *Eucalyptus tetrodonta*) finger joints and found similar challenges as above for their bond durability when assessed against Clause 8.3 of AS 5068 (2006). An alternative assessment method was developed consisting of reconditioning samples back to 12% moisture content after being exposed to the bond durability procedure from AS 5068 (2006), and prior to testing. Faircloth, et al. (2023) measured a reversal in the losses of the bending strength between 56% and 88% (depending on the adhesive type and joint size) when compared to the measured bending strength of samples tested directly after exposure to the durability procedure. However, while the bending strength was affected by reconditioning, the measured wood fibre percentages remained low. This study suggested that the joint performance of some hardwoods is not accurately reflected in the measured wood fibre after joint separation. This same line of thinking could be applied to the southern blue gum finger joints, allowing for the joints to be potentially considered fit for purpose through an alternative assessment process.

Regarding the radiata pine finger jointed samples, the RF samples passed the bond durability requirements in AS 5068 (2006) for RF but the PUR samples failed due to one sample showing a low wood failure percentage of 15% despite the other two samples having a percentage greater than 50%. This result may be attributed to a manufacturing error.

5.3.5.3 Mechanical properties

Table 60 summarises the average and characteristic mechanical properties for the tested GLT beams. The values for each test are also provided in the table. Failure for all bending tests developed at a finger joint in the tension zone (Figure 71 (a)), with the third tested southern blue gum beam failing at two finger joints closely spaced in two proceeding laminates (Figure

71 (b)), likely reflecting the low bending MOR value for that test. Two out of the seven (28.6%) tested shear beams experienced shear failure (Figure 72 (a)), with the remaining five beams failing in bending with failure developing at a finger joint (Figure 72 (b)). The failure developing at the finger joints reflects both (1) the finger jointing challenges, due to the cupping of the southern blue gum boards encountered during the manufacturing of the GLT beams, challenges which can be overcome as developed in Section 6.3.3, and (2) the difficulty in bonding the southern blue gum finger joints in the trials performed as part of this report, with the results provided in Section 5.3.5.2. This premature failure mode reduces the bending and shear strengths.

The average moisture content of the tested GLT beams was measured as 12.6% with a CoV of 3.8%.

***Table 60**: Average and characteristic mechanical properties of the manufactured and tested GLT (CoV in % given in brackets).*

GLT type	Test ID	Bending MOE (MPa)	Bending MOR (MPa)	Shear strength (MPa)
Southern blue gum	1	17,738	50.2	6.3
	2	20,080	45.2	6.0
	3	18,921	32.9	6.9
	4	19,889	59.0	5.9
	Average	*19,157 (5.6)*	*46.8 (23.3)*	*6.3 (6.9)*
	Characteristic	*18,727*	*23.0*	*5.2*
Hybrid	1	18,170	48.9	4.2
	2	15,490	35.1	4.5
	3	16,408	49.9	6.6
	Average	*16,689 (8.2)*	*44.6 (18.6)*	*5.1 (25.1)*
	Characteristic	*16,048*	*23.6*	*2.4*

(a) *(b)*

***Figure 71**: Failure modes observed for the bending tests of the GLT beams, (a) typical failure mode developing at a finger joint and (b) third southern blue gum beam failing at two finger joints closely spaced.*

In terms of characteristic values, Table 61 provides the GL grade in AS 1720.1 (2010) achieved for each measured mechanical property, and the resulting GL grade, i.e., representing the minimum of all grades. In terms of bending MOE, the southern blue gum and hybrid GLT achieved GL18 and GL13 grades, respectively, i.e., equal to or better than the targeted grades.

However, due to the beams tested in bending prematurely failing at a finger joint, the bending characteristic value for the two GLT types was only GL10. Higher grades are to be expected if the bonding of the southern blue gum finger joints can be improved and pass the requirements set in AS 5068 (2006) for adhesive bond durability. In the literature, Martins, et al. (2020) and Lara-Bocanegra, et al. (2020) reported that a GL18 bending strength can be achieved for southern blue gum GLT (Section 2.4.2.1). However, in view of these results and as the bending MOR was also the limiting factor in the simulations, it is recommended to manufacture and test new beams after solving the bond durability of the southern blue gum finger joints.

(a) (b)

***Figure 72**: Failure modes observed for the shear tests for the GLT beams, (a) shear failure (2 out of 7 beams) and (b) bending failure mode developing at a finger joint (5 out of 7 beams).*

In terms of shear strength, while the southern blue gum GLT achieved a GL18 grade, the hybrid GLT did not achieve a grade. The latter is due to the low number of tests performed associated with a high coefficient of variation for those three tests which significantly lowered the shear strength characteristic value in the methodology described in EN 14358 (2016). It is likely that this characteristic value would increase if more tests were performed.

***Table 61**: Average and characteristic mechanical properties of the manufactured and tested GLT (CoV in % given in brackets).*

GLT type	Bending MOE grade	Bending MOR grade	Shear strength grade	Overall grade
Southern blue gum	GL18	GL10	GL18	GL10
Hybrid	GL13	GL10	< GL8	< GL8

5.4 Concluding remarks

This section presented (1) the processing of the southern blue gum and radiata pine logs into sawn boards, (2) the characterisation of those boards, both in terms of mechanical properties and characteristics influencing the manufacturing of GLT beams, (3) scenarios of potential GLT products, with associated volumes, which can be manufactured from the studied resources, and (3) the tests results of GLT manufactured from the sawn boards. In total 124 billets were sawn, resulting in 909 boards.

The key findings of the section can be summarised as follow:

- Planing was efficient in removing the large spring and cup imperfections of the southern blue gum boards, with 72% and 82% of the boards having a spring less than or equal to 2 mm, and a cup less than or equal to 1 mm, respectively, after planing.
- 20% of the southern blue gum boards had high acoustic MOE and density values, i.e., greater than 21,000 MPa and 850 kg/m^3, respectively. For radiata pine, 20% of the boards had acoustic MOE and density values greater than 10,700 MPa and 465 kg/m^3, respectively.
- Characteristics, such as the presence of gum veins, resin pockets, splits, knots and wanes/wants were quantified, providing information on the suitability of the resources for GLT manufacturing based on individual manufacturer's criteria.
- Regarding the mechanical performance of the boards:
  - The tensile, compressive, and bending strengths showed some correlation with the density while the shear strength did not.
  - The tensile strength of the radiata pine boards was low and less than 30 MPa, while high MOE southern blue gum boards reached tensile strength greater than 100 MPa.
  - The compressive strength of the radiata pine boards ranged between 10 MPa and 30 MPa, while compressive strengths up to 70 MPa were encountered for the southern blue gum boards.
  - The bending strength of the radiata pine boards ranged between 20 MPa and 100 MPa, while the bending strength of the southern blue gum boards ranged between 40 MPa and 180 MPa.
  - The average shear strength of the radiata pine and southern blue gum boards was 8.8 MPa and 12.4 MPa, respectively.
- The simulations indicated that GL18 and GL13 grades in AS 1720.1 (2010), as targeted by the market study, could be achieved out of the resources in terms of characteristic MOE and using the right construction strategies. The simulations also indicated that the bending strength may be the limiting factor to achieve the targeted grades.
- On average 41.5% and 46% of the southern blue gum and radiata pine logs, respectively, were recovered into green boards. The net board recovery, reflecting the recovery from logs to finished GLT products, was estimated at 12% and 21.6% for southern blue gum and radiata pine, respectively. These values are consistent with the literature.
- Regarding gluing southern blue gum boards for GLT manufacturing:
  - High density (> 800-850 kg/m^3) southern blue gum boards were found difficult to glue.
  - RF performed better than PUR and is recommended in the manufacturing of southern blue gum GLT.
  - When the boards were conventionally planed before gluing, high density GLT samples failed the glueline integrity requirements in AS/NZS 1328.1 (1998) for both PUR and RF. Planing and sanding the boards before gluing and using RF were found to pass these requirements. This surface preparation method is therefore recommended but requires further validation on a higher number of samples.
- All manufactured and tested southern blue gum finger joints failed the bond durability requirements in AS 5068 (2006), with low wood failure percentages for both PUR and RF. The strength values were low as well. While the low wood failure percentages are consistent with the literature, higher strength values were reported in the literature. Additional work is needed to understand how southern blue gum finger joints should be manufactured to pass the bond durability requirements in AS 5068 (2006) and therefore allowing the resource to be used in GLT beams.
- Regarding the manufactured and tested GLT beams:

- In terms of MOE, the southern blue gum and hybrid beams achieved GL18 and GL13 grade in AS 1720.1 (2010), respectively, and meet the targeted markets.
- However, the characteristic bending strength for both the southern blue gum and hybrid GLT was low due to the beams prematurely failing at the finger joints. This resulted from challenges encountered in the manufacturing (Section 6) and the difficulty in finger jointing southern blue gum boards, as summarised in the dot point above. However, the literature reported that higher bending strength can be achieved for the GLT beams tested. It is recommended to manufacture and test new beams after solving the bond durability of the southern blue gum finger joints to confirm the bending strength of the beams.
- In terms of shear strength, a GL18 grade was obtained for the southern blue gum GLT beams, while a GL10 grade was obtained for the hybrid beams. The latter grade is mainly reflected by the low number of tests associated with a high coefficient of variation significantly lowered the shear strength characteristic value. It is likely that this characteristic value would increase if more tests were performed.

6 Full scale GLT production trial

6.1 Foreword

This section reports on the outcomes of a full-scale production trial, manufacturing the GLT beams tested in Section 5 in an industrial setting. It aims at providing feedback to the steering committee on how the resources performed in a commercial facility, offering information that could support investment. Feedback was obtained from the staff and management team of the commercial facility and observations were made by the authors during the manufacturing process. The feedback obtained and observations made on the different manufacturing phases are reported and discussed in this section. General comments on the final products provided by the management team of the commercial facility are also provided in this section.

6.2 General

6.2.1 Boards used in the manufacture

As developed previously in the report, the boards recovered from the sawing component of the project were used for different purposes before GLT manufacturing, including:

- The boards aimed to be dressed to a cross-section of 42 mm × 19 mm were disregarded as too small for material testing and GLT manufacturing.
- 120 and 240 radiata pine and southern blue gum boards, respectively, aimed to be dressed to a cross-section of 86 mm × 19 mm were randomly selected for material mechanical property testing.
- Additional boards were selected based on density for gluing trials.

After the above work was conducted, approximately 95 and 235 radiata pine and southern blue gum boards, respectively, were left for the full-scale manufacturing of GLT beams as detailed in this section. These boards were a mix of boards aimed to be dressed either to a cross-section of 68 mm × 19 mm or 86 mm × 19 mm. The density of the boards was measured to sort them into packs based on the target construction strategies discussed in Section 6.2.2.

6.2.2 GLT beams to be manufactured

As discussed in Section 5.2.4, the main targeted GLT products are GL18 and GL13. The results of the numerical simulations in Section 5.3.4 and the MOE of the tested beams in 5.3.5.3 indicate that such products can be potentially manufactured. However, based on the available boards, the simulations described in Section 4.2.2 showed that the optimum use of the material (i.e., to have enough material to produce the two GL grades) would produce southern blue gum GL17 and hybrid GL13. These two grades were then targeted instead in the full-scale production trial to manufacture 209 mm deep × 65 mm wide × 6.3 m long GLT beams, with each beam manufactured from 11 × 19 mm thick lamellas. Each beam was to be cut in two, to produce two specimens to be tested in bending and shear.

The construction strategies for the two types of beams are presented in Table 62. The boards were sorted into four groups using the density cut-off values shown in Table 62 corresponding to the inner and outer lamellas of the two grades. The boards were then stacked to be shipped to the commercial facility (see Figure 73).

Table 62: Expected grades and associated construction strategies for 209 mm deep × 65 mm GLT beams to be manufactured in the full-scale production trial.

GLT grade	Lamellas	Species	Density range
GL17	Top two (outer)	Southern blue gum	> 820 kg/m^3
	Seven inner	Southern blue gum	< 750 kg/m^3
	Bottom two (outer)	Southern blue gum	> 820 kg/m^3
GL13	Top two (outer)	Southern blue gum	> 750 kg/m^3 and < 820 kg/m^3
	Seven inner	Radiata pine	Any
	Bottom two (outer)	Southern blue gum	> 750 kg/m^3 and < 820 kg/m^3

Figure 73: Undressed southern blue gum and radiata pine boards strapped in groups and ready to be shipped.

6.2.3 Warrnambool Timber Industry

The GLT beams were manufactured at Warrnambool Timber Industry (WTIBeam) in Dennington, Victoria. WTIBeam was founded in 1988 and specialises in the manufacturing of GLT. The company is one of the largest manufacturers of GLT beams in Australia using only Australian timbers, with the hardwood species being predominately Victoria ash (*Eucalyptus delegatensis* and *Eucalyptus regnans*) and Tasmanian oak (*Eucalyptus delegatensis, Eucalyptus obliqua* and *Eucalyptus regnans*). WTIBeam management serves on various Australian Standards and working groups through the Glue Laminated Timber Association of Australia (GLTAA).

6.3 Manufacturing of the GLT beams

6.3.1 Overall process

A typical production process, as outlined in the GLT handbook (Swedish Wood, 2024) and reproduced in Figure 74, was followed in the production trial with the adhesive commonly used by WTIBeam.

The main steps consisted of:

- Strength grading.
- Finger-jointing short lengths into lamellas.
- Planing of lamellas.
- Glue application and pressing.
- Planing of final product.

Feedback obtained from WTIBeam staff and management team, as well as observations made, will be discussed hereafter for each of the above steps.

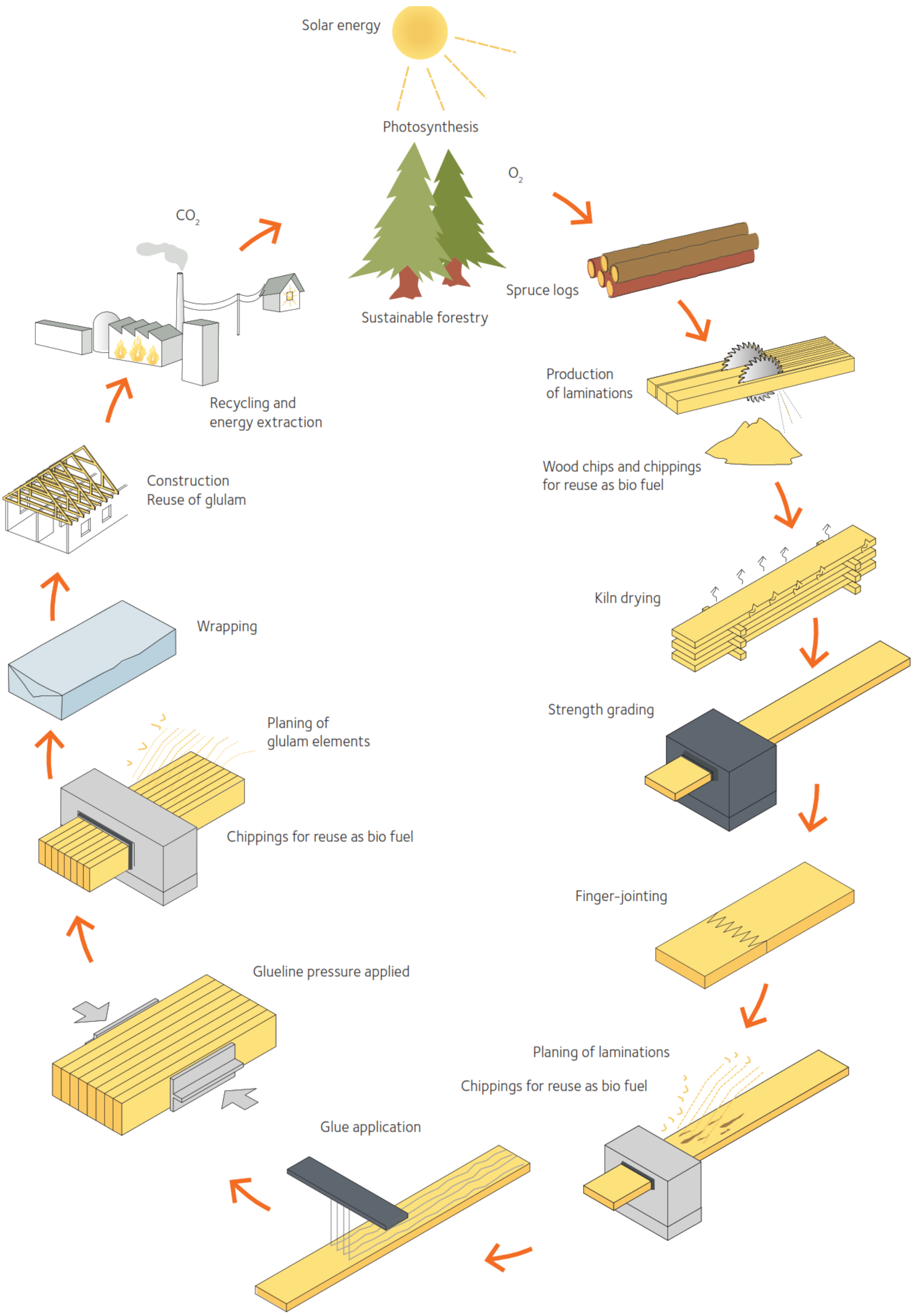


Figure 74: Schematic of GLT production (Swedish Wood, 2024).

As the boards delivered to WTIBeam were of different widths, they were first sawn to a nominal width of 75 mm using a multi-rip saw, as shown in Figure 75, before being graded. In the process, wane and other defects were removed from the boards where possible. Note that this process is not typically performed in commercial production as the mill would deliver 75 mm wide sawn boards to produce the 65 mm wide GLT beams and was only performed due to the width of boards sawn as part of the project. By limiting the large spring variation present in the southern blue gum boards, the process allowed straighter boards than would be encountered from southern blue gum to be used in subsequent manufacturing stages (note that the spring distribution of the southern blue gum boards is presented in Section 5.2.2.2.1). Therefore, WTIBeam highlighted that if a typical feedstock of 75 mm wide sawn southern blue gum boards was delivered (i.e., without prior ripping), the resource would present higher level of spring and would generate higher wastage than for the resources commonly processed by the company.

Figure 75: Boards being ripped to a width of 75 mm in a multi-rip saw.

6.3.2 Strength grading

As commonly practiced in the manufacturing of GLT (Derkowski, et al., 2022, Ong, 2015, Ong, et al., 2022, TLB, 2015), the boards were cut into shorter lengths to remove strength reducing characteristics, such as knots, splits and gum vein, following the grading method used by WTIBeam. Figure 76 shows the grading process in action.

Figure 76: Strength grading process in action.

In GLT manufacturing and as there is a strong correlation between strength, stiffness, and density in the timber material, high-density boards are typically used as the outer lamellas, leaving low-density boards best positioned as inner lamellas. However, high-density boards with large strength reducing characteristics may be used for both inner and outer lamellas after being cut into shorter lengths. The high-density short lengths but with large strength reducing characteristics being downgraded to inner lamellas.

In the trial, the boards were already sorted by density as mentioned in Section 6.2.2, and short lengths of high-density with large strength reducing characteristics were not downgraded to inner lamellas but disregarded. This process ensured tracking the composition of the GLT beams to validate the simulations. This will, in turn, enable reporting in the final milestone which GLT grades can be manufactured from the resources and in what proportion. While this variation of the normal operating process of WTIBeam does not affect the resulting GLT grade, it affected wastage. Despite wastage not being recorded during the grading process, staff at WTIBeam reported that this process generated a significantly higher wastage value than typically encountered in their day-to-day operation. However, they believe that the resources are not substantially different in terms of strength reducing characteristics from the resources they are regularly working with and if their usual grading process was followed, waste values for this manufacturing stage would not be different from that which is usually encountered.

6.3.3 Finger-jointing into lamellas

The short lengths for the outer and inner lamellas were then finger jointed together in lengths of 6.3 m. 10 mm finger joint cutters were used with polyurethane (PUR) single-component adhesive (681 PUR from Jowat adhesives (2019)).

While the radiata pine boards were able to be finger jointed with no disruption to the manufacturing process, southern blue gum boards presented difficulties for the following reasons:

- The boards presented a significant amount of cupping (Figure 77) which led to some boards splitting when they were clamped by the finger jointing machine before pressing the joints together. This splitting resulted in finger misalignments and challenges jointing two short lengths together.
- The southern blue gum boards presented thickness variations, likely due to variation in drying shrinkage coefficients between boards and the presence of collapse, a common phenomenon in southern blue gum dried boards (de Fégely, 2004b, Hansmann, et al., 2008). This thickness variation also presented challenges to producing long lamellas.

WTIBeam provided the following feedback on these difficulties:

- It is believed that if thicker boards were used, i.e., using traditional 35 mm to 45 mm thick lamellas, cupping would be reduced.
- In any cases, if cupping is still an issue in thicker boards, the boards can be pre-dressed to remove some of the cupping, reducing splitting challenges in the finger jointing process. While this would be an additional step to normal operations it was deemed not to considerably impact the production operation overall. In such a case, boards with extra few millimetres in thickness would ideally be sawn to consider the material removed during pre-dressing. However, this operation would increase wastage.
- The variation in thickness would eventually have to be controlled by the sawmill, such as recovering collapse through steam reconditioning (Brennan, et al., 2004). However, if boards need to be pre-dressed as per the previous dot point, the variation in thickness can be managed during this phase.

Overall, WTIBeam was not overly concerned with the challenges encountered during the finger jointing process as solutions exist for 35 mm or 45 mm thick lamellas which would traditionally be used in their commercial production.

Figure 77: Cupped southern blue gum boards.

Figure 78 (a) presents the finger jointing process, while Figure 78 (b) shows dressed finger jointed boards, illustrating board splitting due to excessive cupping and the associated finger jointing challenges.

(a)

(b)

Figure 78: (a) Finger jointing process and (b) dressed finger jointed boards with the bottom board showing splitting due to excessive cupping resulting in finger misalignments.

6.3.4 Planing of lamellas

The 6.3 m lamellas were dressed to the nominal thickness of 19 mm. No challenges were reported during this phase with no disruption to the usual manufacturing process. Figure 79 shows the lamellas ready to be dressed.

Figure 79: Lamellas ready to be dressed to a nominal thickness of 19 mm.

6.3.5 Glue application, pressing and planing of GLT

One-component PUR adhesive (681 PUR from Jowat adhesives (2019)) was applied to the dressed lamellas by a curtain type glue applicator. The lamellas were then positioned in the press (Figure 80). No challenges were reported during these phases with no disruption to the usual manufacturing process. All adhesive application, target open and closed assembly times, press pressure, and duration of time in press, remained consistent to the usual manufacturing process.

Figure 80: Lamellas with PUR ready to be pressed into a GLT.

After the adhesive has cured under pressure, the GLT beams were dressed to a final width of 65 mm. No challenges were reported during this phase. In total, there were enough material to manufacture four of GL17 and three of GL13. The final GLT beams are shown in Figure 81.

Figure 81: Final GLT beams.

6.4 Additional feedback provided by WTIBeam

The following points relevant to the production trial and final products were mentioned by WTIBeam management team after the manufacturing of the beams:

- The southern blue gum was seen as a suited resource for GLT manufacturing as it has no application in the framing sector due to the presence of strength reducing characteristics. As mentioned in Section 6.3.2, GLT offers the possibility to remove these characteristics to manufacture high strength and high stiffness lamellas.
- However, due to large variations in bow, spring and cupping, the southern blue gum boards are less suitable for automation and high-speed production (i.e., large scale GLT plants), but a better fit for more manual GLT operations. Due to these distortions, wastage would also be significant through the entire manufacturing process, more than what is currently encountered by WTIBeam.
- To allow for better recovery and to minimise waste, rough sawn timber can be provided by the mill, resulting in less wastage for the mill and an increased volume of resources to work with for the GLT plant.
- GL18 should be the targeted product grade for the southern blue gum resource as a lower grade manufactured from any hardwood resource would not be accepted by the market. The product would be too heavy relative to softwood beams of the same grade.
- The hybrid product is not recommended to be manufactured. Due to the different values of the shrinkage coefficients of the radiata pine and southern blue gum species, the boards will expand and shrink at different rates when exposed to changing atmospheric environments (moisture contents). This will result in non-uniform cross-sectional shapes which will not be accepted by the clients.
- The final product presents well and is considered a viable product that could be sold.

6.5 Concluding remarks

This section presented the outcomes of a full-scale production trial, manufacturing targeted GL17 southern blue gum and GL13 hybrid (combination of southern blue gum and radiata pine boards) GLT beams from logs traditionally processed as pulpwood. The following key points summarise the observations made, and the feedback obtained from the management team and staff at WTIBeam on how the resources performed in a commercial facility:

- In terms of strength reducing characteristics, the resources are not significantly different from those WTIBeam typically processes. While not recorded, it was believed that wastage during the grading process, if the normal WTIBeam approach was followed, would not be different than usually encountered by the company.

- However, due to large variations in bow, spring, and cupping of the southern blue gum boards, WTIBeam reported that wastage would be significant through the entire manufacturing process. Better recovery can be achieved with the mill supplying rough sawn timber, resulting in less wastage for the mill and an increased volume of resources to work with for the GLT plant.
- Due to the lower than usual thickness of the boards used in the trial and the large amount of cupping present in the southern blue gum boards, finger jointing short lengths of southern blue gum presented challenges. Some of the boards split when clamped by the finger jointing machine before pressing the joints together, resulting in finger misalignments and longitudinal splitting. However, WTIBeam believed that if thicker boards, as usually processed, were used, cupping would be less and splitting would be limited or would have not occurred. Moreover, cupping can also be removed by planing the boards before finger jointing. This potential additional manufacturing step was not deemed to considerably impact the production operation but would increase wastage. In summary, the encountered finger jointing challenges of the southern blue gum boards were more attributed to the lower than usual thickness of the boards rather than the resources itself. No challenges were reported in finger jointing radiata pine boards.
- No challenges were reported in planing the lamellas, glue spreading, pressing and final planing of the GLT beams.
- However, due to large variation in bow, spring and cupping, WTIBeam commented that the southern blue gum resource is less suitable for automation and high-speed production of large scale GLT plants, but is a better fit for more manual GLT operations.
- WTIBeam believed the southern blue gum resources is suited for the manufacturing of GLT beams as it has no market in the framing sector and its strength reducing characteristics can be removed to manufacture high stiffness and strength lamellas.
- Hybrid GLT is not recommended by the company due to the difference in unit-tangential-movement during moisture uptake of the hardwood and softwood species which would affect the cross-sectional shape when subjected to moisture variations and the product not being accepted by the market.
- GL18 should be the target for southern blue gum GLT as hardwood beams of lower grade are too heavy for the market to be installed without lifting equipment.
- WTIBeam was pleased with the final southern blue gum GLT beams and believed it is a product which could be readily sold.

7 Conclusion

This report presented the outcomes of (1) the characterisation of rotary peeled veneers and sawn boards, and (2) the manufacturing and testing of LVL and GLT, as part of the *ATMAC – Splinters to structures project* which aimed at promoting the establishment of an Australian EWP manufacturing platform for the Green Triangle's lesser value resource. These resources consist of southern blue gum, and T1 and T2 radiata pine logs. As part of the project:

- Sixty 15-year-old and sixty 19-year-old southern blue gum trees were harvested near Hamilton in Victoria. The plantations were established and grown for woodchips, with no prior thinning or pruning.
- Thirty T1 (11-year-old) and thirty T2 (18-year-old) radiata pine logs were harvested near Mt. Gambier in South Australia. The plantations were established to provide saw logs for sawn timber production.

Two-thirds and 1/3 of the logs were rotary peeled into veneers and sawn into boards, respectively, at the Salisbury Research Facility of the Queensland Department of Agriculture and Fisheries, near Brisbane. In total, (1) 339 billets were rotary peeled which resulted in 2,164 veneer sheets, and (2) 124 logs were sawn which resulted in 909 boards. The characteristics of the veneers and sawn boards were analysed and presented, including visual grading (veneers), MOE and density distributions (veneers and boards), and other select mechanical properties (boards). LVL and GLT, corresponding to products with mechanical properties valued by the market, were modelled, manufactured and tested. Large-scale GLT samples were manufactured at Warrnambool Timber Industry (WTIBeam) to provide feedback on the suitability of the resources to be handled in an industrial setting. The LVL samples were manufactured at the Salisbury Research Facility. Recovery rates were also estimated for all manufacturing processes.

While the study showed that LVL valued by the market can be manufactured without significant technical challenges, additional work is still required for the GLT to be considered commercially. As explained below and consistent with the literature review, finger jointing southern blue gum boards proved challenging, resulting in the finger joints failing the bond durability requirements in AS 5068 (2006). Further work on gluing the southern blue gum boards is therefore recommended, especially for finger jointing, to be confident that GLT beams manufactured with the studied resources can pass the certification requirements in the relevant Australian standards and meet the targeted grades relevant to the market.

The key findings of this study are summarised as follow:

- From the literature review:
  - Tension wood creates challenges in procession Southern blue gum logs.
  - Twin-saws were recommended when processing small diameter eucalyptus logs. The use of chipper canters was 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.
  - High graded LVL and GLT can be achieved from southern blue gum resource. Hybrid LVL and GLT present an opportunity to maximise the use of hardwood and softwood resources by manufacturing a range of structural products of different grades.

- From rotary peeling the logs into veneers and the associated manufactured LVL:
  - Visual D-grade veneers dominated the feedstock for both the southern blue gum and radiata pine, limiting the manufacturing of appearance veneered-based products.

- The average MOE for the peeled veneers was 15,690 MPa, 20,119 MPa, 8,131 MPa and 10,502 MPa for the 15-year-old southern blue gum, 19-year-old southern blue gum, T1 radiata pine and T2 radiata pine logs, respectively.
- The 19-year-old southern blue gum logs provided veneers with a MOE about 26% higher on average than the 15-year-old blue gum logs.
- The veneer recovery values were consistent with the literature.
- The southern blue gum resource offered enough high MOE veneers to mainly manufacture higher performance LVL (LVL15 and above), with low volumes of commodity LVL12.
- The hybrid LVL is well suited to manufacture large volumes of commodity LVL12, while still enabling lower volumes of high performance LVL (LVL15, LVL18 or LVL21) to be manufactured, as valued by the market.
- Type A bonds can be achieved between veneers using a phenol-formaldehyde type resin and increasing the hot press pressure to 2 MPa for the southern blue gum LVL yielded more consistent conforming bond quality.
- At similar characteristic MOE, the manufactured and tested LVL had similar or higher characteristic strength values than commercially available LVL, and F27 and F34 grades sawn timbers.
- High stiffness (with a characteristic MOE greater than 20,000 MPa) and high strength (with a characteristic edge bending strength greater than 120 MPa) LVL were successfully manufactured.

• From sawing the logs into boards and the associated manufactured GLT:

- Planing was efficient in removing the large spring and cup imperfections of the southern blue gum boards.
- 20% of the southern blue gum boards had high acoustic MOE and density values, i.e., greater than 21,000 MPa and 850 kg/m^3, respectively. For radiata pine, 20% of the boards had acoustic MOE and density values greater than 10,700 MPa and 465 kg/m^3, respectively.
- The simulations indicated that GL18 and GL13 grades in AS 1720.1 (2010), as targeted by the market study, can be achieved out of the resources in terms of characteristic MOE and using the right construction strategies. The simulations also indicated that the bending strength may be the limiting factor to achieve the targeted grades.
- The board recovery values were consistent with the literature.
- High density (> 800-850 kg/m^3) southern blue gum boards were found difficult to glue. Sanding post-planing the boards before gluing and using resorcinol formaldehyde was recommended in the manufacturing of southern blue gum GLT to pass the glueline integrity requirements in AS/NZS 1328.1 (1998). This recommendation needs to be further confirmed on a higher number of samples.
- Southern blue gum finger joints failed the bond durability requirements in AS 5068 (2006), with low wood failure percentages, when glued with either resorcinol formaldehyde or polyurethane. Additional work is needed to understand how southern blue gum finger joints should be manufactured to pass the bond durability requirements and therefore allowing the resource to be used in GLT beams. An alternative assessment process could also be thought.
- In terms of MOE, the tested southern blue gum and hybrid GLT beams achieved GL18 and GL13 grade in AS 1720.1 (2010), respectively, and meet the targeted markets. However, the characteristic bending strengths of the two types were low due to the beams prematurely failing at the finger joints. This resulted from challenges encountered in the manufacturing and the difficulty in finger jointing southern blue gum boards, as summarised in the dot point above. However, the

literature reported that higher bending strength can be achieved for the type of GLT beams tested. It is recommended to manufacture and test new beams after solving the bond durability of the southern blue gum finger joints to confirm the bending strength of the beams.

- From the manufacturing undertaken of GLT beams in a commercial facility, the following feedback was obtained:
  - To minimise waste and optimise recovery, rough sawn timber should be provided by the mill, resulting in less wastage for the mill and an increased volume of resources to work with for the GLT plant.
  - Due to the boards used in this trial being thinner than normally targeted in GLT manufacturing, and the large amount of cupping present in the southern blue gum boards, finger jointing short lengths of southern blue gum presented challenges. It was believed that if thicker boards were used, the finger jointing operation would be similar to normal commercial operations. Moreover, the cupping which resulted in some of the finger jointing challenges could be removed by planing the boards before finger jointing. This potential additional manufacturing step was not deemed to considerably impact the production operation but would increase wastage. No challenges were reported in finger jointing radiata pine boards.
  - If the southern blue gum boards need to be planed to remove cupping before finger jointing and to accommodate for thickness variations, thicker boards would need to be delivered by the mill.
  - No challenges were reported in planing the lamellas, glue spreading, pressing and final planing of the GLT beams.
  - Due to the high level of distortions present in the southern blue gum boards, the resource was deemed less suitable for automation and high-speed production of large scale GLT plants, but is a better fit for more manual GLT operations.
  - The commercial facility believed that southern blue gum is a resource suited for the manufacturing of GLT beams, as the resource has no market in the framing sector and the presumably low-grade material containing strength reducing characteristics can be removed to manufacture high stiffness and high strength GLT lamellas.
  - Hybrid GLT was not a preferred product by the commercial facility due to the difference in unit-tangential-movement during moisture uptake of the southern blue gum and radiata pine species. This would affect the cross-sectional shape when subjected to moisture variation and the product not being accepted by the clients.
  - The commercial facility mentioned that GL18 beams should be the target for the southern blue gum GLT as hardwood beams of lower grade are too heavy to install in the residential market without lifting equipment. Preliminary simulations estimated that using the 40% denser southern blue gum boards could result in GL18 graded beams.
  - The commercial facility believed that a southern blue gum GL18 is a viable product and could be sold readily.

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Appendix: LVL commercial production notes

The following are key LVL production notes relevant to the commercial manufacturing of LVL.

Peeling:

- The southern blue gum and radiata pine logs can be peeled using standard commercial lathes without difficulty, with the use of spindleless lathe recommended to increase the recovery from the logs.
- Veneer recovery was as expected when compared to other similar resources.
- Visual grade D veneers dominated resulting that no visual appearance products can be manufactured only using these resources.

Drying:

- No difficulty was found during the drying process of the veneers in a conventional jet box veneer drying system.
- The veneers dried as expected.

Gluing:

- Type A bond between veneers, as required in Clause 2.5 of AS/NZS 4357.0 (2022) for all structural LVL products, was obtained using phenol-formaldehyde type resin (CASCOPHEN P6638 manufactured by Hexion (2024)).
- This resin type is commonly used in the manufacture of LVL and plywood.
- For hybrid LVL products (alternate of southern blue gum and radiata pine veneers), Type A bond to AS/NZS 2098.2 (2012) was obtained using the parameters recommended by the adhesive manufacturer.
- For southern blue gum LVL, Type A bond to AS/NZS 2098.2 (2012) was obtained if the hot-press pressure was increased from 1.2 MPa (recommended) to 2 MPa. All other parameters recommended by the adhesive manufacturer were followed.
- Apart from increasing the hot-press pressure for the southern blue gum LVL products, the LVL were able to be manufactured without alteration to the standard commercial process.

Characteristics of the final products:

- The southern blue gum resources offered enough high MOE veneers to manufacture:
  - Large volumes of high performance southern blue gum LVL products, with low volumes of commodity LVL.
  - Large volumes of commodity hybrid LVL products, while still enabling lower volumes of high performance LVL.
- A producer can customise their recipes to manufacture different ranges of products from high value southern blue gum LVL to commodity hybrid for instance.
- At similar MOE, the commodity manufactured LVL performed as well or better than commercial LVL.
- The high performance LVL can be a direct substitute to high strength sawn timber F grades (F27 and F34 grades).

Overall notes:

- High stiffness/strength and commodity LVL can be successfully manufactured.
- No technical challenges in manufacturing the product were encountered.