Department of Agriculture, Fisheries and Forestry

High value timber composite panels from hardwood plantation thinnings

R.L. McGavin, H. Bailleres, F. Lane and J. Fehrmann

May 2013

This publication has been compiled by R.L. McGavin, H. Bailleres, F. Lane and J. Fehrmann of Agri-Science Queensland, Department of Agriculture, Fisheries and Forestry.

Acknowledgements

The authors would like to take the opportunity to acknowledge the following organisations and individuals who contributed to the success of this study:

- The Department of Agriculture, Fisheries and Forestry (DAFF) for providing financial support to the project.

- The Forest and Wood Products Association (FWPA) for providing financial support to the project (reference: PRB145-0809).

- The Engineered Wood Products Association of Australasia (EWPAA) for providing financial support to the project. Also to Mr Simon Dorries, General Manager, for extensive technical advice and valuable contribution during the project conception, planning and results interpretation. Also to the EWPAA technical team for assistance with adhesive bond evaluations.

- The Austral Plywood team including Scott Matthews and Stuart Matthews, joint CEOs, Gary Holmes, Sales and Marketing Manager, and Colleen Swifte, Production Manager who each provided extensive support to the project through access to production equipment and also very valuable technical input throughout the project life.

- HQ Plantations Pty Ltd for access and supply for plantation resources and specifically Ian Last, Manager Sustainability and Innovation and Leigh Kleinschmidt, General Manager Hardwood Plantations for technical advice and valuable contribution during the project conception and planning.

- Mr Peter Robinson formerly of BORAL Timber for extensive technical advice and valuable contribution during the project conception, planning and results interpretation.

- Momentive Specialty Chemicals including Klaus Haselhofer and Mark Nowicki for valuable technical input and participation along with the supply of adhesives for various adhesive trials.

- DAFF staff including Michael Kennedy, David Lee, John Huth, Eric Littee, Dan Field, Tony Burridge, Bill Atyeo, Adam Redman, Gary Hopewell, Kevin Harding (former employee), Martin Davies (former employee), Nick Kelly (former employee) for technical support, plantation material provision and sampling, processing, sample preparation and testing.

The support provided by the Queensland Department of Agriculture, Fisheries and Forestry through the provision of the infrastructure and equipment at the Salisbury Research Facility is acknowledged as critical to facilitate much of the testing necessary to complete studies of this nature.

Contents

Summary

Identifying processing strategies and products that suit young plantation hardwoods has proved challenging with low product recoveries and/or unmarketable products being the outcome of many trials. The production of rotary veneer has been demonstrated as an effective method for converting plantation hardwood trees. Across nine processing studies that included six different plantation species (Dunn's white gum, spotted gum, Gympie messmate, spotted gum hybrid, red mahogany and wester white gum), simple spindleless lathe technology was used to process 914 veneer billets totally 37.4m^3.

The recovery of green veneer ranged between 64% – 79% while gross recovery ranged between 55% – 65%. The net recovery of veneer, which represents the volume of saleable veneer ranged between 45% – 53%. These recovery values are up to six times higher than what has been reported to be achieved from similar plantation resources when converted to sawn timber products.

A very high proportion of the recovered veneer meets the requirements of D-grade in accordance with Australian and New Zealand standard AS2269.0:2008 with a small proportion meeting the requirements of higher grade qualities. These results lend the hardwood veneer to be used in mainly non appearance structural products and/or core veneers. Resin pockets were the main reason for preventing veneers achieving a grade quality higher than D-grade. Opportunities potentially exist to review the grading standard as the grade limiting thresholds for resin pockets were probably developed for a softwood resource and potentially unnecessarily penalises the hardwood veneer. Visual grading scenarios undertaken do highlight the complexity that exists with veneers containing multiple grade limiting defects. Further analysis and use of the grade quality scenarios has a great potential to guide forest management decisions and also product market strategies.

The hardwood veneer demonstrated stiffness properties (modulus of elasticity or MOE) that can meet or exceed that of mature plantation pine, despite being sourced from plantations at least half the age. Both spotted gum and Gympie messmate showed superior stiffness properties (average greater than16 000 MPa) followed by red mahogany, western white gum and Dunn's white gum (average of 13 700 MPa, 13 300 and 12 300 MPa respectively). The spotted gum hybrid had an average MOE of 11 700 MPa.

The testing of manufactured products demonstrated the potential of all the species to produce structural products. Low sample numbers for relevant construction strategies prevented the true potential from being recognised. The strategic mixing of softwood and hardwood veneers was well demonstrated with an increase of up to three stress grades being achieved. The use of hardwood veneers in this manner could provide a real benefit to Australian softwood panel producers who may currently struggle to manufacture higher stress grade products (which may be more profitable) from a softwood only resource.

An analytical mechanical model based on Laminated Plate Theory (LPT) was demonstrated to have valuable application in the prediction of panel properties from veneer MOE data measured acoustically. This tool has the potential to be a valuable aid to industry in determining the most effective and economic way to utilise available resources in the most effective construction strategies, targeting the most profitable products.

All species included in the study have a history of challenging bonding behaviour, especially spotted gum. The development of a phenol formaldehyde (PF) adhesive system was targeted as this adhesive allows for weather exposed structural products to be pursued. Under laboratory conditions, several PF adhesive systems under controlled manufacturing conditions did demonstrate satisfactory bond quality across all species. Spotted gum and

spotted gum hybrid proved to be the most challenging. Reliable, high quality bonds using melamine urea formaldehyde (MUF) proved challenging to achieve, despite many trials under very controlled conditions. The polyurethane adhesive trialled performed poorly. Additional studies are required to develop a complete understanding of the bonding behaviour of each of the species and the mechanisms preventing successful and reliable glue bonds. Further studies are also required to establish if the successful PF trials can be replicated in larger semi-industrial scale trials.

Various overlay systems were trialled to establish whether there may be opportunities for the hardwood veneer to used in plywood for forming concrete (known as formwood, formply etc). Preliminary results indicate that even thin overlay systems bond satisfactorily and adequately cover the defects commonly occurring in the hardwood veneer. Additional testing is required to confirm market suitability.

While the project has demonstrated that high quality veneer can be processed from young, fast-grown plantation hardwood and a range of veneer-based composite products can be manufactured with attractive structural qualities, additional research is necessary to establish the economic parameters necessary to ensure commercial profitability. In addition, an intensive market analysis is also required to determine which products and markets are available and the most suitable for the quality and quantity of hardwood veneer that may be available.

1. Introduction

The hardwood sector of Queensland's forest and forest product industries is undergoing significant change. Much of this change is due to reduced availability and/or reduced quality of the native forest resource for commercial harvesting purposes. Significant areas of native hardwood forests across Queensland are being progressively withdrawn from commercial harvesting and managed principally for conservation purposes.

Queensland's hardwood industry has been almost solely reliant on sourcing fibre from native forests. Many of the targeted species from Queensland's tropical and sub-tropical native forests have superior qualities such as very high mechanical properties and very high natural durability. For this reason, the obvious market for these species has been structural and weather exposed products. While the plantation softwood sector quickly dominated much of the light structural market (e.g. sawn framing) over recent decades, hardwood products have remained relatively unchallenged in heavy structural applications (e.g. bearers, girders, sleepers, poles etc.). A small per cent of this resource has also been used to supply other value added products such as decking, flooring, outdoor and indoor furniture etc.

While hardwood plantations are being established to provide industry with an alternative or supplementary resource, there are a range of factors which are preventing direct substitution for native forest sourced hardwood trees. Much research has been conducted in the last decade or so to describe and evaluate the emerging Queensland hardwood plantation resource. This research has included wood and mechanical properties evaluation, and processing and product oriented studies. In general, the research has identified many challenges with processing young plantation trees to produce traditional hardwood products. These challenges have major profitability implications for the plantation growers and processors. The inability to identify a clear strategy to profitably process plantation trees into a product with market demand has created a major impediment to increased investment in continued plantation establishment and suitable processing capacity in Queensland.

The manufacture of veneer-based engineered wood products has been identified as a potential area of opportunity. Some preliminary research activities (McGavin et al., 2006) have indicated that the conversion of plantation hardwood logs into veneer can yield significantly higher recoveries when compared to sawn timber processes. The resulting veneer is reported (Hopewell et al., 2008) to contain structural properties that are suitable for the manufacture of structural products (e.g. plywood, laminated veneer lumber etc) which are in demand by the building industry. This processing method is not without challenges. Reliable adhesive performance and suitable technology to process small diameter logs are among a range of issues requiring further exploration.

1.1. Objectives of the study

The project's objective was to explore the veneer and veneer-based engineered wood product manufacturing prospects for the hardwood species of primary interest for deployment in Queensland plantations. The study aimed to provide solutions to processing problems that arose and to characterise the properties of veneer-based engineered wood products produced from the plantation resource. At a higher level, it aimed to provide valuable data for incorporation into plantation economic models and thus to underpin favourable 'solid timber' hardwood plantation investment decisions, and consequently to contribute to the expansion of the plantation estate in Queensland.

The target resource for the study was *Eucalyptus* and *Corymbia* species that are currently preferred for hardwood plantations in Queensland. These included *E. cloeziana* (Gympie messmate or GMS), *E. dunnii* (Dunn's white gum or DWG), *E. pellita* (red mahogany or

RMY), *E. argophloia* (western white gum or WWG), *Corymbia citriodora* subsp. *variegata* (spotted gum or SPG) and *C. torelliana* x *C. citriodora* subsp. *variegata* hybrid (spotted gum hybrid or CH). Plantation ages of between eight and 15 years-old were targeted to represent early-to mid-age rotation thinnings.

The study aimed to build upon earlier exploratory work undertaken by the Queensland Department of Agriculture, Fisheries and Forestry's (DAFF's) Forestry Science group over the previous decade. This portfolio of earlier work included a number of small scale simple processing trials using industry available processing technologies and currently adopted methodologies to produce samples of plywood panels. These trials, while limited in scientific rigour preventing the provision of firm data for economic modelling or industry investment decisions, produced very valuable information providing an encouraging insight into the potential peeled recovery, grade quality and structural performance of the veneer and veneer-based composite products manufactured from plantation hardwoods. Also, the former work clearly identified that technical obstacles exist preventing the commercial production of plywood products with a young, fast-grown hardwood plantation resource. Problems with achieving reliable glue bonds, suitability of existing technology and identification of suitable process and manufacturing procedures to ensure a consistent high quality product required further detailed investigation.

Building on these previous experiences, this study targeted the use of specialised processing techniques and methodologies to provide solutions to technical problems and to generate the necessary data to support the economic conversion of hardwood plantations into high-value composite products.

1.2. Layout of the report

The report is comprised of several sections. Section 2 includes an overview of the issues faced by industry utilising the Queensland plantation hardwood resource and an overview of some of the recently completed veneer-based studies that provided the catalyst for this study. Section 3 provides the methodology adopted for the project including: plantation selection, material flow, wood quality appraisal, process and veneer quality assessment, product manufacture and quality measurement, and adhesive performance evaluation. Section 4 provides the results with discussion while Section 5 provides some concluding comments.

2. Processing challenges for hardwood plantations in Queensland

A significant amount of research has been completed since the mid 1990s to provide information and industry guidance on the establishment, management and utilisation of Queensland grown hardwood plantations. This has included a range of research activities that focused on describing the wood quality and mechanical properties of a range of candidate plantation species across a number of growing conditions at various ages. In addition, various processing and product oriented studies have explored methods to convert the resource into a range of existing and novel products. These studies have provided valuable data showing that in general, the wood from relatively young (<25 years-old) plantation grown sub-tropical and tropical hardwood species are lower in density, have a lower heartwood proportion, are smaller in diameter, have a shorter merchantable length, have lower mechanical properties and contain a higher proportion of defects when compared to mature wood from native-grown hardwood forests. These outcomes are not necessarily negative. A reduction in density for example has the potential to improve the ease of processing, and while diameters and merchantable lengths may be reduced, the plantation resource is more consistent which lends favourably to more mechanised and automated processing methods. While mechanical properties may be reduced, even at a relatively young age (<10 years old), plantation hardwoods can produce wood with mechanical properties far superior to mature, final harvest plantation softwoods.

Processing methods and suitability of the resource for current products is probably the most notable challenge for the industry in the transition from mature native forest hardwoods to a young plantation grown resource. While solid wood processing (sawn timber) of hardwoods has a long and successful history, the conversion of a plantation hardwood resource is proving most challenging. This is particularly true when using traditional processing methods and technology, and targeting traditional products. Smaller log dimensions, high proportions of juvenile wood, growth stresses and the high presence of knots etc. result in either being unable to cut traditional products at all (e.g. especially large dimension timber) or achieving a limited range with very low sawn recoveries. Previous studies (Leggate *et al* 2000) have indicated grade recoveries between 8% and 19% of log volume when sawn into flooring products (AS2796.2:2006). This is less than half of what would be expected from mature native forest conversion.

Recent international advances in small log sawmilling mainly tailored for the softwood industry may have some application in the processing of plantation hardwoods. The challenge that remains is the economic impacts of high capital investment, large volume throughput requirements, low recovery of product, and the matching of dimensions and qualities of sawn wood to markets. A potential key to success may be with engineered wood products such as glue laminated lumber (Glulam) whereby smaller dimension sawn pieces can be used in the manufacture of larger dimension products. Products such as glue laminated lumber manufactured from tropical and sub-tropical plantation hardwoods have the potential to create a niche market that capitalises on their superior mechanical properties (resulting in a smaller dimension beam or longer span for the same dimension), high natural durability (reducing or eliminating the need for preservative treatment) and/or superior natural aesthetic appeal. Other opportunities exist in the use of emerging thin-sawing techniques to produce attractive ‘overlays’ for products such as composite flooring. This allows the unique properties of these hardwoods such as extreme hardness and high aesthetic appeal to be maximised. However, high costs of production, low recovery rates, competition from other more easily converted forest resources (including Queensland’s native hardwood forest) and poorly established markets continue to make this approach economically challenging.

While veneer production from hardwood species being targeted for plantation development doesn't share the same long production history in Australia as sawn timber, recent research activities have indicated some potential. The Queensland Department of Agriculture, Fisheries and Forestry (DAFF) first began exploratory work in veneer processing of plantation hardwoods in the mid-1990s. Much of this early work focused on plantations with ages of around 30 years and older, which is outside the currently desired final harvest age being considered by plantation growers today of around 20 years. This earlier work did provide the critical first step in exploring the possibility of using Queensland grown hardwood plantation wood in veneer-based composite products. These activities were restricted by the limited availability of plantation resource and were restricted by a lack of knowledge regarding suitable process and manufacturing procedures. While the outcomes of these early activities did highlight problems with direct substitution of a hardwood resource into a predominately softwood focused process, they did indicate that solutions to many of the problems should be able to be overcome with dedicated research. Of most interest, the preliminary work did manage to produce sample plywood products with obvious marketable advantages such as high strength and high natural durability in comparison to the softwood processes being commercially operated in Queensland.

This was followed by a more focused study (McGavin et al, 2006) investigating utilisation options for thinnings from young hardwood plantations (e.g. less than 10 years old). This study was conducted in collaboration with Big River Timbers (BRT) in Grafton. A sample batch of north Queensland grown 8-year-old *E. pellita* (red mahogany) was processed through BRT's facility. Peeled veneer was dried before being manufactured into several test plywood panels in accordance with BRT's standard practise. Plywood panels then underwent a series of mechanical and glue bond tests to validate structural and performance properties. Testing indicated that the young wood could be bonded with B-bond adhesives with reasonable reliability and structural properties were marginally higher than expected from standard softwood products. This study, albeit being restricted to only a small volume of available logs, did further build confidence that veneer-based products can be manufactured from Queensland's hardwood plantations, even at previously unconceivable ages.

The trend of positive information led to a further scaled-up project which focused on north Queensland grown 15-year-old red mahogany (*E. pellita*) and 19-year-old Gympie messmate (*E. cloeziana*). In collaboration with key industry partners, samples of both species underwent peeling, grade quality assessment, seasoning, adhesive trials (both A-bond and B-bond) and structural properties testing of panels manufactured from plantation hardwood veneer and a mixture of plantation hardwood and softwood. This larger scale research activity provided further encouragement to plantation growers and processors with higher than expected grade recoveries being achieved (particularly for Gympie messmate), encouraging glue bond results for A-bond adhesives (a critical hurdle for the manufacture of exterior structural plywood) and structural properties that are superior to plywood products currently manufactured from plantation softwood.

While these trials continued to provide positive and encouraging results, they remained reliant on the use of existing industry adopted processing and manufacturing technologies, most of which are not designed or ideally suited to small diameter fast grown plantation hardwoods. The emergence of new technologies in recent years, particularly in Asia has made available new technologies more ideally suited giving the potential for greater recovery and improved qualities. In particular, spindleless veneer lathes have rapidly expanded throughout China, Vietnam, etc. with the primary focus of peeling small diameter forest resources. Technologies such as these further supports continued and strengthening interest in veneer processing as opposed to other conversion and product approaches for Queensland hardwood plantations.

3. Wood material and methodology

3.1. Plantation selection

3.1.1. Stage 1 trials

3.1.1.1. Dunn's white gum

Material for this study was selected from DAFF's Experiment 624 HWD and is located at Boyle's Land Purchase 4 km east of Urbenville, northern New South Wales (28° 28' S, 152° 35' E). The experiment is located at two separate areas within the property and includes three replicates across different soil types. Replicate one is located on a red kandosol soil for the upper plots and a yellow kandosol for the lower plots. Replicate two is on a brown dermosol soil while replicate three is on a grey chromosol. The long-term average annual rainfall is 1100 mm.

The experiment consists of 12 thinning/pruning treatments replicated three times and is laid out as a randomised complete block design. Treatments focused on a range of thinning regimes with most plots being pruned (Table 1). Where applicable, pre-commercial thinning (PCT) was undertaken at age two years. The commercial thinning treatment (CT) scheduled at age five to seven years was done at age seven years and the commercial thinning scheduled for 10 to 15 years had not been applied.

Table 1. Treatment details

Treatment	PCT (2 years)	CT 1 (5–7 years)	CT 2 (10–15 years)	Pruning
1	800+	800+	800+	pruned
2	800+	800+	800+	unpruned
3	800+	800+	200	pruned
4	800+	200	200	pruned
5	400	400	400	pruned
6	400	400	200	pruned
7	400	400	100	pruned
8	300	300	300	pruned
9	300	300	300	unpruned
10	200	200	200	pruned
11	200	200	100	pruned
12	100	100	100	pruned

PCT = pre-commercial thinning, CT = commercial thinning,
800+ = represents the initial stocking rate acknowledging losses.

Initial site preparation commenced in September 1998 with the removal of isolated forest regrowth. In October 1998, site cultivation to 80 cm depth was conducted utilising a D7 bulldozer. The site was re-cultivated shortly afterwards due to the poor quality of the initial cultivation. After site cultivation was completed, herbicide was applied along the tree rows at a rate of 5 L/ha Simazine and 3 L/ha Round-up immediately prior to planting.

The seedlings were Wallaby Creek (New South Wales) provenance originally located 10 km west of Urbenville. Seedlings were raised in Hiko pots and planted by hand in November

1998. Trees were planted with an inter-row spacing of 4 m with an intra-row spacing of approximately 2.5 m to provide an initial stocking of approximately 1000 stems per hectare (spha). Treatment plots with a gross size of 10 rows × 40 m (1600 m^2) and a net size of 6 rows × 30 m (720 m^2) were established in the routine plantation. The total experimental area is 5.76 ha.

Trees were fertilised at the time of planting with 50 g/tree mono-ammonium phosphate (MAP) buried using a pottiputki. This application equated to approximately 4 kg/ha of nitrogen, 9 kg/ha of phosphorus and 0.6 kg/ha of sulphur. The first follow-up weed control treatment was conducted in April 1999 involving either Round-up (3 L/ha) or Verdict (3 L/ha) and Lontrel (0.75 L/ha). Cattle were introduced to the site at age 2.25 years.

In March 2009, (age 10.3 years) 60 trees were harvested for veneer processing trials. Selection targeted 15 trees from four treatment combinations. These included a combination of un-thinned (800+ spha) and thinned (200 spha with thinning occurring at age two years) as well as pruned and un-pruned. Pruned trees were selected from within three diameter classes measured at breast height over bark (15–20 cm, 20–25 cm and 25–30 cm) with dominant trees being selected from each class. Given the lack of un-pruned representation within the plots, un-pruned trees were sampled from plantation areas surrounding the plots and were selected to match the diameters of the selected pruned trees. Selection of the thinned and unpruned trees were made from the surrounding plantation biasing trees with the largest diameters (measured at breast height over bark) to closely match the selected thinned and pruned trees; however, individual tree spacings were not always comparable.

To facilitate comparisons between thinned and unthinned trees that will eventually become final crop trees, only defect free, co-dominant or dominant trees were sampled from the unthinned treatment. That is, trees selected were those that would normally be retained in a thinning operation to be grown through to final harvest.

The target merchandised log length was 7 m. Further merchandising aimed to provide up to three 1.4 m long veneer billets. Each billet also had to meet the minimum form requirements such as straightness, have a small end over-bark diameter (SEDOB) no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.1.2. Spotted gum - Site 1

Material for this study was selected at Reid’s Land Purchase approximately 10 km north-west of Urbenville, northern New South Wales (28° 25’ S, 152° 32’ E). Soil types vary across the experiment with replicate one being located on a brown kurosol and replicate three on a grey kurosol. Replicate two is located within a transitional zone between these two soil types. The long-term average annual rainfall is 1100 mm.

The experiment consists of eight thinning/pruning treatments replicated three times. The trial is laid out as a randomised complete block design. Treatments targeted a range of thinning regimes with most plots being pruned (Table 2). The commercial thinning treatments that were scheduled at age 10 years had not yet been applied.

Table 2. Treatment details

Treatment	PCT (3 years)	CT (10 years)	Pruning
1	600+	600+	pruned
2	600+	600+	unpruned
3	600+	200	pruned
4	400	400	pruned
5	400	200	pruned
6	200	200	pruned
7	200	200	unpruned
8	100	100	pruned

PCT = pre-commercial thinning, CT = commercial thinning,
600+ = represents the expected minimum stocking rate at age 3 years

Initial site preparation commenced in October 1996 with the removal of isolated forest regrowth patches using a D6 bulldozer. In November 1996, the total area was tractor-broadcast sprayed with Round-up (3 L/ha). Site cultivation was conducted one week later with a D7 bulldozer, mounted with a winged ripper (to 80 cm depth) and trailing a Savanna mounding plough. The rows were re-cultivated shortly afterwards due to the poor quality of the initial cultivation. After the site cultivation was completed, herbicide was applied along the tree rows with Simazine (5 L/ha) and Round-up (3 L/ha).

Seedlings were raised in Hiko pots before being planted by hand in March 1997. Trees were planted with an inter-row spacing of 4 m and an intra-row spacing of 3 m to provide an initial stocking of approximately 833 spha. Treatment plots with a gross size of 8 rows x 35 m (1228 m^2) and a net size of 4 rows x 25 metres (400 m^2) were established in the routine plantation.

Follow-up weed control treatment was conducted in May 1997 utilising back-packs spraying a combination of Round-up and Simazine. Trees were also fertilised at this time with 50 g/tree mono-ammonium phosphate (MAP) buried using a pottiputki. This application equated to approximately 4 kg/ha of nitrogen, 9 kg/ha of phosphorus and 0.6 kg/ha of sulphur. Minor replanting to replace deaths was conducted in October 1997 utilising trees from the Bagawa State Forest provenance (near Coffs Harbour, New South Wales). A final follow-up weed-control treatment was applied in October 1997 using a Round-up and Simazine mix. An inter-row slashing was conducted in early 1998 and cattle were introduced to the site in mid-1999 (age 2.25 years).

In May 2009, (age 12.2 years) 60 trees were harvested for veneer processing trials. Selection targeted 15 trees from four treatment combinations. These included a combination of un-thinned (600+ spha) and thinned (400 spha with thinning occurring at age 3 years) as well as pruned and un-pruned. Pruned trees were selected from within three diameter classes measured at breast height over bark (15–20 cm, 20–25 cm and 25–30 cm) with dominant trees being selected from each class. Given the lack of un-pruned representation within the plots, un-pruned trees were sampled from plantation areas surrounding the plots and were selected to match the diameters of the selected pruned trees. Selection of the thinned and unpruned trees were made from the surrounding plantation biased towards trees with the largest diameters (measured at breast height over bark) to closely match the selected thinned and pruned trees; however, individual tree spacings were not always comparable.

To facilitate comparisons between thinned and unthinned trees that will eventually become final crop trees, only defect free, co-dominant or dominant trees were sampled from the unthinned treatment. That is, trees selected were those that would normally be retained in a thinning operation to be grown through to final harvest.

The target merchandised log length was 7 m. Further merchandising aimed to provide up to three 1.4 m long veneer billets. Each billet also had to meet the minimum form requirements such as straightness, have a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.1.3. Gympie messmate - Site 1

Material for this trial was selected from DAFF's Experiment 537 HWD in Compartment 208, Yurol State Forest, approximately 2 km south-east of Pomona (26° 23' S, 152° 52' E). The total experimental area is 1.36 ha. The soil is classified as a red earth and the long-term average annual rainfall is 1470 mm.

The experiment consists of a factorial combination of five nitrogen x three phosphorous treatments which have been replicated twice (Table 3). A further two treatments (inclusion of potassium and potassium plus trace elements) and a control with no fertiliser applied are included in the design. The trial is laid out as a randomised complete block design.

Table 3. Treatment details

Treatment	Factorial			Rates of Application (kg/ha)			
	Nitrogen (N)	Phosphorus (P)	Years	Nitrogen (N)	Phosphorus (P)	Potassium (K)	Trace Elements
1	1	1	1.0	100	30	0	0
2	1	2	1.0	100	60	0	0
3	1	3	1.0	100	120	0	0
4	2	1	1.0	200	30	0	0
5	2	2	1.0	200	60	0	0
6	2	3	1.0	200	120	0	0
7	3	1	1.0	400	30	0	0
8	3	2	1.0	400	60	0	0
9	3	3	1.0	400	120	0	0
10	2	1	1.5	200	30	0	0
11	2	2	1.5	200	60	0	0
12	2	3	1.5	200	120	0	0
13	3	1	1.5	400	30	0	0
14	3	2	1.5	400	60	0	0
15	3	3	1.5	400	120	0	0
16	2	2	1.5	200	60	50	0
17	2	2	1.5	200	60	50	Cu (5), Zn (5), B (2.5)
18	0	0	0.0	0	0	0	0

Initial site preparation commenced in late 1996 following the final harvest of a rose gum (*E. grandis*) plantation. The area was de-stumped using an excavator and the stumps and all logging refuse pushed, heaped and burnt. The area was also chopper-rolled to break-up any remaining refuse. The compartment design and survey were conducted in January 1996, with the planting lines then cultivated using a single pass of the Stubby TP-3 machine with an attached set of trailing disks to improve soil tilth. Planting rows were kept weed free prior to planting using Round-up. The trees were obtained from Beerburrum nursery and had been grown in solid-wall net pots (70 cc volume).

The trees were planted in March 1997 with an inter-row spacing of 4 m and an intra-row spacing of 2.25 m to provide an initial stocking of approximately 1111 spha. Each treatment plot had a gross plot size of 6 rows x 7 trees (378 m^2) and a net plot size of 4 rows x 5 trees (180 m^2). Simazine was applied at a rate of 6 L/ha in March 1997. Minor tree refilling was performed during March and April 1997 to boost the 95% initial survival rate. The first fertiliser treatment was applied during March 1997.

In August 2009 (age 12.4 years), 30 trees were harvested for veneer processing trials. Tree growth data collected just prior to tree harvesting was used to establish the spread and frequency of diameters (over bark) that existed within the experiment and this data was used to set the primary selection requirement for tree selection (Table 4). Merchandised log length targeted was 7.5 m providing up to five 1.4 m long billets that met the minimum form requirements such as straightness, had a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

Table 4. Selection methodology

Number of trees	Diameter class (cm)
2	< 18
2	18–21
2	21–24
6	24–27
10	27–30
6	30–33
2	>33

3.1.1.4. Spotted gum hybrid

Material for this study was selected from DAFF’s Experiment 469d HWD at “Poulson” Compartment 1 near Amamoor, Queensland (26°21’ S, 152°31’E). The soil is a yellow podsol with clay at 350 mm depth. The long-term average annual rainfall is 1030 mm.

The experiment was established to evaluate the potential of hybrids between *Corymbia torelliana* and the spotted gums (*Corymbia* spp.) for growth, form and wood properties. The experiment is an alpha design with four replications of 60 treatments as five-tree line plots. These line plots are randomly allocated to each replication (group of 5 blocks). One block consists of six rows x 10 trees with plots being one row x five trees. In total there are 240 plots (20 blocks x 12 plots).

Tree planting commenced in September 2001 with an inter-row spacing of 4 m and an intra-row spacing of 1.5 m to provide an initial stocking of approximately 1667 spha. The total experimental area is 0.72 ha.

In September 2010 and November 2010, 23 trees (age 9.0 years) and 20 trees (age 9.2 years) respectively were harvested, providing 43 trees for veneer processing trials. As the experiment is an active tree breeding experiment, access for destructive sampling was limited to two of the better performing families (153 CT2-011 x CV2-025 and 146 CT2-002 x CV2-025) sourced from within five of the 20 plots. Tree selection criteria favoured trees with diameters over 190 mm. Merchandised log length targeted as many 1.5 m billets as possible that met the minimum form requirements such as straightness, had a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.1.5. Red mahogany

The material for this study was selected from DAFF's Experiment 767a ATH at the Ingham Forest Nursery, 5 km south of Ingham, northern Queensland (18°40'S, 146°8'E). The soil is a fine sandy clay loam of yellow-greyish colour deposited from granite rocks. The long-term average annual rainfall is 2200 mm.

The experiment is a second generation progeny trial. Material for this trial was collected from superior phenotypes from seedling seed orchards established in the early 1990s in Kairi, Damper and Ellerbeck, with infusions from natural stands in Papua New Guinea and north Queensland. Since 2001, this trial has been managed for the sole purpose of seed production.

The experiment design is an incomplete block design of four replications. There are 123 families, each represented by a five-tree line plots in each replicate. The replicate size is six rows x 100 trees. The total experimental area is 1.44 ha.

All stock was raised at DAFF's Walkamin nursery with seed being direct sown into Vic pots containing peat/vermiculite mix. Trees were planted in May 1997. with an inter-row spacing of 5 m and a intra-row spacing of 1.6 m to provide an initial stocking of approximately 1250 spha. Some refilling to replace deaths was undertaken in June and August 1997. An application of fertiliser, equivalent to 50 kg/ha was completed in June 1997.

In May 2010 (age 13 years), 38 trees were harvested for veneer processing trials. Selection was based upon representation of the four major genetic groupings and representation of the available tree diameters. Merchandised log length targeted as many 1.5 m billets as possible that met the minimum form requirements such as straightness, had a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.1.6. Western white gum

The material for this study was selected from DAFF's Experiment 574 HWD located on private property 5 km south-west of Coominya, south-east Queensland (27° 25' S, 152° 25' E). Soil type varies across the site with replicate one being positioned on brown sodosol while replicate two is located on brown kandosol. The long-term average annual rainfall is 800 mm.

The experiment treatments investigate a combination of two species (western white gum and spotted gum) with two cultivation treatments, two weed control treatments and two fertiliser treatments, each replicated twice. The trial is laid out as a factorial strip-split plot design. Each replicate of 16 plots was split into two main blocks, with cultivation treatments allocated to either main block. Each main block was further split into two sub-blocks with fertiliser treatments allocated to either sub-block. The two species x two weed control treatments were randomly allocated within these sub-blocks to give a total of 32 plots.

Each treatment plot has a gross plot area of 420 m^2 (6 rows x 7 trees) and a net plot area of 200 m^2 (4 rows x 5 trees). Trees were planted at an inter-row spacing of 4 m and an intra-row spacing of 2.5 m to provide an initial stocking of 1000 spha. An additional one tree isolation separates the cultivation and fertiliser treatments. The total experimental area is 1.4 ha.

Initial site preparation commenced in January 1998 with cultivation treatments being performed with a D7 dozer and plough. A pre-plant application of Round-up (6 L/ha) was conducted in late February in preparation for planting.

The trees were raised in Vic pots at the Beerburrum nursery and planted in late March 1998. All trees received approximately two litres of water immediately after planting along with a fertiliser treatment. For the optimum fertiliser treatment, the second application of nitrogen was performed in July 1998. A Simazine treatment was applied in April 1998; however, the effectiveness for weed control was poor. In May 1998, all plots were sprayed with Round-up and Fusilade. For the complete weed control treatments only, a second Simazine application was also applied at this time. Re-filling to replace tree deaths was conducted in April 1998.

In April 2010 (age 12.1 years), 12 trees were harvested for veneer processing trials. The selection criteria targeted trees with diameters over 200 mm. Merchandised log length targeted as many 1.5 m long billets as possible that met the minimum form requirements such as straightness, had a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.2. Stage 2 trials

3.1.2.1. Spotted gum - Site 2

Material for this study was selected from a thinning trial established in a plantation owned by Forest Enterprises Australia (FEA). The trial was established to evaluate the impact of thinning regimes on the product quality of spotted gum growing on two contrasting sites; one in New South Wales and one in Queensland (Section 3.1.2.2), both with known and similar management histories but contrasting high-rainfall and low-rainfall histories. The plantation is known as Reids plantation and is located at Ellangowan, approximately 50 km south-west of Lismore in northern New South Wales (29° 02’ S, 153° 05’ E). The soil type is described as kurosol. The mean annual rainfall for the period 2001–2010 at Ellangowan was 1096 mm.

Initial site preparation included Round-up spraying (4 L/ha) of the planting rows prior to ripping to a depth of 0.6 of a metre, followed by a spray application of Simazine (2.5 kg/ha) and Duel (1.5 L/ha) prior to planting.

Trees were planted between February and March 2001 with an inter-row spacing of 4 m and an intra-row spacing of 2 m providing an initial stocking of approximately 1250 spha. A post-planting application of fertiliser (100 g of di-ammonium phosphate per tree) was applied. Weed control spraying was conducted after planting using Verdict 520 (0.5 L/ha) and Verdict (0.8 L/ha).

The thinning trials were established between October and December 2008 (age 7.8 years) and included three thinning treatments (300 spha, 500 spha and an unthinned control at approximately 900 spha). A randomised complete block design was implemented with four replicates. Treatment plots were square and 0.06–0.07 ha in area, with between 53 and 89 trees per plot in the unthinned control plots. Each experimental plot was surrounded by a two-row buffer, to which the same thinning treatment was applied.

In August 2011 (age 10.4 years), 10 trees were harvested for veneer processing trials. Five were selected from un-thinned plots and five trees from a plot thinned to the equivalent of 300 spha. The selection process favoured the dominant trees. Log merchandising targeted two 1.5 m long billets. From the ground line, the billet positions were approximately 0.55–

2.05 m and 5.8–7.3 m. Each billet also had to met the minimum form requirements such as straightness, have a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.2.2. Spotted gum - Site 3

Material for this study was selected from a thinning trial established in a plantation owned by Forest Enterprises Australia (FEA). The thinning trial was established to evaluate the impact of a thinning regime on product quality of spotted gum growing on two contrasting sites; one in Queensland and one in New South Wales (Section 3.1.2.1), both with known and similar management histories but contrasting high-rainfall and low-rainfall histories. The plantation is known as Dower's plantation and is located 2 km South-west of Tingora, Queensland (26° 22' S, 151° 48' E). The soil type is described as ferrosol. The long-term average annual rainfall for the period 2001–2010 was 783 mm.

Initial site preparation included Round-up spraying (4 L/ha) of the planting rows prior to ripping to a depth of 0.6 m, followed by a spray application of Simazine (2.5 kg/ha) and Duel (1.5 L/ha) prior to planting.

Trees were planted between February and March 2001 with an inter-row spacing of 4 m and an intra-row spacing of 2 m providing an initial stocking of approximately 1250 spha. A post-planting application of fertiliser (100 g of di-ammonium phosphate per tree) was applied. Weed control spraying was conducted after planting using Verdict 520 (0.5 L/ha) and Verdict (0.8 L/ha).

The thinning trials were established between October and December 2007 (age 6.75 years) and included three thinning treatments (300 spha, 500 spha and an unthinned control at approximately 900 spha). A randomised complete block design was implemented with four replicates. Treatment plots were square and 0.06–0.07 ha in area, with between 53 and 89 trees per plot in the unthinned control plots. Each experimental plot was surrounded by a two-row buffer, to which the same thinning treatment was applied.

In late August 2011 (age 10.4 years), 10 trees were harvested for veneer processing trials. Five were selected from un-thinned plots and five trees from a plot thinned to the equivalent of 300 spha. The selection process favoured the dominant trees. Log merchandising targeted two 1.5 m long billets. From the ground line, the billet positions were approximately 0.46–1.95 m and 5.0–6.5 m. Each billet also had to met the minimum form requirements such as straightness, have a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.1.2.3. Gympie messmate - Site 2

Material for the second Gympie messmate study was selected from DAFF's Experiment 616 HWD on State Forest 589, 3.5 km north of Beerburrum, Queensland (26°23'S, 152°52'E). The soil is classified as kurosol and the long-term average annual rainfall is 1500 mm.

The experiment was designed to demonstrate the effects of three pre-commercial thinning rates on growth. The experiment followed on from an earlier residual herbicide experiment (Experiment 637 NC). The experiment is a simple design of un-replicated plots of three spacing treatments. Plot one measured 81 m x 14 m (5 rows x 54 trees), and plots two and three each measured 42 m x 28 m (10 rows x 28 trees). The total experimental area is 0.78 ha.

The seedlings were grown at Toolara nursery from Cooloolabin Road Yandina provenance (seed batch 131). Seeds were direct-sown into nets containing the standard eucalypt potting mix.

Initial site preparation commenced in April 1996 with a two-step ploughing using a 'Savannah' 3-disk plough followed by an off-set disk plough. A spray application with Round-up herbicide was applied in early May 1996 to control germinating weeds.

Trees were planted in May 1996 with an inter-row spacing of 2.8 m and intra-row spacing of 1.5 m to provide an initial stocking of 2381 spha. An application of fertiliser (7.7% N, 9.1% P, 7.8% K, 9.7% S, 6.6% Ca) at a rate of 100 g/tree was buried 150 mm from the base of the tree.

A pre-spacing thinning treatment was conducted in July 1998 (age 2.2 years) which removed the worst two stems in every four, reducing the stocking to approximately 1190 spha. The blocks were further thinned in December 1999 (age 3.6 years) to achieve the following regime:

Block/Plot 1 – approximately 625 spha.

Block/Plot 2 – approximately 400 spha.

Block/Plot 3 – approximately 204 spha.

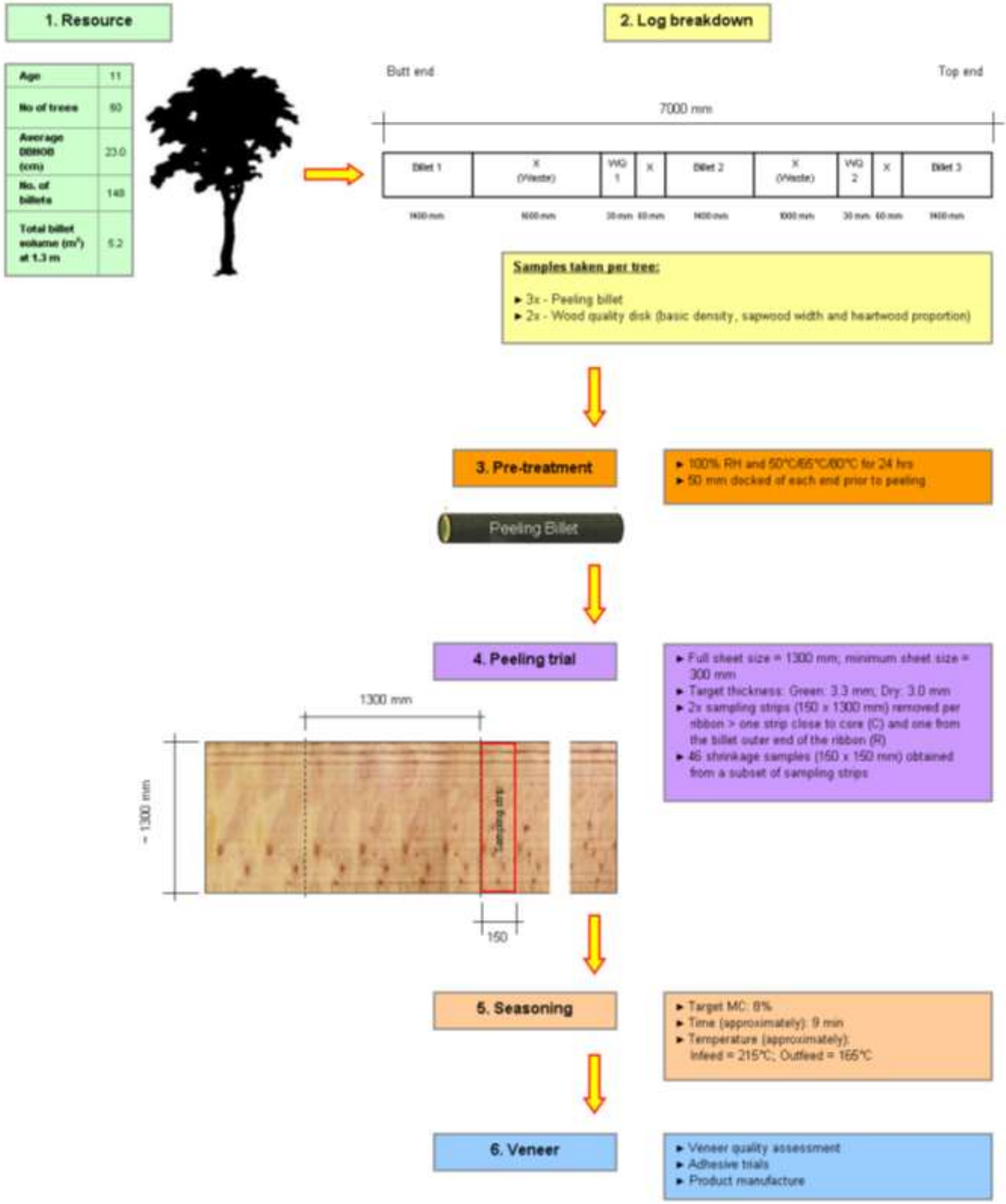
In June 2000 (age 4.1 years), all stems were pruned to 6 m.

In December 2011 (age 15.6 years), 29 trees were harvested for veneer processing trials. The selection process favoured trees with the largest diameter. Merchandised log length targeted was 5.2 m which would provide two 2.6 m long billets per tree. Logs were also required to meet the minimum form requirements such as straightness, have a small end over-bark diameter no less than 120 mm, along with an absence of ramicorns, double leaders, major branches and visible external injuries.

3.2. Sample and material flow

The following provides a summary of sample and material flows including the resource selection, log merchandising strategy and veneer billet processing.

3.2.1. Dunn's white gum

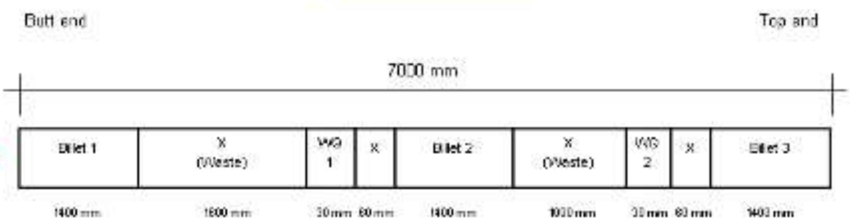


3.2.2. Spotted gum - Site 1

1. Resource

Age	12
No of trees	60
Average DBHOB (cm)	19.9
No. of billets	175
Total billet volume (m³) at 1.3 m	4.6

2. Log breakdown



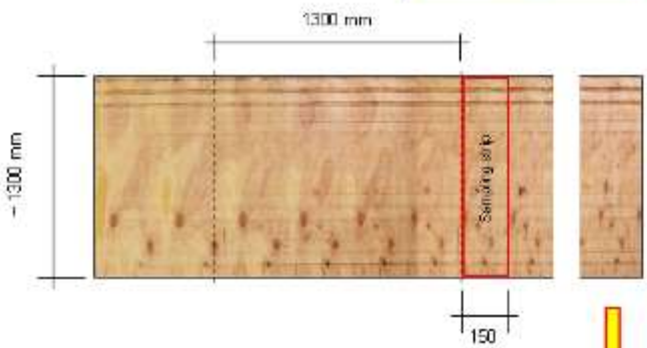
Samples taken per tree:

- 3x - Peeling billet
- 2x - Wood quality disk (basic density, sapwood width and heartwood proportion)

3. Pre-treatment

- 100% RH and 60°C/80°C/100°C for 24 hrs
- 50 mm docked of each end prior to peeling

4. Peeling trial



- Full sheet size = 1300 mm; minimum sheet size = 300 mm
- Target thickness: Green 3.3 mm; Dry: 3.0 mm
- 2x sampling strips (150 x 1300 mm) removed per ribbon > one strip close to core (C) and one from the billet outer end of the ribbon (R)
- 27 shrinkage samples (150 x 150 mm) obtained from a subset of sampling strips

5. Seasoning

- Target MC: 8%
- Time (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.2.3. Gympie messmate - Site 1

1. Resource

Age	12
No of trees	30
Average DBHOB (cm)	27.4
No. of billets	144
Total billet volume (m^3) at 1.3 m	6.7

2. Log breakdown

Butt end — 7500 mm — Top end

Billet 1	WQ 1	X	Billet 2	Billet 3	Billet 4	WQ 2	X	Billet 5
1400 mm	25 mm	200 mm	1400 mm	1400 mm	1400 mm	25 mm	200 mm	1400 mm

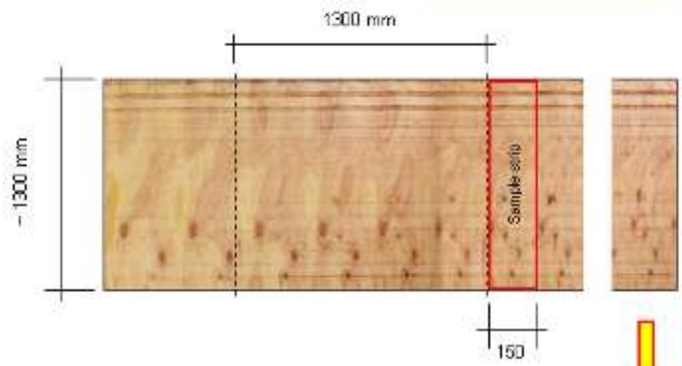
Samples taken per tree:

- 5x - Peeling billet
- 2x - Wood quality disk (basic density, sapwood width and heartwood proportion)

3. Pre-treatment

- 100% RH and 60°C/80°C/100°C for 24 hrs
- 50 mm docked of each end prior to peeling

4. Peeling trial



- Full sheet size = 1300 mm; minimum sheet size = 300 mm
- Target thickness: Green: 3.3 mm; Dry: 3.0 mm
- 2x sampling strips (150 x 1300 mm) removed per ribbon > one strip close to core (C) and one from the billet outer end of the ribbon (R)
- 40 Shrinkage samples (150 x 150 mm) obtained from a subset of sampling strips

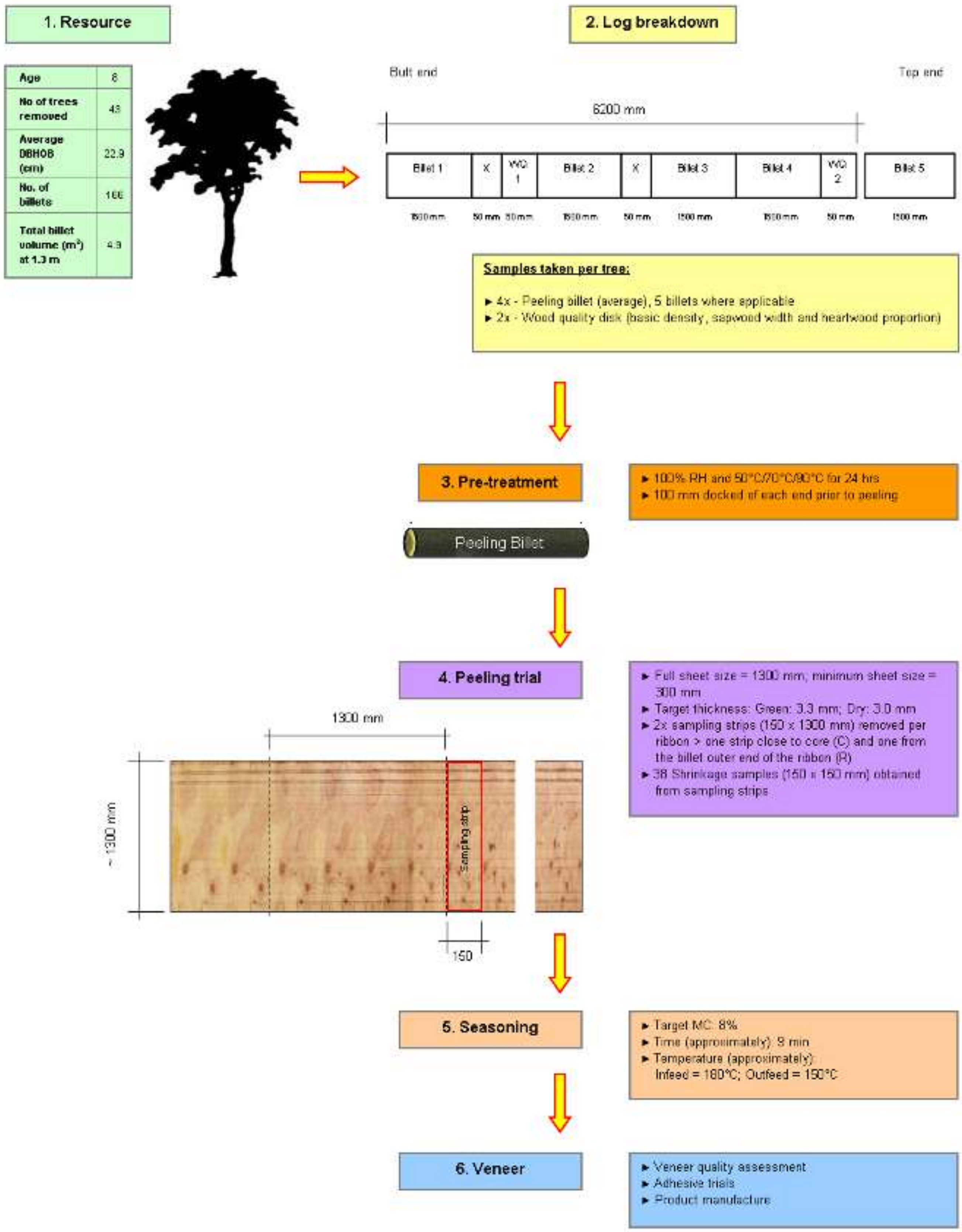
5. Seasoning

- Target MC: 8%
- Time: (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.2.4. Spotted gum hybrid



3.2.5. Red mahogany

1. Resource

Age	13
No of trees removed	36
Average DBHOB (cm)	28.1
No. of billets	130
Total billet volume (m^3) at 1.3 m	6.4

2. Log breakdown

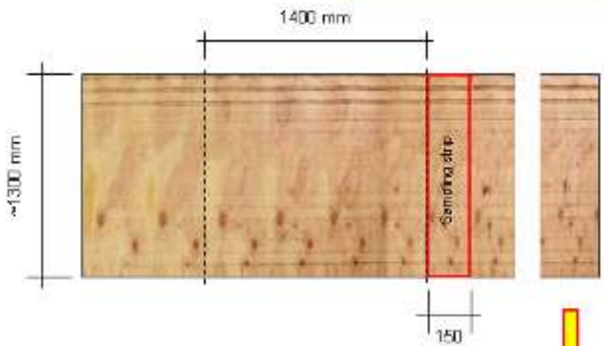
Samples taken per tree:

- 4x - Peeling billet (minimum), 5 billets taken where available
- 2x - Wood quality disk (basic density, sapwood width and heartwood proportion)
- Third disk was taken if more than 4 billets were available

3. Pre-treatment

- 100% RH and 50°C/80°C/100°C for 24 hrs
- 100 mm docked of each end prior to peeling

4. Peeling trial



- Full sheet size = 1400 mm; minimum sheet size = 300 mm
- Target thickness: Green 3.3 mm; Dry: 3.0 mm
- 3x sampling strips (150 x 1300 mm) removed per ribbon for billet 1 and billet 2 > one strip close to core (C), one in the middle (M) and one from the billet outer end of the ribbon (R)
- 2x sampling strips (C and R; 150 x 1300 mm) removed where applicable
- 40 Shrinkage samples (150 x 150 mm) obtained from a subset of sampling strips

5. Seasoning

- Target MC: 8%
- Time (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

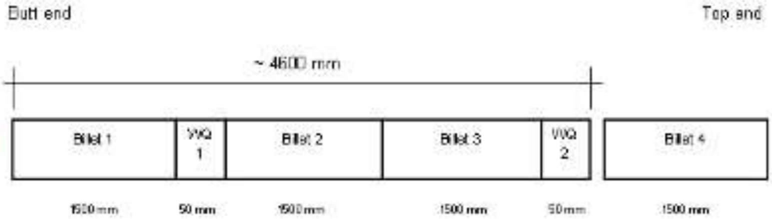
- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.2.6. Western white gum

1. Resource

Age	12
No of trees removed	12
Average DBHOB (cm)	23.7
No. of billets	33
Total billet volume (m^3) at 1.3 m	1.1

2. Log breakdown



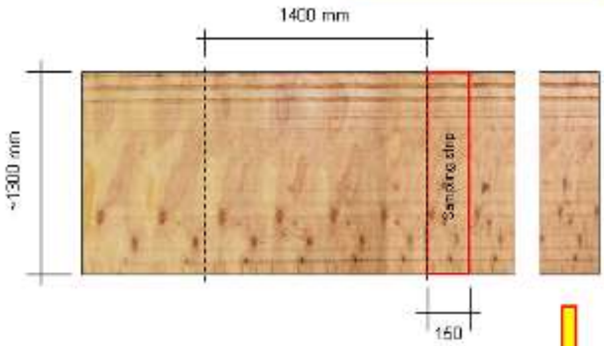
Samples taken per tree:

- 3x - Peeling billet (minimum); 4 billets taken where available
- 2x - Wood quality disk (basic density, sapwood width and heartwood proportion)
- Removal of waste material at butt end due to deformities (average 1000 mm)

3. Pre-treatment

- 100% RH and 60°C/80°C/100°C for 24 hrs
- 100 mm docked of each end prior to peeling

4. Peeling trial



- Full sheet size = 1400 mm; minimum sheet size = 300 mm
- Target thickness: Green: 2.6 mm; Dry: 2.4 mm
- 2x sampling strips (150 x 1300 mm) removed per ribbon > one strip close to core (C) and one from the billet outer end of the ribbon (R)
- 40 Shrinkage samples (150 x 150 mm) obtained from a subset of sampling strips

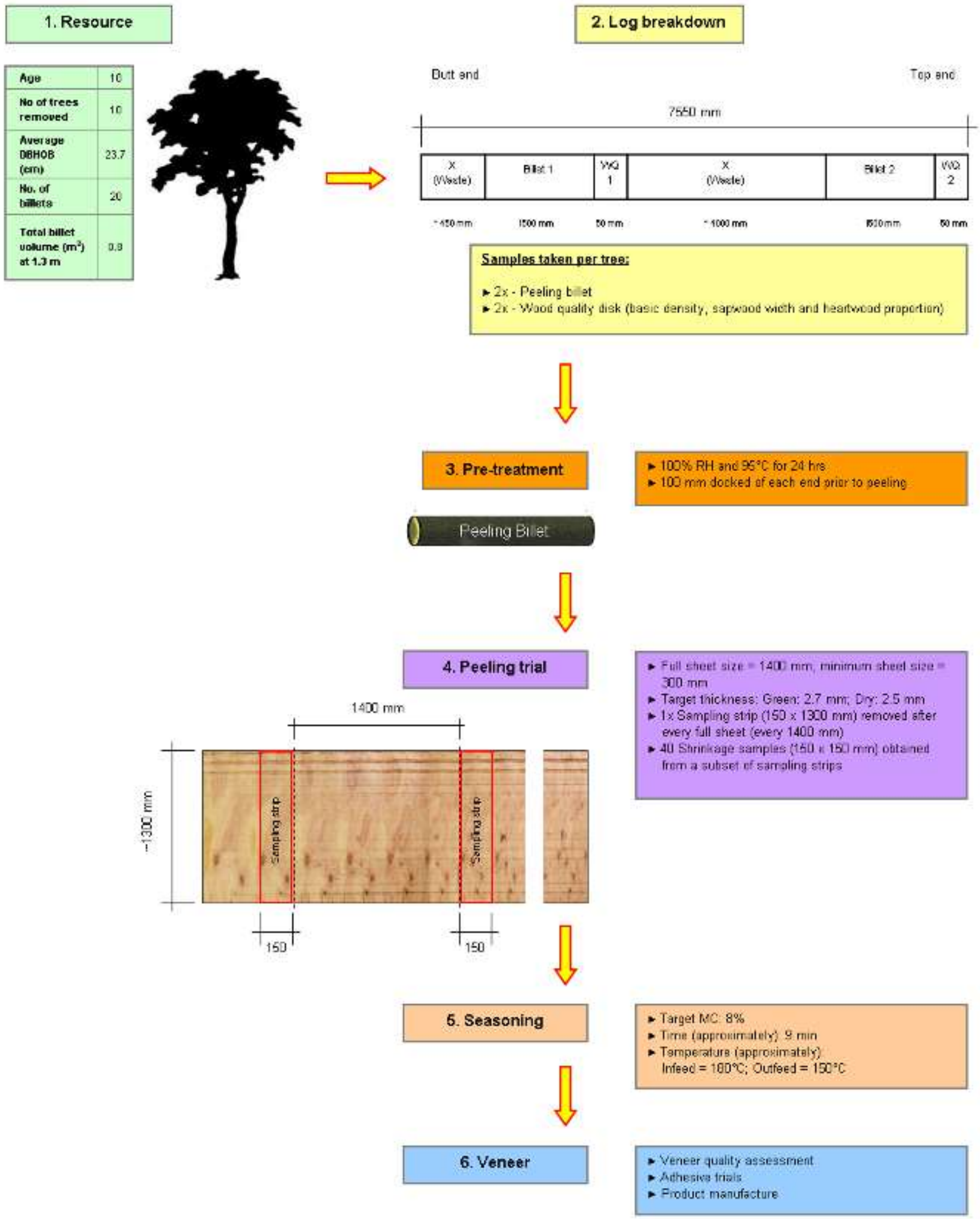
5. Seasoning

- Target MC: 8%
- Time (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.2.7. Spotted gum - Site 2



3.2.8. Spotted gum - Site 3

1. Resource

Age	10
No of trees removed	10
Average DBHOB (cm)	21.7
No. of billets	20
Total billet volume (m^3) at 1.3 m	0.6

2. Log breakdown

Samples taken per tree:

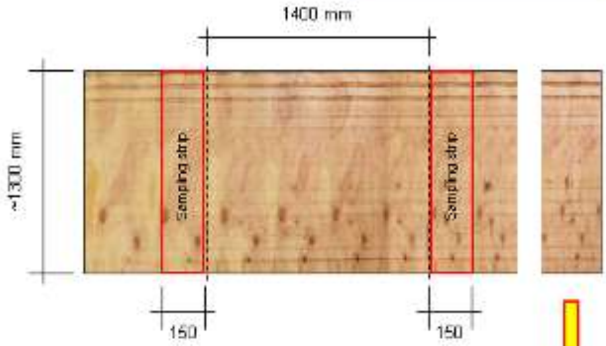
- 2x - Peeling billet
- 2x - Wood quality disk (basic density, sapwood width and heartwood proportion)

3. Pre-treatment

- 100% RH and 95°C for 24 hrs
- 100 mm docked of each end prior to peeling

4. Peeling trial

- Full sheet size = 1400 mm; minimum sheet size = 300 mm
- Target thickness: Green: 2.7 mm, Dry: 2.5 mm
- 1x sampling strip (150 x 1300 mm) removed after every full sheet (every 1400 mm)
- 40 Shrinkage samples (150 x 150 mm) obtained from a subset of sampling strips



5. Seasoning

- Target MC: 8%
- Time (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

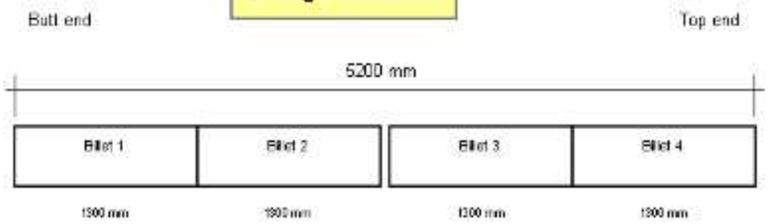
- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.2.9. Gympie messmate - Site 2

1. Resource

Age	15
No of trees removed	29
Average DBHOB (cm)	37.5
No. of billets	76
Total billet volume (m^3) at 1.3 m	7.2

2. Log breakdown



Samples taken per tree:

- 2x - 2600 mm billets pre-rounded in industrial mill

Further merchandising:

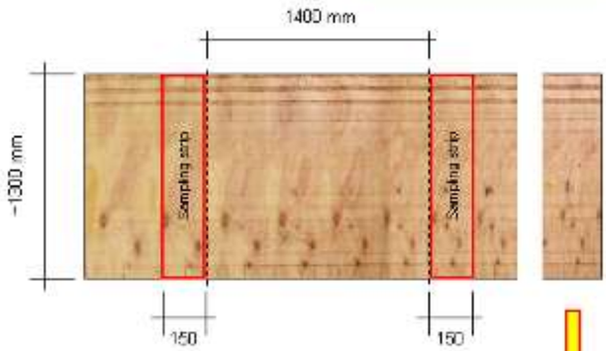
- 4x - 1300 mm peeling billet (post roundup)

3. Pre-treatment

- 100% RH and 90°C for 24 hrs
- NO docking of billets prior to peeling

4. Peeling trial

- Full sheet size = 1400 mm, minimum sheet size = 300 mm
- Target thickness: Green: 2.7 mm; Dry: 2.5 mm
- 1x sampling strip (150 x 1300 mm) removed after every full sheet (every 1400 mm) for billet 2 only
- 34 shrinkage samples (150 x 150 mm) obtained from sampling strips



5. Seasoning

- Target MC: 8%
- Time (approximately): 9 min
- Temperature (approximately): Infeed = 180°C; Outfeed = 150°C

6. Veneer

- Veneer quality assessment
- Adhesive trials
- Product manufacture

3.3. Wood quality

3.3.1. Basic density

Basic density is the measurement of actual wood mass (with all moisture removed) and is calculated as the oven-dry mass of a timber section divided by its green (saturated) volume. It is a useful indicator for characteristics such as hardness, strength, workability and pulping properties.

Disks were cut generally from the top of the first billet (referred to as the butt disk) and the top of the top billet (top disk) of all harvested trees (Section 3.2). From each disk, two wedges were removed which were further divided into three segments representing inner heartwood, outer heartwood and sapwood. The inner and outer heartwood boundary was determined as 50% of the heartwood zone radial distance (see Figure 1). In some instances, where the heartwood proportion was low, only one heartwood segment was taken. These segments were then used for basic density calculations. Disks were not removed and therefore basic density not measured for the Gympie messmate from site two. In addition, the heartwood zone was not separated into inner and outer zones for spotted gum from sites two and three.

Basic density was determined in accordance with Australian and New Zealand Standard *AS/NZ 1080.3:2000 Timber – Method of test - Method 3: Density* (Standards Australia, 2000). Green volumes were determined by water displacement before oven-drying to a consistent weight. Basic density was then calculated from the following equation:

Basic density (kg/m^3) = oven-dry weight / green volume

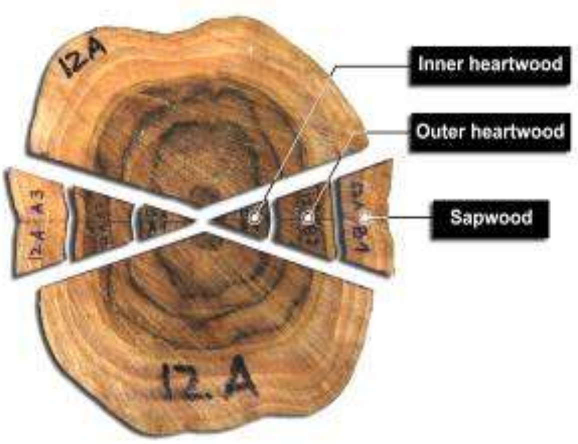


Figure 1. Basic density sample distribution

3.3.2. Heartwood proportion and sapwood width

The proportion of heartwood and the sapwood width within a log can have utilisation and processing implications, particularly where durability and appearance properties are required, and also with lyctus susceptible species. A smaller sapwood band is generally desirable as it means less timber is wasted if the sapwood is required to be removed or less chemical preservatives are required if the sapwood is to be treated.

Heartwood proportion and sapwood width were measured and calculated from the disks (the same disk used for basic density measurement (Section 3.3.1) removed from each tree for each plantation site with the exception of Gympie messmate from Site 2. The disks were sprayed with a methyl orange solution (pH indicator) to stain and demarcate the heartwood zone. The sapwood and heartwood dimensions were measured in a radial direction at four points across each disk. Sapwood was recorded as a measure of width in the radial direction while heartwood proportion was calculated as a percentage of disk basal area under bark.

3.4. Processing and veneer quality

3.4.1. Veneer billet pre-treatment

Veneer billet pre-treatment or conditioning commonly involves the heating of the billet prior to peeling. For most species, especially those in the higher density ranges, billet conditioning has significant advantages including smoother veneer surfaces with reduced lathe checking, improved gluability, improved veneer strength and reduced knife wear.

The disadvantages of pre-treatment can include lathe spin-out and surface roughness of the veneer, due to over-softening of the wood. Particularly in eucalypts, pre-conditioning may be associated with drying defects such as collapse, excessive shrinkage and end checking when the veneer is dried. Usually these disadvantages can be limited by optimisation of the conditioning schedule. Traditional methods of billet conditioning include hot water soaking and steaming in both batch and continuous processes.

For the study, all billets underwent a pre-treatment processing involving saturated steam at temperatures between 50 and 100 degrees Celsius for a period of approximately 24 hours (Section 3.2). Heated billets were removed from the pre-treatment chamber in very small batches (usually 3-4 billets) to ensure billet temperature was maintained for rotary peeling.

3.4.2. Rotary peeling

Rotary veneer production has a history in Australia that exceeds a century in duration (EWPAA, 2009). While rotary peeling technology has evolved and improved to become more efficient, faster and more suited to todays forest resources, the majority of lathe designs used today retain the traditional approach of using spindles to hold and turn the billet during peeling. This approach is particularly challenging for the small diameter plantation hardwoods as the wood volume remaining after peeling (i.e. peeler core) can represent an unacceptably large portion of the original billet volume, or in some circumstances where the spindle design is large and/or billet diameters are low, billets may be physically unable to be processed.

For the study, a spindleless veneer lathe was used. This technology was originally developed to further process large peeler cores produced from spindled lathes, however in recent years, they have been further developed and have been quickly adopted through many Asian countries including China, Vietnam etc. for processing very small-diameter billets with good success. The lathe used for the study was capable of processing billets with a maximum length of 1350 mm, maximum log diameter of 400 mm and was capable of peeling to a peeler core size of approximately 47 mm. For the study, either a 2.4 mm, 2.5 mm or 3.0 mm thick seasoned veneer was targeted (Section 3.2).

3.4.3. Veneer management

Immediately after peeling, the veneer ribbon was marked and labelled into sheets, prior to being clipped (Figure 2). Priority was given to full width sheets which in earlier trials were 1300 mm wide, however this dimension was increased to 1400 mm for latter trials to ensure adequate sheet dimensions post drying for standard panel manufacturing (Section 3.2). In addition, sampling strips were also targeted from each veneer ribbon. These strips were used to collect green veneer thickness measurements at three points along the veneer length (i.e. parallel to the grain) and also provide samples for additional testing such as stiffness evaluation, shrinkage and unit shrinkage, and/or green moisture content testing. Labelling started in numerical order from the core end and progressed towards the last veneer sheet removed from the outer section of the billet. Each veneer sheet was allocated a unique six-digit code allowing easy future identification of experiment number, tree number, log number, billet number, sheet number and the sheet code. The sheet coding consisted of:

F - full width sheets

P - part width sheets being between 300 mm and full width

B - sampling strips to be used for acoustic stiffness evaluation (150 mm wide)

BS - sampling strips to be used for acoustic stiffness evaluation and shrinkage/unit shrinkage measurements (150 mm wide) and

W - sheets less than 300 mm wide or sheets that obviously failed to meet the D-grade requirements of *AS/NZS 2269.0:2008: Plywood – Structural – Specifications*.

Veneer seasoning was undertaken within an industrial scale jet-box drier under normal commercially operated conditions for the seasoning of softwood veneer. Given the industrial nature of the drier (e.g. limited ability to fine tune variables), the broad criteria for drying methodology was to target final veneer moisture content of approximately 8%. Kiln in-feed and out-feed temperatures of approximately 180 and 150 degrees Celsius respectively were targeted.

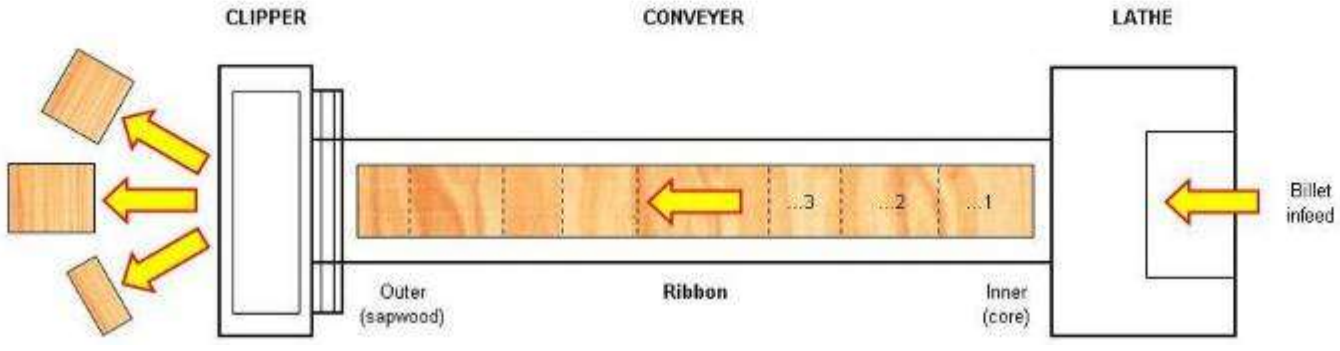


Figure 2. Veneer processing

3.4.4. Veneer recovery

Veneer recovery can be measured in a variety of ways. The following provides an explanation of the methods adopted for the study.

3.4.4.1. Green recovery

Green recovery provides a useful measure of the maximum recovery possible taking into account log geometry (sweep, taper, roundness which affect rounding requirements) and lathe limitations (e.g. peeler core size, length of ribbon wasted before desired thickness is achieved). Green recovery disregards internal log quality.

Green recovery has been calculated as the volume of green veneer which meets at least the minimum requirements of D-grade in accordance with *AS/NZS 2269.0:2008* by percentage of billet volume. The formula used for this calculation was:

$$\text{Green recovery \%} = \frac{\text{Average green ribbon thickness} \times \text{green ribbon length} \times \text{peeled billet length}}{\pi \times ((\text{green SEDUB} + \text{green LEDUB})/4)^2 \times \text{green billet length}}$$

The billet volume was calculated using the billet diameter (average of billet small-end and large-end diameter) measured under bark (SEDUB and LEDUB) and the length of the billet as presented to the lathe excluding any billet docking that occurred pre or post billet pre-treatment.

The veneer volume was calculated from dimensions taken in the green (unseasoned) condition. A single green thickness value was applied to all veneer within each processing batch which represented the average of all thickness measurements taken from the sampling strips within the processing batch. Veneer width was calculated as the total width of veneer which met at least the minimum requirements of D-grade in accordance with *AS/NZS 2269.0:2008*. The billet length at time of peeling was used as the veneer length.

3.4.4.2. Gross recovery

Gross recovery provides a useful measure of the maximum recovery of dried, graded veneer that can possibly be achieved. Gross recovery includes the losses accounted for in green recovery but also includes additional losses due the seasoning process (e.g. veneer shrinkage, splits etc).

Gross recovery has been calculated as the volume of dried veneer which meets at least the minimum requirements of D-grade in accordance with *AS/NZS 2269.0:2008* by percentage of billet volume. The volume of veneer associated with sampling strips was assumed to meet the requirements of D-grade. The formula used for this calculation was:

$$\text{Gross recovery \%} = \frac{\text{Average dry veneer thickness} \times \text{width of dry graded veneer (inc sampling strips)} \times \text{peeled billet length}}{\pi \times ((\text{green SEDUB} + \text{green LEDUB})/4)^2 \times \text{green billet length}}$$

The billet volume was measured as per green recovery (Section 3.4.4.1). The veneer volume was measured from dimensions taken in the dry (seasoned) condition. Three thickness measurements per veneer sheet were collected as illustrated in Figure 4. For each batch, these values were averaged to calculate a single dry veneer thickness value which was applied to all veneers within each batch for gross recovery calculation. Veneer width (perpendicular to grain) was the actual dried graded width while the billet length at time of peeling was used as the veneer length.

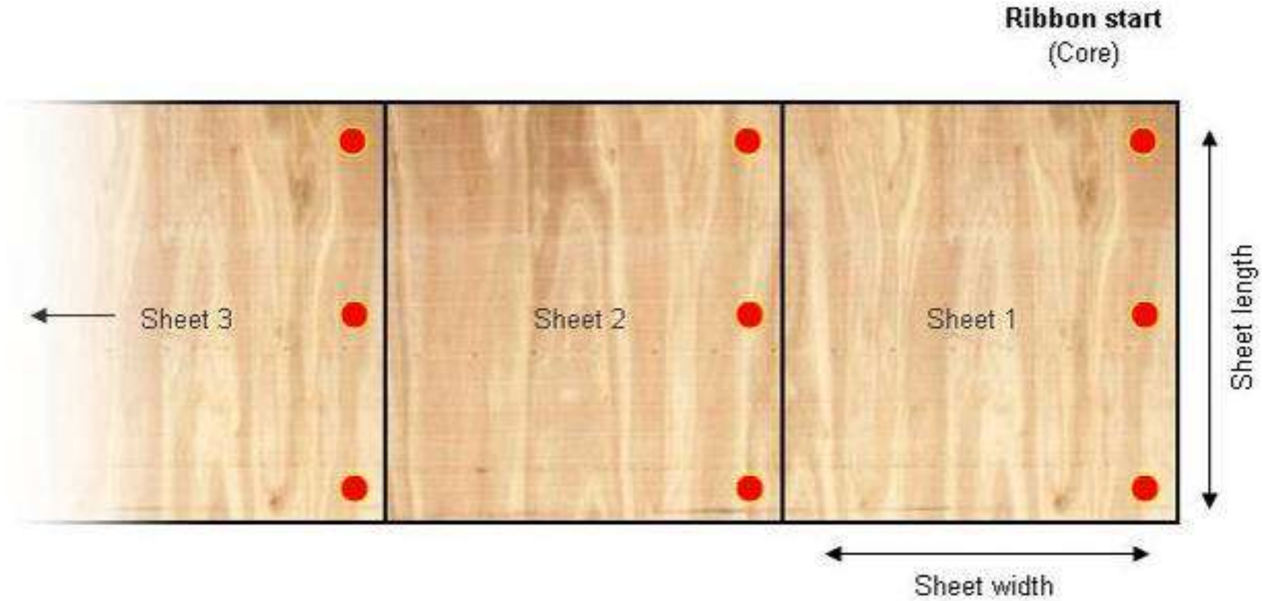


Figure 3. **Location of thickness measurements on dried veneer sheets**

3.4.4.3. Net recovery

Net recovery provides a useful measure of process efficiency as it identifies the saleable product taking into account the product manufacturing limitations. Net recovery includes the losses accounted for in gross recovery but also includes the additional losses due to the trimming of veneer before, during and after product manufacture. This includes reduction to final product size and squareness.

Net recovery has been calculated as the volume of dried, trimmed to size veneer which when manufactured into products meets the quality specifications of *AS/NZS 2269.0:2008* by percentage of billet volume. The formula used for this calculation was:

$$\text{Net recovery \%} = \frac{\text{Width of dry graded veneer (inc sampling strips)} \times 0.96 \times 1200 \text{ mm} \times \text{nominal thickness}^{**} \text{ in mm}}{\pi \times ((\text{green SEDUB} + \text{green LEDUB})/4)^2 \times \text{green billet length}}$$

*** trial dependent (2.4, 2.5 or 3.0 mm)*

The billet volume was measured as per green recovery (Section 3.4.4.1). The veneer thickness value used was the original nominal thickness (i.e. either 2.4 mm, 2.5 mm or 3 mm). Veneer sheet length was 1200 mm and sheet width was the dried width (as applied in gross recovery) minus a 4% trimming factor.

3.4.4.4. Grade recovery

Grade recovery provides a useful measure of the distribution of visual qualities attained from the net recovered volume. Grade recovery includes the losses accounted for in net recovery but also includes the additional losses resulting from focusing on an individual grade quality in accordance with *AS/NZS2269.0:2008* (i.e. A, B, C or D-grade).

Grade recovery has been calculated for each grade quality as the volume of veneer that meets the quality requirements of the given grade in accordance with *AS/NZS2269.0:2008* (i.e. A, B, C or D-grade) by percentage of billet volume. The formula used for this calculation was:

$$\text{Grade recovery \%} = \frac{\text{Width of dry graded veneer (A,B,C or D)} \times 0.96 \times 1200\text{ mm} \times \text{nominal thickness}^{**}\text{ in mm}}{\pi \times ((\text{green SEDUB} + \text{green LEDUB})/4)^2 \times \text{green billet length}}$$

*** trial dependent (2.4, 2.5 or 3.0 mm)*

The billet volume was measured as per green recovery (Section 3.4.4.1). The veneer volume applies the same measurement criteria as net recovery; however, it focused only on the volume that meets the quality requirements of a specific grade (i.e. A, B, C or D grade).

3.4.5. Visual grading

Veneer quality was assessed by visual grading in accordance with *AS/NZS 2269.0:2008*. This standard separates structural veneer into four main veneer surface qualities according to severity of imperfections and defects (Table 5).

In additional to ‘standard’ grading whereby a sheet is assigned a grade based on the limiting defect, additional information (Table 6) was collected assessing the impact of a range of imperfections and defects with a clear separation between whether the down-grading could be attributed to the forest resource or the processing techniques adopted. This approach was selected to facilitate a clearer understanding of the resource and process impacts on veneer quality and also allow various scenarios to be analysed to identify areas where the most impact can be gained on recovery improvement.

Veneer sheets which did not meet the grade requirements of D grade in accordance with *AS/NZS 2269.0:2008* as a full sheet, were re-evaluated to assess the potential to recover smaller ‘salvage’ sections. If a section of veneer with a width of at least two-thirds of the full sheet width met the D grade or higher requirements of *AS/NZS 2269.0:2008*, 67% of the sheet was classified as ‘S1’ and included within the applicable grade recovery. Similarly, if a section of veneer with a width between one-third and two-thirds of a full sheet met the D grade or higher requirements of *AS/NZS 2269.0:2008*, 33% of the sheet was classified as ‘S2’ and included within the applicable grade recovery.

Table 5. Veneer quality grade descriptions

Veneer grade	Description
A	A high quality appearance grade veneer suitable for clear finishing. This appearance grade quality should be specified for the face veneer in plywood where surface decorative appearance is a primary consideration.
B	An appearance grade suitable for high quality paint finishing. This face veneer quality should be specified for applications requiring a high quality paint finish.

C	Defined as a non-appearance grade with a solid surface. All open defects such as knot holes or splits are filled. Plywood with a quality C face is designed specifically for applications requiring a solid non-decorative surface such as in plywood flooring which is to be overlaid with a decorative flooring surface.
D	Defined as a non-appearance grade with permitted open imperfections. Plywood manufactured with face veneer quality D is the lowest appearance grade of plywood. It is designed specifically for structural applications where decorative appearance is not a requirement e.g. structural plywood bracing.

(source: EWPAA, no date)

Table 6. Grade limiting defects and imperfections

Forest resource	Processing techniques
1. Intergrown knots	1. Splits
2. Encased knots (sound and unsound)	2. Holes and tear out
3. Holes	3. Discoloration
4. Splits	4. Wane
5. Bark/decay	
6. Gum and resin pockets	
7. Gum veins	
8. Insect tracks	
9. Kino/bark	
10. Discoloration	
11. Compression	
12. Grain breakout	
13. Cumulative defects	
14. Roughness	

3.4.6. Acoustic grading

Vibration analysis in the acoustic domain is a simple and efficient way of characterising the elastic properties of a mass. This analytical technique is being used to an increasing extent in wood sciences and has been well accepted in industrial grading machines, especially veneer grading. Natural vibration analysis is used to characterise the longitudinal and the shear modulus of elasticity of various geometrical types of beams. A lateral or an axial percussion at one end of a beam set up on elastic support produces longitudinal or bending vibrations respectively. Considering the hypothesis of the homogeneity of geometrical and mechanical properties of the beam, basic dynamics theorems can be applied to obtain the motion equations of longitudinal and transverse vibrations. The resolution of the differential equation for longitudinal or transverse motion leads to a search for solutions to the frequency equation.

This technique is one of the most convenient methods for measuring the modulus of elasticity (MOE) with high precision. The method requires measurements of the resonance frequencies in different modes (longitudinal, flexure or torsional) of simple structures for which the geometry and boundary conditions are known (Brancheriau and Bailleres, 2002). The fact that the technique is based on well-defined resonant structure ensures that frequency measurements are precise. The technique can be extended to measure damping parameters and several signal descriptors.

To illustrate these methods, consider a prismatic, homogenous and isotropic beam with a length (L), height (h) and width (w). After an impact hits the beam either longitudinally or laterally, it vibrates freely in compression or bending respectively. For a longitudinal wave (also known as compression or P-wave), the particles vibrate parallel to the direction the wave is travelling. In transversal wave (also known as shear wave or S-wave), the motion of the particles is perpendicular to its direction of propagation.

Because of these different kinds of movements, the longitudinal method is used to estimate the compression and tension characteristics, while the transversal method determines the bending characteristics. By measuring the movement of a vibrating beam, the fundamental resonant frequency can be determined by a Fast Fourier Transform (FFT) algorithm. The following expression shows the relationship between frequency and apparent speed:

$$f_n = \frac{n}{2L} V_X \, , n \in \mathrm{N}*$$

Where:

- L is the length
- f_n is the natural frequency (rank n)
- n is the frequency rank
- V_x is the wave propagation speed (at the given frequency rank)

In this study, the longitudinal method was applied on veneer samples. The dynamic modulus of elasticity along the longitudinal direction of the veneer sample produced by a compression stress can be calculated using the following equation:

$$E \ = 4L^2 \rho \frac{f_n^{\ 2}}{n^2}$$

Where:

- E is the longitudinal dynamic longitudinal MOE
- ρ is the wood density
- fn is the natural frequency (rank n)
- n is the frequency rank

Acoustic grading was performed on the sampling strips (Section 3.4.3) which measured 150 mm wide x approximately 1300 mm long (sampling strips used for acoustic grading only i.e. sheet code B) or 1150 mm long (sampling strips used for acoustic grading and shrinkage i.e. sheet code BS). The sampling strips were air-dried to 12% MC prior to testing.

Sample dimensions (length, width, thickness) and weight (grams) were measured before being positioned on two elastic supports so that the longitudinal propagation of vibration is as free as possible and can be induced by a simple percussion on one end in the grain direction (Figure 5). At the other end, a Lavalier type microphone records the vibrations and transmits them via an anti-aliasing filter (low-pass) to an acquisition card including an analog-to-digital converter which provides to a computer the digitized signal. A Fast Fourier Transform processes this signal in order to convert the information from the time domain to the frequency domain. The mathematical processing of selected frequencies is software-made from the geometrical characteristics and the weight of the sample using the equation above.

Comparative tests showed a very good correlation with results obtained by conventional quasi-static transversal tests (3 and 4 points) on wood samples of all sizes, with and without defect (Brancheriau and Bailleres, 2002).

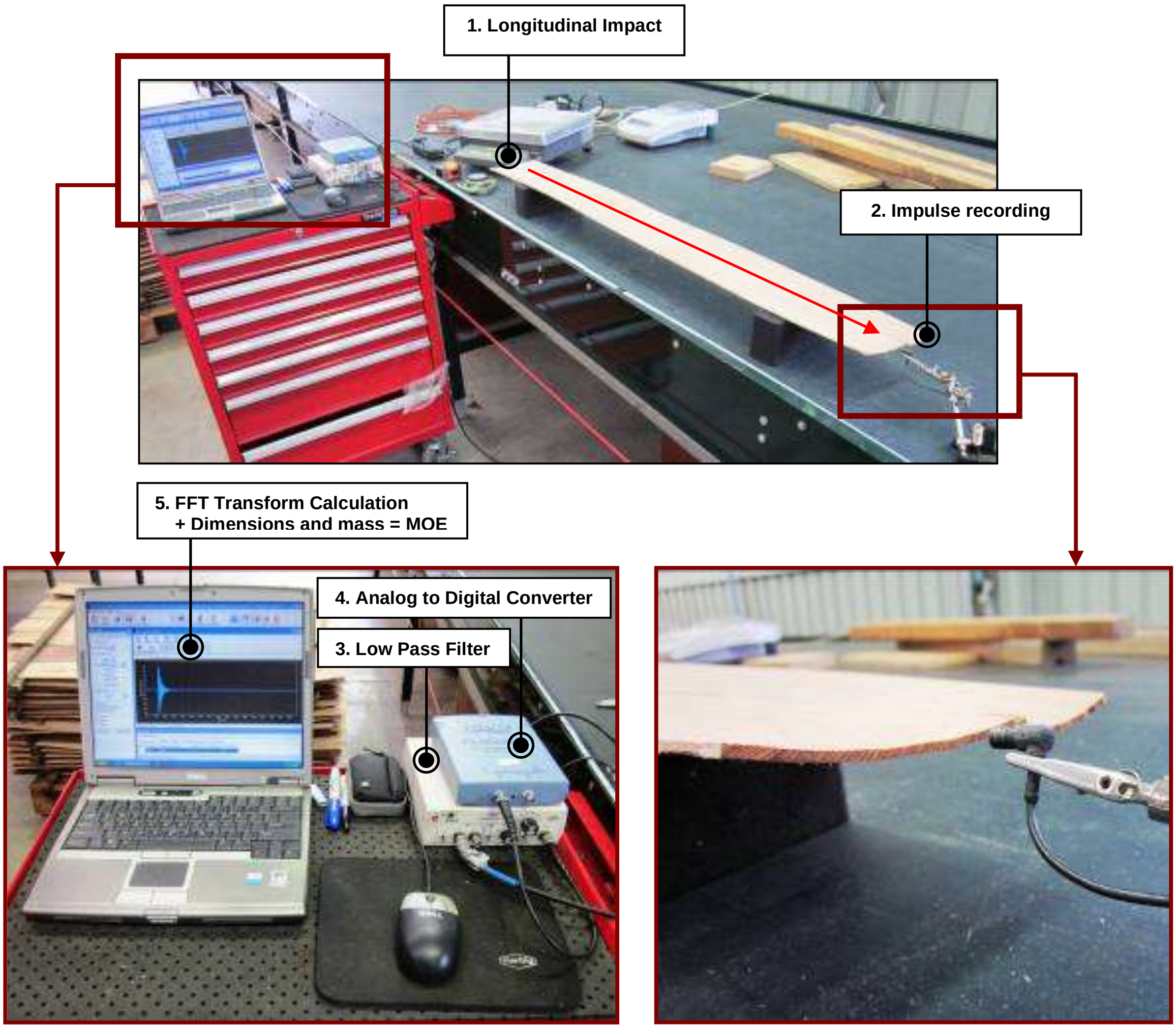


Figure 4. Experimental setup for the acoustic testing (using BING)

3.4.7. Shrinkage and unit shrinkage

Shrinkage will occur in wood after the moisture content falls below a particular level, called the ‘fibre saturation point’ (FSP), At this point, the wood cell cavities are empty of free water, but the cell walls are still saturated with chemically bound water. As moisture is removed from the cell walls, the wood shrinks until it reaches the local equilibrium moisture content (EMC), where the moisture content of the wood stabilises to that of the surrounding atmosphere. A measurement of the shrinkage that occurs in veneer as it dries or seasons provides processors with an indication of the unseasoned dimensions required (i.e. necessary extent of oversizing) to ensure that the seasoned product will be available in the required dimensions. Different species have different rates of shrinkage.

Unit shrinkage is another important measure that provides an indication of the dimensional change that can be expected with seasonal variations, where timber will either increase or decrease in moisture content (and therefore dimension) as the temperature and humidity of the surrounding atmosphere fluctuates. Unit shrinkage is expressed as the percentage of dimensional change per one per cent change in moisture content and can be applied between about 5% and 25% moisture content where the relationship is considered linear.

Shrinkage and unit shrinkage values were measured on peeled veneer and therefore cannot be directly compared to published data collected from solid timber. In addition, values collected from veneer may differ from the movement expected when veneers are combined in a final product.

For the stage 1 trials (i.e. Dunn's white gum, spotted gum - Site 1, Gympie messmate - Site 1, spotted gum hybrid, red mahogany and western white gum), only unit shrinkage was measured. Samples measuring 150 mm x 150 mm were removed from seasoned veneer sheets originating from butt and top billets from a subset of larger diameter trees.

Stage 2 trials (i.e. spotted gum - Sites 2 and 3; and Gympie messmate - Site 2) had both shrinkage and unit shrinkage measured with samples being removed immediately after peeling (i.e. unseasoned). The samples measuring 150 mm x 150 mm were removed from the sampling strips (Figure 3).

A summary of sample origin is described below:

1) Dunn's white gum - Two to four veneer samples randomly removed from each veneer ribbon sourced from either two (i.e. towards the butt and top) or three billets (i.e. towards the butt, middle and top) from five trees provided 46 samples.

2) Spotted gum - Site 1 - Two to four veneer samples randomly removed from each veneer ribbon sourced from a billet towards the butt and top (i.e. 2 billets) from five trees (with the exception of one tree which only provided samples from the butt billet) provided 27 samples.

3) Gympie messmate - Site 1: Four veneer samples randomly removed from each veneer ribbon sourced from a billet towards the butt and top (i.e. 2 billets) from five trees provided 40 samples.

4) Spotted gum hybrid - Three or four veneer samples randomly removed from each veneer ribbon sourced from a billet towards the butt and top (i.e. 2 billets) from five trees provided 38 samples.

5) Red mahogany - Four veneer samples randomly removed from each veneer ribbon sourced from a billet towards the butt and top (i.e. 2 billets) from five trees provided 40 samples.

6) Western white gum - Four veneer samples randomly removed from each veneer ribbon sourced from a billet towards the butt and top (i.e. 2 billets) from five trees provided 40 samples.

7) Spotted gum - Site 2: One veneer sample removed from veneer originating near the core of the billet and one veneer sample originating from the outer edge of the billet from a butt and top billet (i.e. 2 billets) from 10 trees provided 40 samples.

8) Spotted gum - Site 3 - One veneer sample removed from veneer originating near the core of the billet and one veneer sample originating from the outer edge of the billet from a butt and top billet (i.e. 2 billets) from 10 trees provided 40 samples.

9) Gympie messmate - Site 2: One veneer sample removed from veneer originating near the core of the billet and one veneer sample originating from the outer edge of the billet from the second billet of 17 trees provided 34 samples.

Each sample collected from the Stage 2 trials were weighed and digitally scanned in the 'green' condition (immediately after peeling) before being conditioned to target moisture contents of 8%, 12%, 16% and 0% moisture content (oven-dry). At each target moisture content, the samples were reweighed (to verify actual sample moisture content) and re-scanned. Samples collected from Stage 1 trials were first weighed and digitally scanned at 8% moisture content and followed the same procedure thereafter (i.e. conditioned, weighed and scanned at 8%, 12%, 16% and 0% moisture content). For each scanned image, the sample area (measured in pixels) was determined using digital image analysis software (ImageJ). This was then used to calculate the change of area for each sample due to moisture uptake or loss.

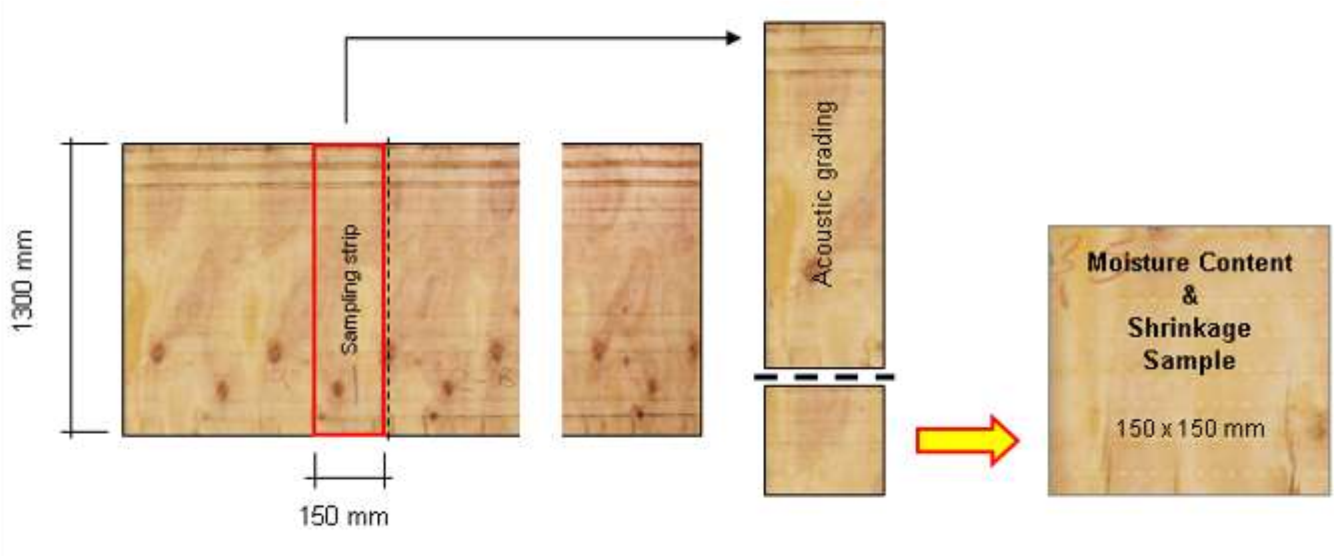


Figure 5. Shrinkage sample removed from sampling strips for stage 2 trials

3.5. Adhesive performance

There are currently four bond types specified for plywood and laminated veneer lumber (LVL) manufacture in Australia under *AS/NZS2754.1:2008 Adhesives for timber and timber products – Adhesives for manufacture of plywood and laminated veneer lumber* (Standards Australia, 2008). These bond types (A, B, C and D) represent the adhesives durability in relation to different applications.

Type A bonds are intended to withstand prolonged exposure to severe exterior conditions without failure of the glueline. Type A bonds are normally suitable for weather exposed, structural and marine applications where rigidity and durability are required. They have a design durability life for 50+ years in fully exposed situations and indefinite durability in semi-exposed and interior applications.

Type B bonds are intended to withstand occasional wetting and drying without delamination and can be used in exterior plywood applications such as concrete formwork and exterior door skins. They have a design durability life of five to 10 years in fully exposed situations, up to 20 years for semi-exposed applications and indefinite service life in fully protected sites.

Type C bonds are intended to withstand infrequent wetting and drying without delamination as may occur in interior applications fully protected from the weather.

Type D bonds are intended for normal interior, non-structural applications including furniture and fittings.

To capitalise on the high mechanical properties and high natural durability that are characteristic of most of the hardwood species included in the study, achieving reliable B bond performance is critical. To enable a much wider scope of structural markets to be explored, achieving reliable A bonds would be extremely beneficial. To date, achieving reliable B bonds have proven challenging with hardwood species such as those included in this study and achieving reliable A bonds has been impossible. Within the Australian industry, phenol formaldehyde (PF) adhesive systems are usually adopted where A bonds are targeted while melamine urea formaldehyde (MUF) adhesive systems are commonly used to achieve B bonds. Polyurethanes (PU) have gained some acceptance in Europe as durable structural adhesives; however, they do not currently comply with the applicable Australian standards.

For this study, MUF adhesives were favoured for product manufacturing given the expectation of satisfactory bond quality conformance. Phenol formaldehyde adhesives were initially the primary focus for the laboratory trials with the primary objective of identifying the limiting factor preventing this bonding system reliably achieving A bonds when applied to hardwoods. A total of five trials using PF adhesive systems were completed. Some disappointing outcomes in the early MUF trials resulted in a total of seven laboratory scale trials being conducted using the MUF adhesive system. While not used in Australia at this stage, one trial using a PU was also included. Two trials using overlay systems were included as a focus towards the potentially high-value formply market.

3.5.1. Phenol formaldehyde

A total of five laboratory scale adhesive trials were conducted using phenol formaldehyde (PF) adhesive systems. These trials used seven adhesive types supplied by Momentive Specialty Chemicals and one adhesive type supplied by Dynea. The fabrication protocols are described in Table 7.

The objective of trial one (PF 1) was to investigate the impact of adhesive application strategy on bond quality. Two different application strategies were adopted including spreading adhesive on both sides of all veneers and spreading adhesive on both sides of alternate veneers (i.e. cross bands only). One plywood panel (320 mm x 320 mm x 33 mm) per species (four species included) for each application strategy was included providing a total of eight panels. Veneers were all conditioned to between 6 and 7% moisture content prior to manufacture.

Trial PF 2 had two components. The objectives of trial PF 2-1 was to provide benchmark data for two common and commercially available PF adhesive systems, and the objective of trial PR 2-2 was to investigate the effect that product thickness and resulting heat transfer during hot pressing had on bonding quality. To enable this evaluation, two product thicknesses were used including a thin product (15 mm plywood) and thick product (33 mm

LVL). Six plywood panels (320 mm x 320 mm x 15 mm) and six LVL panels (320 mm x 320 mm x 33 mm) per species (four species included) for each adhesive type provided a total of 96 panels. Veneers were all conditioned to between 6% and 7% moisture content prior to manufacture. The improved bond performance demonstrated within trial PF 1 resulted in the adoption of applying adhesive to both veneer faces for trial PF 2.

Given the relatively poor results from earlier trials, trial PF 3 was conducted in very close collaboration with Momentive Specialty Chemicals in their Melbourne based laboratory. Four Momentive supplied formulations were trialed including a dark PF resin designed for 'difficult to glue' tropical species (HL 4645), a dark PF resin commonly used to commercially produce softwood plywood and LVL (DPL 6381) and a white PF resin (low pH) with and without a catalyst added (XB-91MO and XB-91MO +AlCL3). In-line with Momentive's in-house procedures for laboratory adhesive trials, the adhesive was applied with a hand roll applicator to the tight side of every veneer (Image 1). The trial included the manufacture of one 300 mm x 300 mm x 15 mm plywood panel per species (five species included) per adhesive formulation (i.e. total of 20 panels). Veneers were all conditioned to between 5% and 6% moisture content prior to manufacture.

Trial PF 4 aimed to deviate away from hardwood to hardwood bonding and investigate the bonding performance of mixing hardwood and softwood veneers. For this trial, a readily available commercial PF adhesive system (Momentive's PP1158) which hadn't been included in previous trials was applied with a hand roll applicator to the tight side of every veneer. Five different construction strategies were adopted using a combination of either Gympie messmate or spotted gum with slash pine as well as a slash pine control to produce 15 panels (three per construction strategy) measuring 300 mm x 300 mm x 17 mm. Veneers were all conditioned to between 5% and 6% moisture content prior to manufacture.

Trial PF 5 was developed after a positive result was observed using Momentive's PP1158 adhesive system in trial PF 4. The adhesive was applied with a hand roll applicator to the tight side of every veneer. Ten plywood panels measuring 300 mm x 300 mm x 17 mm plywood were manufactured using either Gympie messmate (five panels) or spotted gum (five panels). Veneers were all conditioned to between 4% and 6% moisture content prior to manufacture.

The veneer samples for trials PF 1 and 2 including representation from the inner and outer parts of the billets while trials PF 3, PF 4 and PF 5 sourced veneer samples randomly.

Image 1: Accurately measured adhesive added to veneer (left) before being spread using a hand roll applicator (right)

Table 7. Phenol formaldehyde laboratory trial fabrication methodology

Trial no.	Species	Resin system and product	Glue application	Glue spread (SGL gsm[1])	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (°C)	Hot press pressure (MPa)	Hot press time (min)
PF 1	SPG CH GMS DWG	DPL 6381 33 mm 11-ply plywood	On both sides of every veneer On both sides of alternate veneers	200 200	20 10–15	135 135	1.03 1.03	15 15	145 145	1.38 1.38	22 22
PF 2-1	SPG CH GMS DWG	DPL 6381 15 mm 5-ply plywood 33 mm 11 ply LVL	On both sides of every veneer	200 (ply-wood) 200 (LVL)	15–30	90–150	1.03	15	147	1.38	10 (ply-wood) 22 (LVL)
PF 2-2	SPG CH GMS DWG	Prefere 14L004X[2] 15 mm 5-ply plywood 33 mm 11 ply LVL	On both sides of every veneer	200 (ply-wood) 200 (LVL)	15–45	90–180	1.03	15	147	1.38	10 (ply-wood) 22 (LVL)
PF 3	SPG CH GMS DWG RMY	HL4645 DPL 6381 XB-91MO XB-91MO +AlCL3 15 mm 5-ply plywood	On the tight side of every veneer	180	5–10	10	1.03	10	145	1.30	10
PF 4	1. GMS faces with slash pine cores. 2. SPG faces with slash pine cores. 3. Slash pine only. 4. GMS faces and long bands with slash pine cross bands. 5. SPG faces and long bands with slash pine cross bands.	Momentive PP1158 17 mm 7-ply Plywood	On the tight side of every veneer	200	15	15	1.03	15	140	1.21	14
PF 5	GMS, SPG	Momentive PP1158 17 mm 7-ply Plywood	On the tight side of every veneer	200	15–30	15–30	1.03	15	140	1.21	14

[1] SGL gsm – total grams of adhesive per square metre of glue line.
[2] Adhesive supplied by Dynea.

3.5.2. Melamine urea formaldehyde

The melamine urea formaldehyde (MUF) adhesive system used for all trials was supplied by Momentive Specialty Chemicals and is recommended for the bonding of sub-tropical and tropical hardwood veneers. The product is marketed as Cascomel BPLY 8188 (also known as Cascomel BPLY 8166). The standard mix for this adhesive system is as follows:

1) BPLY 8188 - 90 parts by weight

2) Wheat flour (plain) - eight parts by weight and

3) Hardener (formic acid) - two parts by weight.

A total of seven adhesive trials were conducted using the MUF adhesive system. The fabrication protocols for each trial are described in Table 8.

Trials MUF 1 to MUF 3 specifically examined the effects of variables such as glue spread rates, veneer moisture content and assembly times. Each trial included the manufacture of three plywood and three LVL panels per veneer origin (selected as originating from either the inner or outer parts of the billet) per species (five species included) providing a total of 30 plywood panels and 30 LVL panels for each trial. Panels measured 300 mm x 300 mm x either 15 mm for the plywood panels or 33 mm for the LVL panels. The veneer moisture content range was progressively reduced for each trial from 11% to 16% for trial MUF 1, to 6% to 9% for trial MUF 2 (product dependent) and 2.5% to 6% (product dependent) for trial MUF 3.

Trial MUF 4 followed as a result of inconclusive results from the earlier three trials and was designed to include a ‘heavy’ and ‘light’ glue spread rate across two target veneer moisture contents representing ‘high’ and ‘low’. For this trial, 30 Gympie messmate plywood panels (five per target veneer moisture content per adhesive spread rate) and 12 softwood plywood panels (two per target veneer moisture content per adhesive spread rate) were manufactured. The panels measured 300 mm x 300 mm by either 15 mm for the Gympie messmate panels or 12 mm for the softwood panels.

Trial MUF 5 focused on the effect of macadamia nut shell flour (MNSF) as an alternative filler within the adhesive system on bond quality. The use of alternative filler combinations was investigated with the aim of reducing the reoccurring ‘washout’ that was evident in all earlier trials. Three glue mixes were prepared:

1) a standard mix

2) a mix which substituted 3% of the wheat flour with 5% MNSF and

3) a mix added 4% MNSF while maintaining 8% wheat flour.

The resin weight was adjusted to maintain the same glue mix weight. Twenty panels per species (Gympie messmate and hoop pine) were manufactured in total comprised of 10 using the Mix 1 (standard mix), seven with Mix 2 (substituted filler) and three panels with Mix 3 (additional filler) per species. Panels measured 220 mm x 220 mm x either 15 mm for the Gympie messmate panels and 12 mm for the hoop pine panels. The target veneer moisture content was between 4% and 5%.

Trial MUF 6 investigated the effect of increasing the hardener level in the adhesive mix. This was based on a theory that the adhesive may not be fully curing and may explain the consistently good bonds when testing dry but poor bonds when tested after water soaking. Two adhesive mixes were prepared and included a standard mix (i.e. 2% hardener) and one that included 4% hardener. Twenty plywood panels (measuring 300 mm x 300 mm x 12 mm) per adhesive mix were prepared using spotted gum veneer. A target veneer moisture content of 3% was adopted.

With the potentially encouraging outcome from trial MUF 5, trial MUF 7 was developed as a larger scale trial to further validate the effect of substituting 3% of the wheat flour with 5% MNSF. A total of 40 plywood panels (measuring 300 mm x 300 mm x 12 mm) were manufactured using either the standard mix (20 panels) or a mix which substituted 3% of the wheat flour with 5% MNSF (20 panels). A target veneer moisture content of 4% was adopted.

Trials MUF 1 and MUF 2 used a large hot press to manufacture up to eight samples at once. However, after poor bonds due to low pressing pressure were observed, the methodology for all later trials was modified with panels being pressed individually in the laboratory press to ensure satisfactory control. For all trials, the adhesive was spread on both sides of alternate veneers (i.e. crossbands only) for plywood and both sides of every veneer for LVL (Image 2). For trials MUF 4 to MUF 7 all veneer was sourced randomly from available stocks.

Image 2: Glue application

Table 8. Melamine urea formaldehyde laboratory trial fabrication methodology

Trial No	Product	Species	Glue spread (SGL gsm[3])	Veneer moisture content (%)	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (oC)	Hot press pressure (MPa)	Hot press time (min)
MUF 1	15 mm 5-ply plywood 33 mm 11-ply LVL	SPG CH GMS DWG RMY	205–215 (plywood) 250 (LVL)	11–16	15	25–90	0.86	15	121–126	1.03	9 (ply-wood) 24 (LVL)
MUF 2	15 mm 5-ply plywood 33 mm 11 ply LVL	SPG CH GMS DWG RMY	230 (plywood) 245–265 (LVL)	8–9 (plywood) 6–7 (LVL)	5–15 (plywood) 4–20 (LVL)	65–75 (plywood) 60–75 (LVL)	1.03	15	128–131 (ply-wood) 128–134 (LVL)	1.20	10–12 (ply-wood) 24–25 (LVL)
MUF 3	15 mm 5-ply plywood 33mm 11 ply LVL	SPG CH GMS DWG RMY	230 (plywood) 280 (LVL)	6 (plywood) 2.5 (LVL)	5–10 (plywood) 25–30 (LVL)	15–20 (plywood) 15–47 (LVL)	0.004[4]	15	130	1.21	6 (ply-wood) 27 (LVL)
MUF 4	15 mm 5-ply hardwood plywood 12 mm 5 ply softwood plywood	GMS *Pinus* sp.	240 and 175	10, 5 and 2.5	9–20	1–9	0.002[4]	15	128–136	1.21	9
MUF 5	15 mm 5-ply hardwood 12mm 5-ply Softwood	GMS Hoop	235	5 GMS 4 hoop	13–20	1–3	0.002[4]	12–18	127–133	1.21	9
MUF 6	12 mm 5-ply plywood	SPG	235	3	15–30	9–15	0.002[4]	3–49	127–136	1.21	8
MUF 7	12 mm 5-ply Plywood	SPG	235	4	11–30	7–46	0.002[4]	7–12	126–137	1.21	8

[3] SGL gsm – total grams of adhesive per square meter of glue line.
[4] Low pre-press conditions are a result of using a static weight rather than a press. Despite the low values, the pre-press result (e.g. adhesive transfer and tack) was considered satisfactory.

3.5.3. Polyurethane

As polyurethane (PU) is gaining acceptance on the international market (particularly in Europe) as a structural adhesive, a small trial (PU1) was conducted using this glue type. A Purbond polyurethane marketed as HBS 309 was used. Gympie messmate, spotted gum, spotted gum hybrid, Dunn's white gum and red mahogany veneer were included in the trial. The veneer storage time (time between peeling and adhesive trial) varied between species from two months for red mahogany and 17 months for Dunn's white gum. Veneer samples were sourced from surplus veneer material remaining from sampling strips (150 mm wide) that were removed from both the inner and outer part of the billet. The veneer samples were conditioned to 11% moisture content and cut into 300 mm lengths. When fabricated as pairs (i.e. two pieces 150 mm x 300 mm), a sample size of 300 mm x 300 mm was manufactured. No pre-surface treatments were used.

For each species, two samples of 15 mm, 5-ply plywood panels and one sample of 33 mm, 11-ply LVL panel were fabricated. Calibrated scrapers supplied by Purbond were used to spread the adhesive to a targeted glue spread of 200 gsm single glue line. A lay up/open assembly time of approximately 25 minutes was targeted followed by a 75 minute press time at 1.0 MPa glue line pressure. All pressing was conducted at ambient temperatures.

3.5.4. Overlaid plywood

Plywood with high mechanical properties which has the face veneers overlaid with a paper/resin film has the potential to be a high-value product with demand from the construction industry for forming concrete (known as formwood, formply etc). The market demands a high quality surface finish for this product and to achieve this, it is common practice to use very thin veneer faces (e.g. 0.9 mm) which are defect free, tight and straight grained from species often sourced from rainforest areas of Asia, Africa etc. Continuing restrictions and limitations on illegal logging combined with a general reduction in available grade quality is making suitable faces for this product range increasingly difficult to source and increasingly more expensive. Market demand however, remains strong and the product range can be quite profitable (Dorries *pers comm*. 2013).

Two trials with overlaid plywood were conducted as a result of industry interest to determine whether plantation hardwood veneers have the potential to be a substitute for currently available supplies of face veneers for overlaid panels. The fabrication protocols for each trial are described in Table 9.

Trial OL 1 was conducted using Gympie messmate faced plywood with a commercially available overlay system to evaluate the resulting surface finish and bond quality. Three 7-ply plywood panels (measuring 300 mm x 300 mm x 17 mm) were prepared using 0.9 mm Gympie messmate face veneers (conditioned to an average of 6.1% MC) and 3.0 mm slash pine core veneers. One panel used A grade face veneers (e.g. defect free) while the other two used B grade face veneers (which included small, sound and intergrown knots up to 25 mm diameter) in accordance with *AS/NZS 2269.0:2008*. Momentive's PP1158 PF adhesive was used to manufacture the panels and a thick overlay CCFO paper (220/450) supplied by Australian Panel Products was used.

Trial OL 2 followed with the objective of assessing the surface quality that may be able to be achieved using lighter grade overlay systems. Three overlay systems supplied by Australian Panel Products were trialed on seven 7-ply plywood panels (measuring 300 mm x 300 mm x 17 mm) and included:

1) Four panels - 45/130 (45 gsm paper; total weight 130 gsm)

2) Two panels - 60/150 (60 gsm paper; total weight 150 gsm) and

3) One panel - 80/220 (80 gsm paper; total weight 220 gsm).

Of the four panels which used the thinnest overlay system (45/130), two contained A grade and two contained B grade 0.9 mm Gympie messmate faces (Image 3). For the two panels that used the 60/150 overlay system and the one panel that used the 80/220 overlay system, B grade 0.9 mm Gympie messmate faces were used. Any holes that were present in the B grade face veneers were filled prior to the overlay being applied. The core veneers in all panels were radiata pine. The panel fabrication methodology was consistent with trial OL 1.

Image 3: Knotty faced B grade face veneer (left) and A grade clear faced veneer (right)

Table 9. Overlaid plywood laboratory trial fabrication methodology

Trial No	Resin system / product	Species / overlay type	Glue application	Glue spread (SGL gsm[5])	Face veneer target moisture content (%)	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (oC)	Hot press pressure (MPa)	Hot press time (min)
OL 1	Momentive PP1158 17 mm 17-ply Formwood (17-10-7)	GMS faces (0.9 mm) with slash pine core (3 mm) CCFO overlay (220/450)	On the tight side of every veneer	200	6	15	15	1.03	15	140	1.21	14
OL 2	Momentive PP1158 17 mm 17-ply Formwood (17-10-7)	GMS faces (0.9 mm) with radiata pine core (3 mm) 45/130 Overlay 60/150 Overlay 80/220	On the tight side of every veneer	200	6	15	15	1.03	15	140	1.21	14

[5] SGL gsm – total grams of adhesive per square metre of glue line.

		Overlay										

3.5.5. Bond evaluation (PF and MUF)

The evaluation of bond quality for plywood and LVL were conducted in accordance with the test methods described in Australian and New Zealand standard *AS/NZS 2098.2.2012 Methods of test for veneer and plywood, Method 2: Bond quality of plywood (chisel test)* (Standards Australia, 2012). This test method aims to forcibly remove veneers along the glue line allowing for the percentage of wood fibre to be estimated in the exposed surface and the glueline to be evaluated. A quality glueline will demonstrate substantial wood fibre failure on the separated veneers while a poor bond will have little or no wood fibre remaining (indicating the adhesive has failed).

3.5.5.1. Sample preparation

Four test sample preparation categories are described within *AS/NZS 2098.2:2012* inline with the four bond types (type A, B, C and D bond) and are summarized as follows:

- Type A bond - samples are steamed for 6 hours at 200 ± 7kPa; or boiled for 72 hours at 100 degrees Celsius
- Type B bond - samples are boiled for 6 hours at 100 degrees Celsius
- Type C bond - samples are boiled for 6 hours at 70 degrees Celsius
- Type D bond - samples are submerged in water at ambient temperature for between 16 and 24 hours.

For type A, B and C bonds, at the completion of boiling (or steaming for type A bonds), samples are placed in room temperature water and allowed to cool to the ambient temperature. Testing must be completed within 24 hours of removal from hot water or steam. Type D bonds are to be tested immediately upon removal from water submersion.

Trials which utilised a PF resin system were tested against the type A bond conditions while trials which utilised a MUF resin system were tested against the type B bond conditions. Test samples were prepared to a dimension of approximately 150 mm x 65 mm x sample thickness prior to being exposed to the sample preparation conditions.

3.5.5.2. Test and evaluation procedure

The test procedure, as described in *AS/NZS2098.2:2012*, utilised a pneumatic chisel to force the gluelines apart in a direction perpendicular to the grain of the veneer (Image 4). This was completed for each glueline within the samples. Separated samples were dried before wood fibre failure assessments were completed.

At the completion of veneer separation and veneer drying, individual veneers from each glueline were assessed to determine the estimated percentage area covered by wood fibre failure (Images 4 and 5) and a bond quality value was assigned for each glueline (Table 10). Under normal circumstances, a sample pass or failure would be determined in accordance with the specification outlined in the relevant standard depending on the product (e.g. *AS6669:2007, AS/NZS2269.0:2012, AS/NZS2271:2004, AS/NZS 4357.0:2005*) with each of the standards essentially requiring a sample to have an average bond quality score of not less than 5 with any individual glue line not less than a bond quality score of 2. However for the purposes of the project, glue line performance was analysed as individual glue lines rather than being grouped within samples.

Image 4: Pneumatic chisel used to separate veneers

Image 5: Separated veneers facilitate assessment of wood fibre failure

Table 10. Bond quality scale

Estimated wood-failure (%)	Bond quality value
0–5	0
6–15	1
7–25	2
26–35	3
36–45	4
46–55	5
56–65	6
66–75	7
76–85	8
86–95	9
96–100	10

3.5.6. Bond evaluation (polyurethane)

Polyurethane adhesives are not an approved structural adhesive for plywood and LVL in Australia and the bond evaluation systems adopted in Australia (i.e. *AS/NZS2098.2:2012*) were not intended for the evaluation of polyurethane adhesives. In view of this, International Standard *ISO 12466.1:2007 Plywood – Bonding quality - Part 1 Test methods* and *ISO 12466.2:2007 Plywood – Bonding quality – Part 2: Requirements* were used to assess the polyurethane glueline performance on plywood samples. International standards *ISO/DIS 10033.1:2009 Laminated veneer lumber – Bonding quality – Part 1: Test methods* and *ISO/DIS 10033.2:2009 Laminated veneer lumber – Bonding quality – Part 2: Requirements* were used to assess the polyurethane glueline performance on LVL samples. These standards detail three bonding classes (or bond types), based on adhesive moisture resistance. These classes are:

- Class 1: Dry conditions - appropriate for plywood intended for use in normal interior climates
- Class 2: Tropical-dry/humid conditions - appropriate for protected external situations, but capable of resisting weather exposure for short periods.
- Class 3: High humidity/exterior conditions - appropriate for prolonged exposure to weather over sustained periods.

Class 3 was chosen as the adhesive performance criteria for the trial, being similar to type A bond (see Section 3.5).

For plywood samples assessment, a combination of a mechanical lap shear test and a visual assessment of the apparent cohesive wood failure were used to determine the quality of the bond. For LVL samples assessment, a delamination test was adopted along with an optional mechanical lap shear. *ISO/DIS 10033.1:2009* also has provision for another optional chisel test (similar to plywood test method) however this method was not adopted for the study.

3.5.6.1. Sample preparation

For lap shear testing of both plywood and LVL, samples measuring 75 mm long x 25 mm x sample thickness (i.e. 15 mm and 33 mm respectively) were removed from the manufactured test panels. Each test sample had saw cuts extending from the faces to a nominated crossband (Image 6) in accordance with the standard. For the LVL delamination testing, samples measuring 75 mm x 75 mm x sample thickness (i.e. 33 mm) were removed from the manufactured test panels.

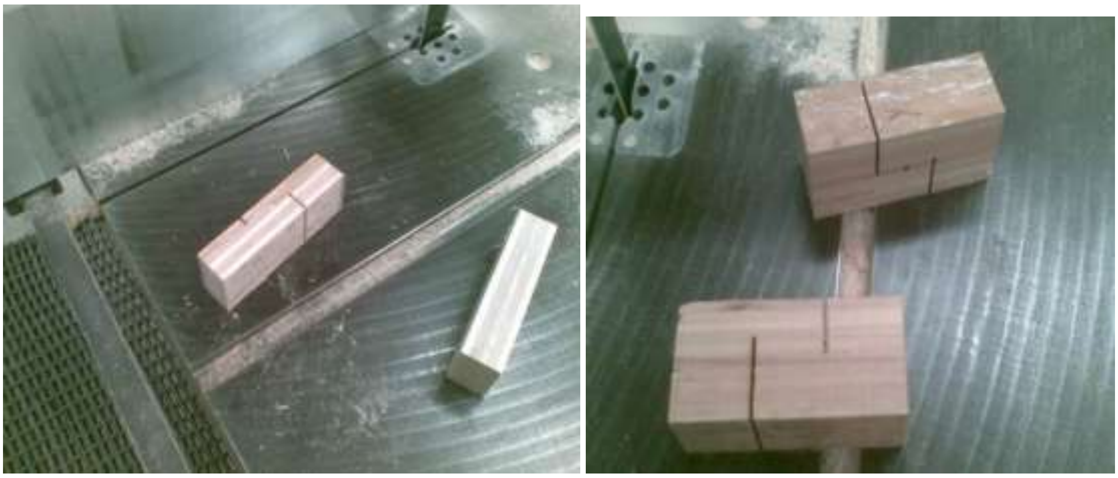


Image 6: Plywood (left and LVL (right) samples prepared for lap shear testing

Prepared samples were then pre-treated. For each of the bond classes, *ISO 12466.2:2007* and *ISO/DIS 10033.2:2009* describes the relevant sample pre-treatment requirements for plywood and LVL respectively (Table 11). This includes a basic pre-treatment of either 24 hour water soak or a vacuum pressure treatment and for class 2 and 3 tests; an additional pre-treatment is required. For the trial, the basic pre-treatment was skipped and samples (plywood and LVL) were immediately exposed to steam additional treatment (200+-7 kPa for six hours +-15 minutes). Table 12 illustrates the number of samples for each test type.

Table 11. Pre-treatment schedule

Bonding class	Pre-treatment						
	Basic pre-treatment			Additional pre-treatment			
	24 hour soak	Vacuum pressure treatment	Hot water soak (LVL only)	6 hour boil	Boil, dry, boil treatment	72 hour boil	Steam
1	X	X	X	-	-	-	-
2	X	X	-	X	X	X	X
3	X	X	-	-	X	X	X

Source: adapted from *ISO 12466.2:2007* and *ISO/DIS 10033.2:2009*

Table 12. Polyurethane bonded plywood and LVL sample allocation

Panel type	Test procedure	Number of test samples
Plywood (15 mm, 5-ply)	Lap shear	150 (5 species x 15 test samples x 2 cross bands)

LVL (33 mm, 11-ply)	Lap shear	45 (5 species x 1 test samples x 9 glue line pairs)
LVL (33 mm, 11-ply)	Delamination test	200 glue lines (1 panel x 4 test samples x 5 species (SPG, DWG, CH, RMY and GMS) x 10 glue lines

3.5.6.2. Test and evaluation procedure

After pre-treatment, samples were dried. The lap shear samples were then clamped with grips and using a universal testing machine, samples were pulled in tension until sample failure. The shear strength was then calculated in megapascals (MPa). A visual assessment and percentage of the apparent cohesive wood failure was determined from the tested lap shear samples.

ISO/DIS 10033.2:2009 requires each tested glueline to comply with two criteria: the mean shear strength and the average apparent cohesive wood failure, as outlined in table 13.

Table 13. Lap shear and cohesive wood failure glueline requirements

Mean shear strength MPa	Average apparent cohesive wood failure %
$\tau < 0.2$	Not applicable
$0.2 \leq \tau < 0.4$	≥ 80
$0.4 \leq \tau < 0.6$	≥ 60
$0.6 \leq \tau \leq 1.0$	≥ 40
$1.0 < \tau$	No requirement

For the LVL delamination tests, samples are dried after the pre-treatment process and the length of delamination in each glueline on the four sides of the test piece was measured allowing the ratio of the delamination in each glueline to the total length of the glueline on four sides to be determined. In addition, the ratio of the total length of delamination on the four sides to the total length of all gluelines on four sides was also calculated as a percentage.

ISO/DIS 10033.2:2009 requires each test sample to meet the following criteria:

- Ratio of delamination (%) in each separate individual glueline shall not exceed 25
- Ratio of delamination (%) for the total length of all gluelines shall not exceed 5.

3.5.7. Bond evaluation (overlay)

Bond evaluation was conducted in accordance with Appendix F Test methods for overlays - bond quality and durability testing as detailed in *AS669:2007*. This test method establishes the bond quality and durability between the overlay paper and the plywood substrate. As the overlay paper is impregnated with phenolic resin (PF system), the Type A bond test in accordance with *AS/NZS 2098.2:2012* is used.

3.5.7.1. *Sample preparation*

Samples were subjected to the standard Type A bond procedure which includes samples being steamed for 6 hours at 200 ± 7kPa; or boiled for 72 hours at 100 degrees Celsius. Following this, samples are allowed in cool in room temperature water and allowed to cool to the ambient temperature.

3.5.7.2. *Test and evaluation procedure*

Once the samples have been prepared, the sample surfaces are inspected for any areas of delamination or blisters. Any samples displaying severe delamination or blistering results in immediate test failure.

Following the visual inspection, an area on the overlay face was scored in a cross hatch pattern using a sharp knife making small squares approximately 6–10 mm. A pneumatic chisel (same apparatus used for PF and MUF glue bond testing - See 3.5.5.2) was used to remove the overlay from the face veneer. An average of 50% wood plus overlay paper failure is the minimum requirements to pass.

3.6. Veneer product manufacture

A typical structural plywood panel and laminated veneer lumber (LVL) were the two product categories chosen for product manufacture and structural properties validation. Two variations of plywood panels were included which consisted of a single specie construction along with a mixed hardwood and softwood species panel. The LVL products were single species only.

3.6.1. Plywood (single species)

For the main plywood trial (PLY 1), four species were selected and included spotted gum - Site 1, spotted gum hybrid, Gympie messmate - Site 1 and Dunn's white gum. Twenty plywood panels (1180 mm x 1180 mm x 15 mm) per species were manufactured using a standard five-ply construction (i.e. 5 veneers x 3.0 mm veneer thickness = 15 mm panel thickness). In addition to the main trial, trial PLY 2 included the use of red mahogany veneers with a total of 72 panels (1180 mm x 300 mm x 15 mm) being manufactured using the same veneer construction.

The selection of veneer was guided by the results of veneer acoustic grading. The acoustic values were used to assign percentile cut offs for each specie allowing the selection of approximately 240 veneers to represent high MOE (H) and approximately 240 veneers to represent low MOE (L) for each species. Approximately half of these veneers were used for the plywood panel manufacture while the balance was used for LVL manufacture (Section 3.6.2). Red mahogany was the only variation to this methodology with 180 veneers selected to represent high MOE (H) and 180 veneers to represent low MOE (L). The percentile cut offs and MOE thresholds are detailed in table 14.

Table 14. Veneer selection criteria for single specie plywood product manufacture

Species	Low percentile cut off	Low MOE cut off (MPa)	High percentile cut off	High MOE cut off (MPa)
Spotted gum	50	<16 117	50	>16 117
Spotted gum hybrid	30	<10 312	70	>13 176
Gympie messmate - Site 1	20	<11 797	80	>19 978

Dunn's white gum	25	<9 915	75	>15 095
Red mahogany	15	<9 877	85	>18 098

Four different construction strategies were utilised across all species to demonstrate the impact of veneer grading and construction strategies on manufactured panel mechanical properties. The construction strategies for the five different five-ply sheets were:

1) High MOE veneer throughout the panel thickness (i.e. H,H,H,H,H).

2) Low MOE veneer throughout the panel thickness (i.e. L,L,L,L,L).

3) High MOE veneer on the two faces and low MOE veneer for the three internal core veneer (i.e. H,L,L,L,H).

4) Low MOE veneer on the two faces and high MOE veneer for the three internal core veneers (i.e. L,H,H,H,L).

For trial PLY 1, five panels per construction strategy per species where manufactured. For trial PLY 2, 18 panels per construction where manufactured. The fabrication protocols for each trial are described in Table 15. Once removed from the hot press, panels were sprayed with a light coating of water to restore some moisture back into the face veneers before being block stacked. Images 7 to 9 provide illustration of the process. The manufactured panels were then subjected to adhesive bonding evaluation and mechanical properties testing (Section 3.7).

Table 15. Single species plywood panel fabrication methodology

Trial No	Resin system/ Product	Species	Glue application	Glue spread (SGL gsm[6])	Veneer moisture content (%)	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (°C)	Hot press pressure (MPa)	Hot press Time (min)
PLY 1	Momentive Cascomel BPly 8188 15 mm 5-ply	SPG CH DWG GMS	On both sides of alternate veneers	220–240	4	5–15	15–45	1.03	15	130	1.21	8
PLY 2	Momentive Cascomel BPly 8188 15 mm 5-ply	RMY	On both sides of alternate veneers	170–200	9	5–15	15–25	1.03	15	130	1.21	10

[6] SGL gsm – total grams of adhesive per square metre of glue line.

Image 7: Reference veneer including acoustic grade (left) and veneer prepared for sequential assembly (right)

Image 8: Veneer cross bands having adhesive applied (left) and panels being cold pressed (right)

Image 9: Hot pressing panels (left) and water spraying plywood panels after manufacture (right)

3.6.2. Laminated Veneer Lumber (single species)

For the LVL trial, four species were selected (spotted gum - Site 1, spotted gum hybrid, Gympie messmate - Site 1 and Dunn's white gum). Eight panels (1180 mm x 1180 mm x 39 mm) per species were manufactured using 13 veneers per panel (i.e. 13 veneers x 3.0 mm veneer thickness = 39 mm panel thickness). Veneer selection was guided by veneer acoustic grading to provide high and low MOE veneers for each species (Section 3.6.1).

Four different construction strategies were utilised across all species to demonstrate the impact of veneer grading and construction strategies on manufactured product mechanical properties. The construction strategies were:

1) Two panels – 13 high MOE veneer sheets throughout the panel thickness (i.e. H,H,H,H,H,H,H,H,H,H,H,H,H).

2) Two panels – 13 low MOE veneer throughout the panel thickness (i.e. L,L,L,L,L,L,L,L,L,L,L,L,L).

3) Two panels – two high MOE veneers on the two faces and nine low MOE veneer for the internal core veneer (i.e. H,H,L,L,L,L,L,L,L,L,L,H,H).

4) Two panels – two low MOE veneer on the two faces and nine high MOE veneer for the internal core veneers (i.e. L,L,H,H,H,H,H,H,H,H,H,L,L).

The fabrication protocols for each trial are described in Table 16. Upon removal from the hot press, panels were sprayed with a light coating of water to restore some moisture back into the face veneers before being block stacked. The manufactured panels were then subjected to adhesive bonding evaluation and mechanical properties testing (Section 3.7).

Table 16. Single species LVL fabrication methodology

Trial No.	Resin system / product	Species	Glue application	Glue spread (SGL gsm[7])	Veneer moisture content (%)	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (°C)	Hot press pressure (MPa)	Hot press time (min)
LVL 1	Momentive Cascomel BPly 8188 15 mm 5-ply	SPG CH DWG GMS	On both sides of every veneer	260–290	4	5–15	15–45	1.03	15	130–139	1.21	38

3.6.3. Plywood (mixed species)

For the mixed species plywood panels, Gympie messmate - Site 2 veneers were used along with radiata pine (*Pinus radiata*) veneers which were supplied as graded structural veneer from a commercial plywood mill. Seventy panels (1180 mm x 1180 mm x 12 mm) were manufactured to investigate the comparative advantages of manufacturing plywood panels using a combination of plantation hardwood faces and softwood cores versus panels manufactured from radiata pine only. A standard five-ply construction (i.e. five veneers x 2.5 mm veneer thickness = 12.5 mm panel thickness) was adopted with 35 panels being manufactured using only radiata pine while the remaining 35 panels were manufactured

[7] SGL gsm – total grams of adhesive per square meter of glue line.

using a combination of radiata pine veneers in the core and Gympie messmate veneers on the faces.

Similar to the single species plywood and LVL trials (Sections 3.6.1 and 3.6.2), from the analysed acoustic grading data, percentile cut offs were selected to provide the required number of veneer sheets (70 face veneers) which contained the highest MOE (e.g. top 20% of veneers selected). The same percentile cut off (i.e. top 20% of veneers selected) was applied to the available radiata pine veneers for the selection of 70 face veneers. Sufficient core material was randomly chosen from the remaining radiata pine veneers that remained (which all had an MOE of less than 13 544 MPa). As these veneers measured 2500 mm x 1250 mm, each veneer was cut in half allowing one half to be allocated to the two different construction strategies. Accurate records were maintained ensuring that individual placement of veneers resulted in identical panels with the face veneer being the only variable (i.e. either high MOE Gympie messmate or high MOE radiata pine). The percentile cut offs and MOE thresholds for the face veneers are detailed in table 17.

Table 17. Face veneer selection criteria for mixed specie plywood product manufacture

Species	High percentile cut off	High MOE cut off (MPa)
Gympie messmate - Site 2	80	>18 807
Radiata pine	80	>13 544

The selected veneers were conditioned to a target moisture content of between 6-8%. The conditioned veneer was immediately plastic wrapped to prevent/minimise any moisture uptake during cooling and temporary storage.

The fabrication protocols for each trial are described in Table 18. Upon removal from the hot press, panels were sprayed with a light coating of water to restore some moisture back into the face veneers before being block stacked. Image 10 provides illustration of the process. The manufactured panels were then subjected to adhesive bonding evaluation and mechanical properties testing (Section 3.7).

Table 18. Mixed specie plywood fabrication methodology

Trial No	Resin system / product	Species	Glue application	Glue spread (SGL gsm[8])	Veneer moisture content (%)	Open assembly time (min)	Closed assembly time (min)	Pre-press pressure (MPa)	Pre-press time (min)	Hot press temp (°C)	Hot press pressure (MPa)	Hot press time (min)
PLY 3	Momentive PP1158 12 mm 5-ply	1. GMS faces with radiate pine core 2. Radiata pine face and cores	On both sides of alternate veneers	195	6–8	15	45	1.03	15	135	1.03	10

[8] SGL gsm – total grams of adhesive per square metre of glue line.

Image 10: Applying adhesive to the veneer (left) and water spraying plywood panels after manufacture (right)

3.7. Veneer product performance

3.7.1. Plywood (single species)

The manufactured plywood panels produced from the main plywood manufacture trial were used to establish a range of basic mechanical properties including bond performance. Due to the range of construction strategies adopted and the relatively small number of samples per species, the objective of the testing was to provide an indication of the spread of mechanical properties that may be expected from the various plantation species and also demonstrate the impact of veneer grading and the benefits of efficient construction strategies.

Mechanical properties test samples were in principle prepared and tested in accordance with Australian and New Zealand standard *AS/NZS 2269.1:2008 - Plywood structural - Part 1: Determination of structural properties – Test methods*. However, due to the panel size being much smaller compared to a conventional commercially produced plywood panel (i.e. nominally 1200 mm x 1200 mm versus 2400 mm x 1200 mm) a modified sample cutting pattern was developed (Figure 6). Note that Figure 6 illustrates the cutting pattern per construction strategy per species. Immediately after the test samples were sawn, they were stored in a controlled environment (20°C/65% RH) and conditioned to 12% moisture content until testing was conducted.

Adhesive bond evaluation was also conducted on between four and six samples per species (spotted gum, spotted gum hybrid, Dunn's white gum and Gympie messmate). For red mahogany, three samples per construction strategy were provided for bond evaluation (total of 12 samples). As the adhesive used was an MUF, bond evaluation was performed in accordance with the test requirements for type B bond (Section 3.5.5).

For the red mahogany plywood panels, only 4-point static bending (modulus of elasticity or MOE and modulus of rupture or MOR) parallel to the grain was conducted.

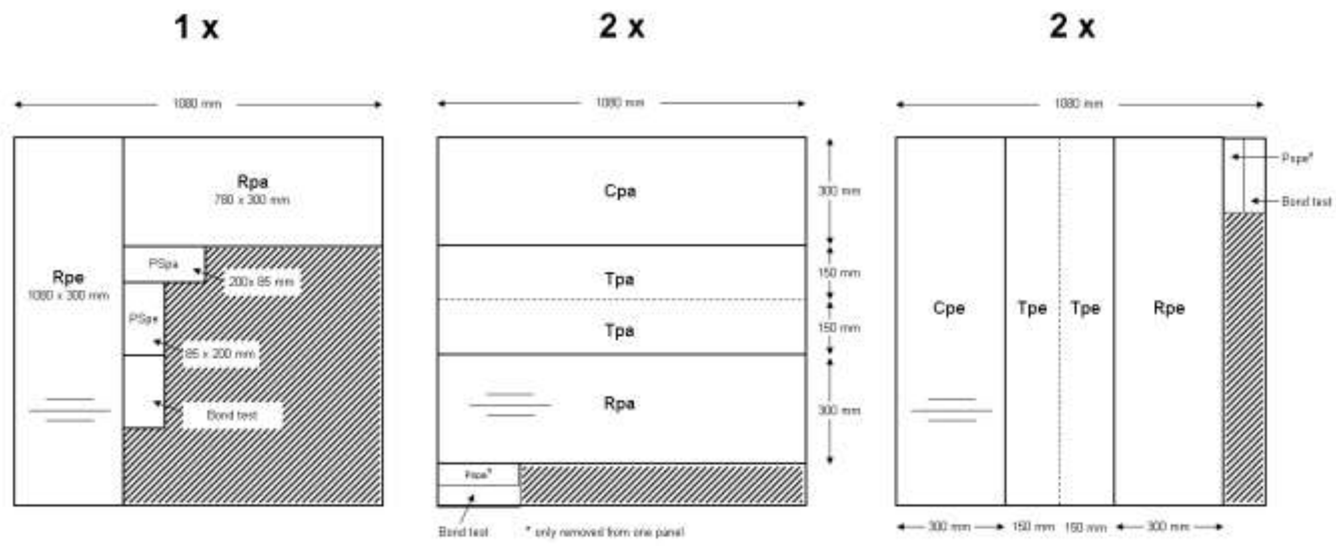


Figure 6. Plywood panel sample cutting pattern per construction strategy.

Table 19 illustrates the number of test samples per species for each test along with the sample dimensions. The only variation was for the red mahogany plywood panels which included four-point static bending parallel to the grain for only 72 samples. All mechanical properties tests were conducted within DAFF's NATA registered engineering laboratories located within the Salisbury Research Facility. A Shimadzu AG-X universal testing machine (Image 11) was used to conduct the static bending and shear tests for all plywood samples. The tension and compression testing were performed using a custom built tensile and compression test machine (Image 12).

Table 19. Number and dimension of test samples per species for each mechanical property test

Mechanical test	Test sample code	No. of samples	Sample size (mm)
4-point static bending (MOE/MOR) – parallel	Rpa	12	1080 or 780 × 300
4-point static bending (MOE/MOR) – parallel **red mahogany only	Rpa	72	1050 × 300
4-point static bending (MOE/MOR) – perpendicular	Rpe	12	1080 × 300
Shear – parallel	PSpa	12	200 × 85
Shear – perpendicular	PSpe	12	200 × 85
Compression – parallel	Cpa	8	1080 × 300
Compression – perpendicular	Cpe	8	1080 × 300
Tension – parallel	Tpa	16	1080 × 150
Tension – perpendicular	Tpe	16	1080 × 150

Image 11: Mechanical testing on plywood

Image 12: Tensile and compression test machine

3.7.2. Laminated veneer lumber (single species)

Manufactured LVL panels were used to provide a range of basic mechanical properties. Due to the range of construction strategies adopted and the relatively small number of samples per species, the objective of the testing was to provide an indication of the spread of mechanical properties that may be expected from the various plantation species and also demonstrate the impact of veneer grading and the benefits of efficient construction strategies.

Mechanical properties test samples were in principle prepared and tested in accordance with Australian and New Zealand standard *AS/NZS 4357.2:2006 - Structural laminated veneer lumber – Part 2: Determination of structural properties – Test methods*. However, due to the samples being sourced from panels which were manufactured to 1080 mm x 1080 mm, a modified cutting pattern had to be applied. In addition, due to the inability to test the tensile samples (Tpa) effectively as a direct result of the short sample length providing insufficient grip area, an alternative sample preparation methodology was adopted from *ASTM D3500-90:2003*. This resulted in a 'dog bone' style sample (Figure 7). Figure 8 illustrates the adopted cutting pattern for the LVL samples. Immediately after the test samples were sawn, they were stored in a controlled environment (20°C/65% RH) and conditioned to 12% MC until testing was conducted.

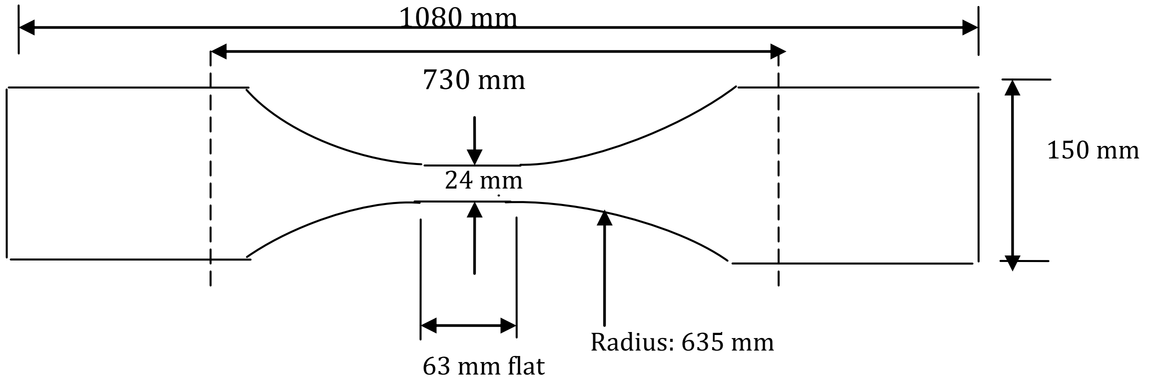


Figure 7. 'Dog bone' tensile sample

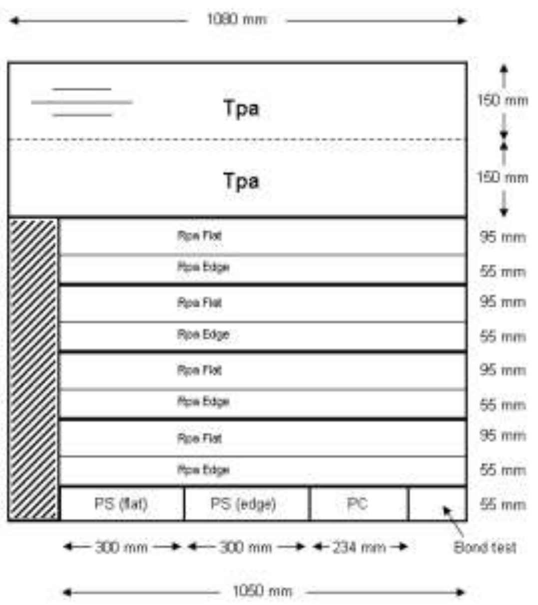


Figure 8. LVL sample cutting pattern

Table 20 illustrates the number of samples per species for each test along with the sample dimensions. All mechanical properties tests were conducted with DAFF's NATA registered engineering laboratories located within the Salisbury Research Facility. A Shimadzu AG-X universal testing machine was used to conduct the static bending, shear and compression tests. The tension tests were performed using a custom built tensile and compression test machine.

Adhesive bond evaluation was also conducted on three samples per construction strategy (total of 12 samples). As the adhesive used was an MUF, bond evaluation was performed in accordance with the test requirements for type B bond (Section 3.5.5).

Table 20. Number and dimension of samples per species for each mechanical property test

Mechanical test	Test sample code	No. of samples	Sample size (mm)
4-point static bending (MOE/MOR) – flat	Rpa flat	32	1050 × 95
4-point static bending (MOE/MOR) – edge	Rpa edge	32	1050 × 55
Shear – flat	ps flat	8	300 × 55
Shear – edge	ps edge	8	300 × 55
Compression	pc	8	234 × 55
Tension	Tpa	8	1080 × 150

3.7.3. Plywood (mixed species)

Mechanical properties test samples were in principle prepared and tested in accordance with *AS/NZS 2269.1:2008 - Plywood structural - Part 1: Determination of structural properties – Test methods*. However, testing was restricted to two static bending samples per manufactured panel tests (i.e. one sample in the parallel and one sample in the perpendicular direction). Due to the panel size being much smaller than a conventional commercially produced panel (approximately 1050 mm x 1050 mm versus 2400 mm x 1200 mm) a modified cutting pattern was applied as illustrated in Figure 9. Immediately after the test samples were prepared, they were stored in a controlled environment (20°C/65% RH) and conditioned to 12% MC until testing was conducted.

Adhesive bond evaluation was also conducted on 21 samples (11 samples from Gympie messmate face and radiata pine core panels and 10 samples from radiata pine panels). As the adhesive used was a PF, bond evaluation was performed in accordance with the test requirements for type A bond (Section 3.5.5).

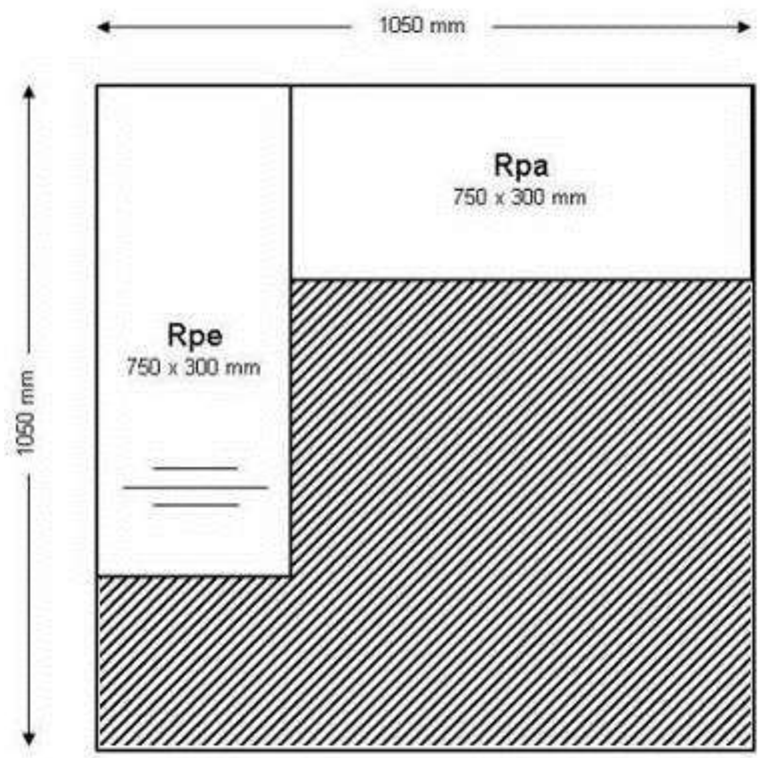


Figure 9. Plywood panel cutting pattern (mixed species)

Table 21 illustrates the number of samples for each test along with the sample dimensions. All mechanical properties testing were conducted within DAFF's NATA registered engineering laboratories located within the Salisbury Research Facility. A Shimadzu AG-X universal testing machine was used to conduct the static bending tests.

Table 21. Type of mechanical property test, number of specimens and sample dimensions

Mechanical test	No. of samples	Sample size (mm)
4-point static bending (MOE/MOR) – parallel (Rpa)	35	750 × 300
4-point static bending (MOE/MOR) – perpendicular (Rpe)	35	750 × 300

3.8. Product modelling

Product modelling has the potential to provide a tool that allows important mechanical properties of laminated wood based products such as plywood or LVL to be predicted from basic veneer information. An analytical mechanical model based on Laminated Plate Theory (LPT) was chosen using the longitudinal MOE of each laminate or veneer as the critical input. The capacity to measure longitudinal MOE of veneer is already commercially available through the use of in-line equipment such as such as the Metriguard 2800 or Raute Mecano analyser.

3.8.1. Introduction to laminated plate theory

Laminated plate theory (LPT) or classical lamination theory (CLT) is a basic design tool based on mechanical model in the elastic domain and can be used for evaluating different laminates (e.g. plywood or LVL) when experimental data is not available (Berthlot 1999) LPT can be used to combine properties and the orientation of each ply in a predetermined stacking sequence to predict the overall performance characteristics for a laminated product. LPT is based on the assumptions that laminate deforms under conditions of plane stress and that the strains experienced by the individual layers of the laminate are compatible with the strains in the neighbouring layers. The mechanical properties (i.e. the moduli and Poisson's ratios) of the unidirectional composite are required before LPT can be applied and these are best obtained from mechanical tests. In-plane loading and loading from bending can be considered. LPT can also be used to assess the stresses that arise through temperature and moisture changes. This theory provides the in-plane stresses and strains for each lamina of the laminate and can be combined with failure criteria for individual plies.

In other words, laminate theory enables analytical stress-strain analysis of the arbitrary laminated structures (with plane laminate) subjected to mechanical or thermal load. Arbitrary number of layers, layer thicknesses and material type (isotropic, anisotropic) can be taken into account. The classical laminate theory enables the calculation of stresses and strains within layers, apparent laminate properties or total deformation of the laminate (bending, twisting). Laminate theory considers the structure of the infinite dimensions, so the stresses and strains which are obtained, corresponds to the state far enough from the free edges of the real finite laminate.

Key aspects of LPT include:

- used in situations where loading is uniform in-plane or from bending
- used to analyse stress fields that are free from local stress concentrations
- easily combined with failure criteria to identify first ply failure
- rapid solutions can be extracted allowing multiple designs to be analysed
- implemented in many software packages.

The basic assumptions of Classical Lamination Theory are similar to the Euler-Bernoulli beam theory and the plate theory. The classical lamination theory is only valid for thin laminates (span > 10× thickness) with small displacement (w) in the transverse direction (w << thickness). It shares the same classical plate theory assumptions based on Kirchhoff’s Hypothesis:

- normals remain straight (they do not bend)
- normals remain unstretched (they keep the same length)
- normals remain normal (they always make a right angle to the neutral plane)

In addition, perfect bonding between layers is assumed:

- the bonding itself is infinitesimally small (there is no flaw or gap between layers).
- the bonding is non-shear-deformable (no lamina can slip relative to another).
- the strength of bonding is as strong as it needs to be (the laminate acts as a single lamina with special integrated properties).

For the calculation of the panel mechanical properties, in addition to the stacking sequence of the laminate, the ply material properties (mechanical elasticity modulus) of the composite material must be defined:

- E_x, E_y, G_{xy}: in-plane modulus (x is the fibre direction).
- γ_{xy}: in-plane Poisson's ratio.

For veneer obtained by peeling these properties are E_L, E_T, G_{LT} and γ_{LT}, L and T being longitudinal and tangential direction of the grain.

3.8.2. Simulation procedures

The laminate mechanical properties calculations were implemented through a Microsoft Excel application of the LPT developed by Bos and Guitard (1995). Many similar applications based on LPT with different functionalities can be downloaded e.g. OSU laminate or the

Laminator. The originality and specificity of trial approach included the use of acoustic longitudinal MOE (EL) obtained from BING measurement and the prediction of the other moduli through the veneer density (ET, GLT and γLT) from the models developed by Guitard and El Amri (1987). These predictive models of three-dimensional elastic behaviour satisfactorily predict the complete matrix of elastic compliances for a wood whose density and moisture content are known. A detailed procedure is provided in Appendix 1.

3.8.3. Relationship between model simulations and standard measurements

In order to assess the prediction capacity of the model, three experiments were implemented including two on plywood (PLY 1 and PLY 2 – see Section 3.6.1) and one on LVL samples (LVL 1 – see Section 3.6.2). The principle of these trials was to use the longitudinal MOE measurements gathered on veneers to manufacture panels with differentiated lamination lay up.

For plywood, four types of 5-ply panels were manufactured in order to obtain a wide range of mechanical properties:

- made only with low MOE veneers (**LLL**)
- made only with high MOE veneers (**HHH**)
- made with high MOE veneers on both faces and three low MOE veneers inside (**HLH**)
- made with low MOE veneers on both faces and three high MOE veneers inside (**LHL**)

For LVL, four types of 13-ply beams were manufactured in order to obtain a wide range on mechanical properties:

- made only with low MOE veneers (**LLL**)
- made only with high MOE veneers (**HHH**)
- made with two high MOE veneers on both faces (4 high MOE veneers) and low MOE veneers inside (9 veneers) (**HHH**)
- made with two low MOE veneers on both faces (4 low MOE veneers) and high MOE veneers inside (9 veneers) (**LLL**)

4. Results and discussion

4.1. Plantation resource

Table 22 details a summary of the plantation species harvested for processing, the tree age at time of harvesting, the average diameter at breast height over bark (DBHOB) of harvested trees, the number of billets recovered from the harvested trees, average billet small end diameter under bark (SEDUB), average billet volume and the total volume of billets processed. Figure 10 illustrates the distribution of DBHOB of selected trees across the various harvested sites. The variations between sites that exist can be attributed to a range of factors including plantation age, quality of site and tree selection methodology (e.g. selecting trees across the plantation diameter distribution versus selecting the largest diameter trees available). Figure 11 illustrates the distribution of SEDUB of billets which were processed.

Table 22. Summary of harvested trees and processed billets

	Age	No. of trees	Average DBHOB (cm)	No. of billets	Average billet SEDUB (cm)	Average billet volume (m^3)	Total volume (m^3)
Dunn's white gum	11	60	23	148	18	0.035	5.2
Spotted gum - Site 1	12	60	20	175	15	0.026	4.6
Gympie messmate - Site 1	12	30	27	144	20	0.047	6.7
Spotted gum hybrid	8	43	23	166	16	0.030	4.9
Red mahogany	13	38	28	130	21	0.049	6.4
Western white gum	12	12	24	33	18	0.035	1.1
Spotted gum - Site 2	10	10	24	20	19	0.038	0.8
Spotted gum - Site 3	10	10	22	20	17	0.031	0.6
Gympie messmate - Site 2	15	29	38	78	29	0.092	7.2
Average		**32**	**25**	**102**	**19**	**0.043**	**4.2**
Total		**292**	**-**	**914**	**-**	**-**	**37.4**

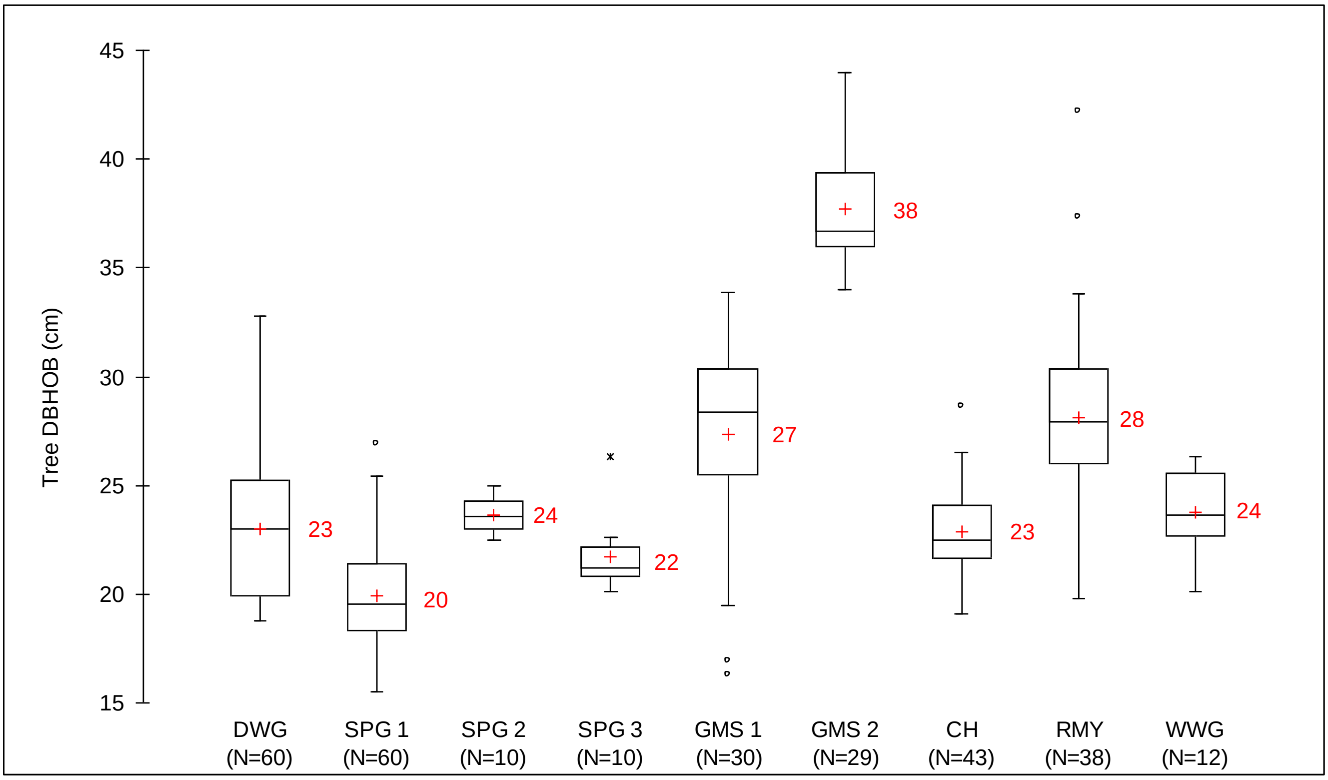


Figure 10. **Distribution of selected tree diameters at breast height over bark**

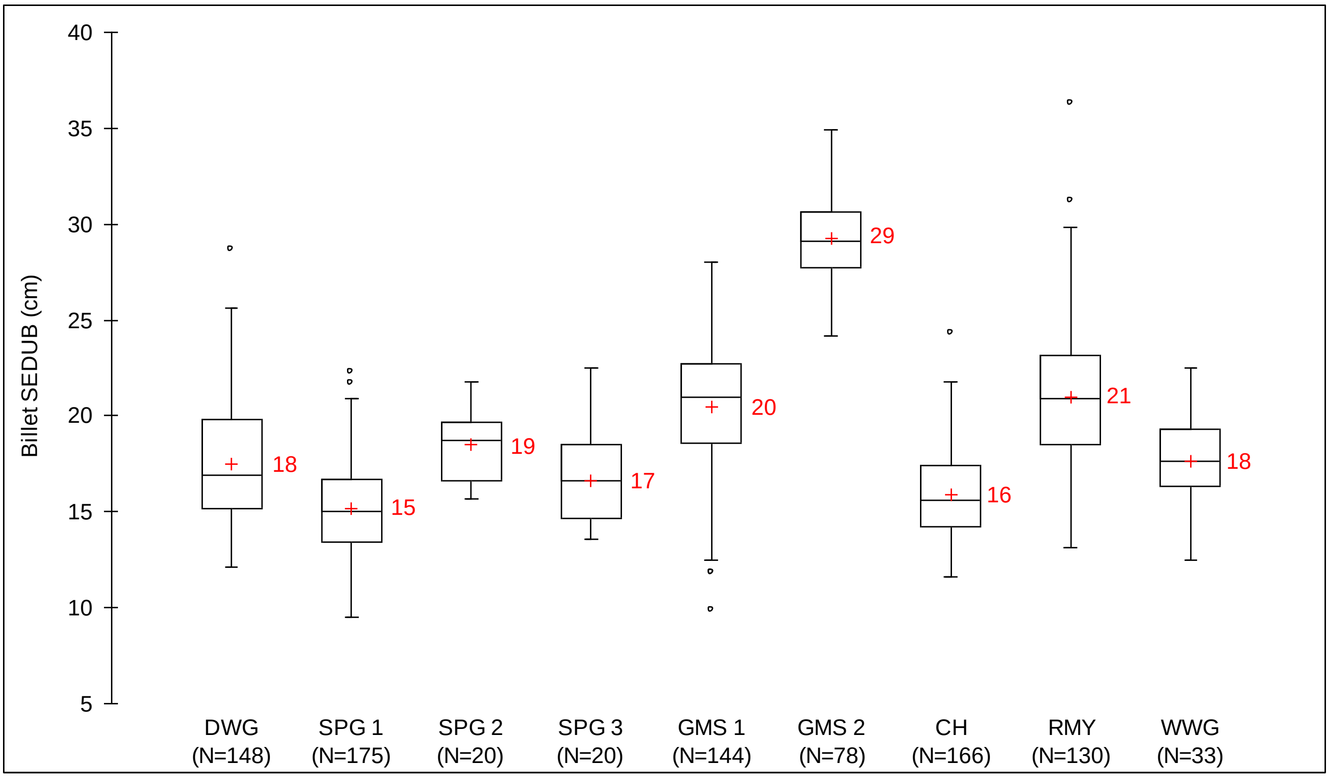


Figure 11. **Distribution of billet small end diameters under bark**

4.2. Wood quality

4.2.1. Basic density

Figure 12 illustrates the distribution of average tree basic density measures from the butt disks. The measured densities are within the expected range for these species and ages, and are consistent with many published data (McGavin et al. 2006, McGavin and Bailleres 2007, Bailleres et al. 2008). The average tree basic density of Dunn's white gum is noticeably lower than the other species and is consistent with the original preference for this species to target pulp products. The average tree densities for spotted gum across the three sites are very similar although the spotted gum hybrid is much lower. This may be due to the much younger age of the spotted gum hybrid.

Figures 13 to 20 illustrate the basic density radial variation that was measured from the butt disks.

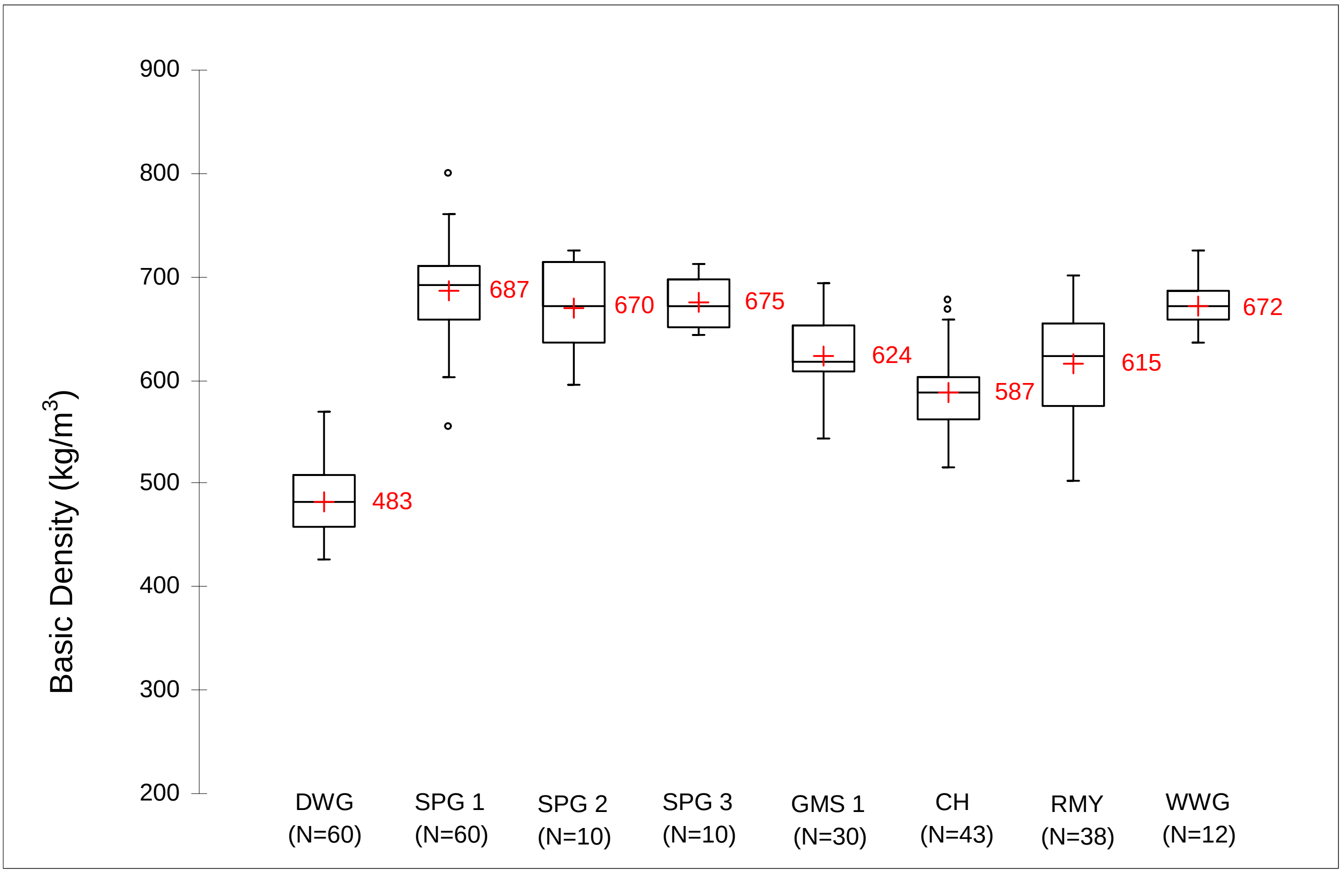


Figure 12. Distribution of average tree basic density

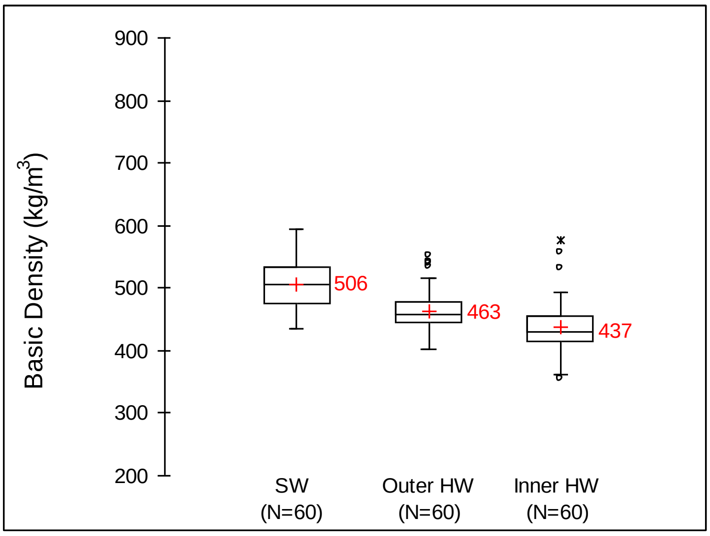


Figure 13. Dunn's white gum basic density radial variation

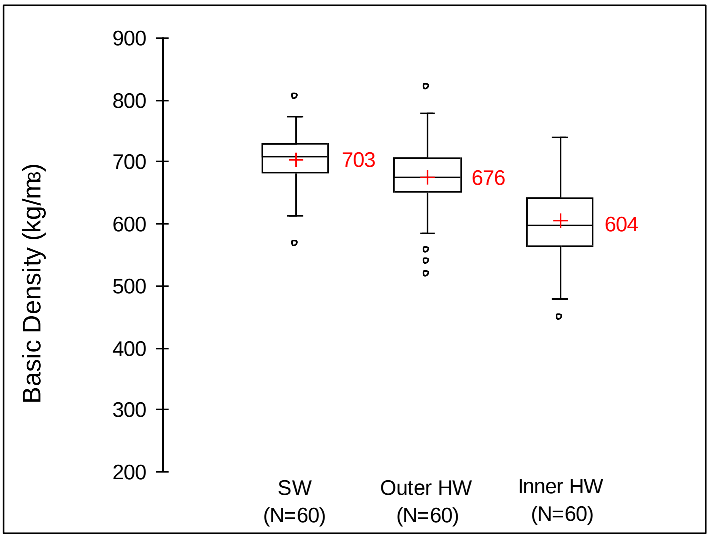


Figure 14. Spotted gum - Site 1 basic density radial variation

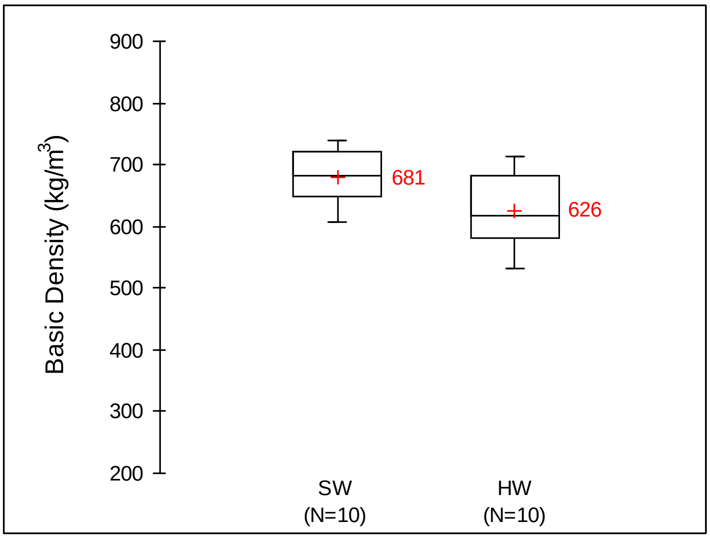


Figure 15. Spotted gum - Site 2 basic density radial variation

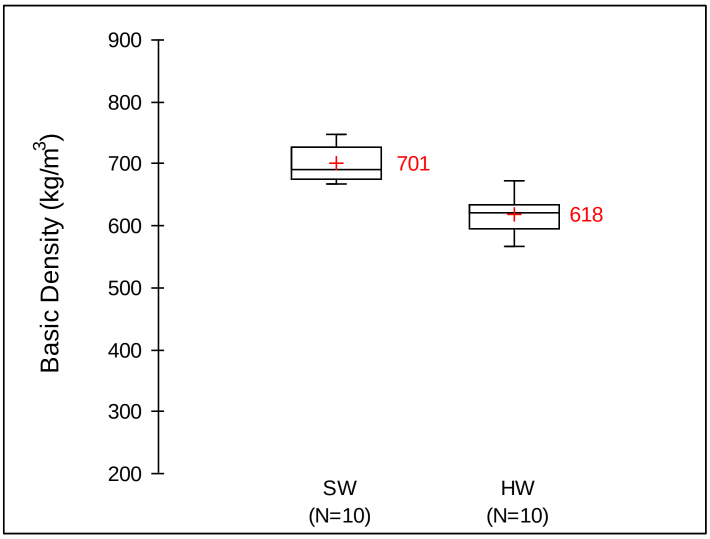


Figure 16. Spotted gum - Site 3 basic density radial variation

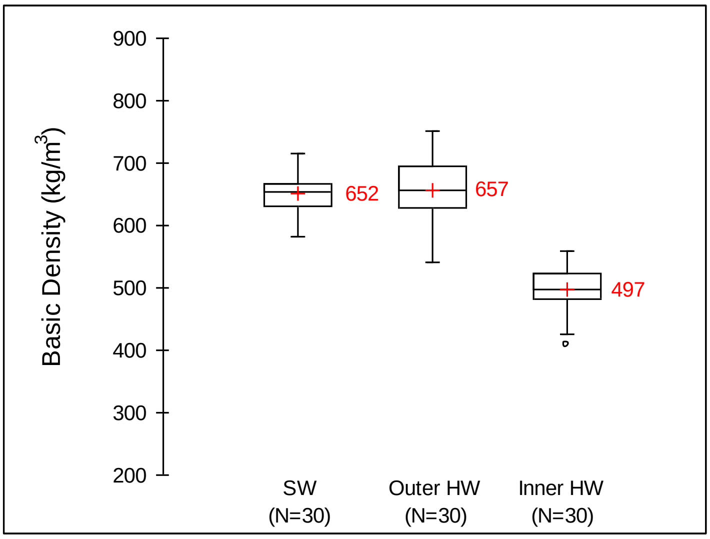


Figure 17. Gympie messmate - Site 1 basic density radial variation

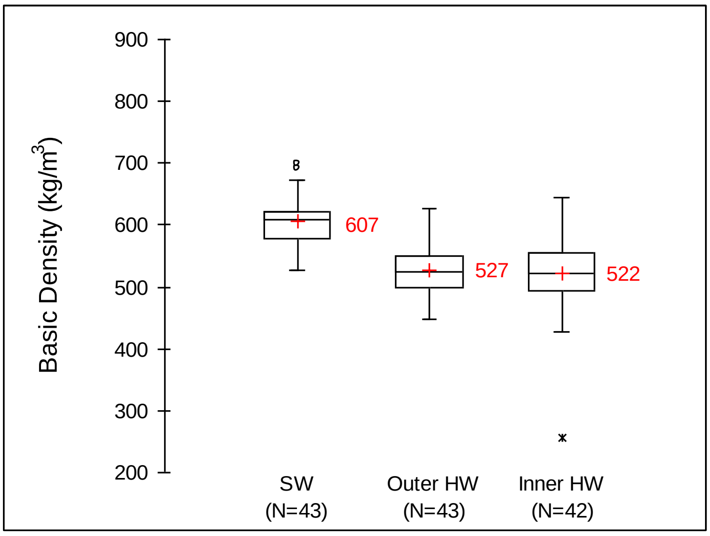


Figure 18. Spotted gum hybrid basic density radial variation

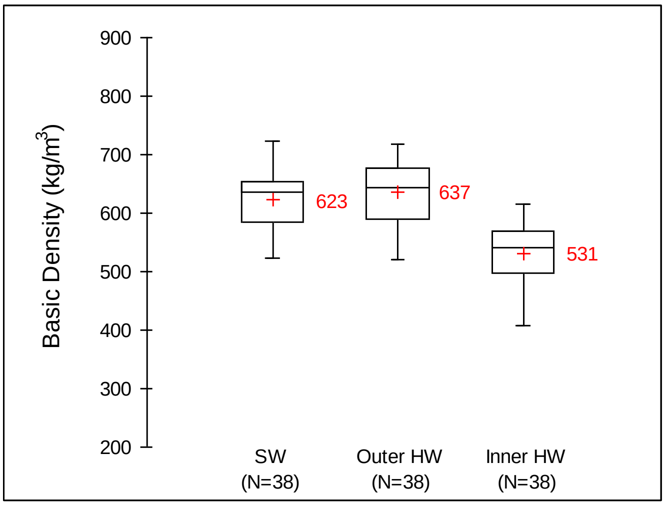


Figure 19. Red mahogany basic density radial variation

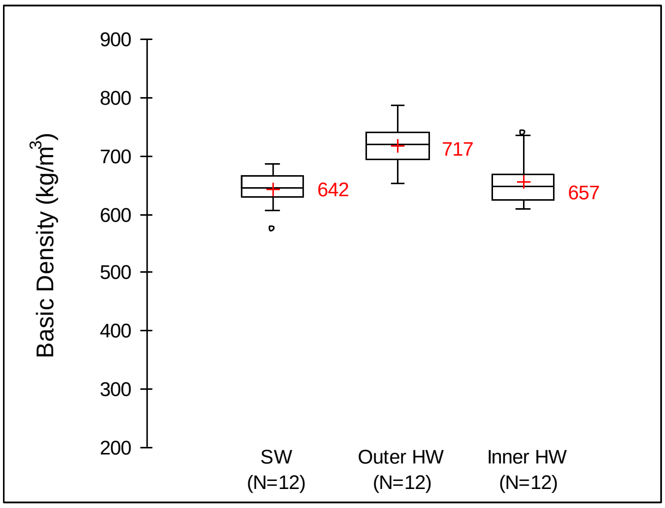


Figure 20. Western white gum basic density radial variation

Figure 21 illustrates the difference in basic density that can be expected up the tree. The results all show relatively small increases (average of between 4 and 8 kg/m^3 between species) per lineal metre in average stem basic density from the butt to the top of the merchandised section of the tree.

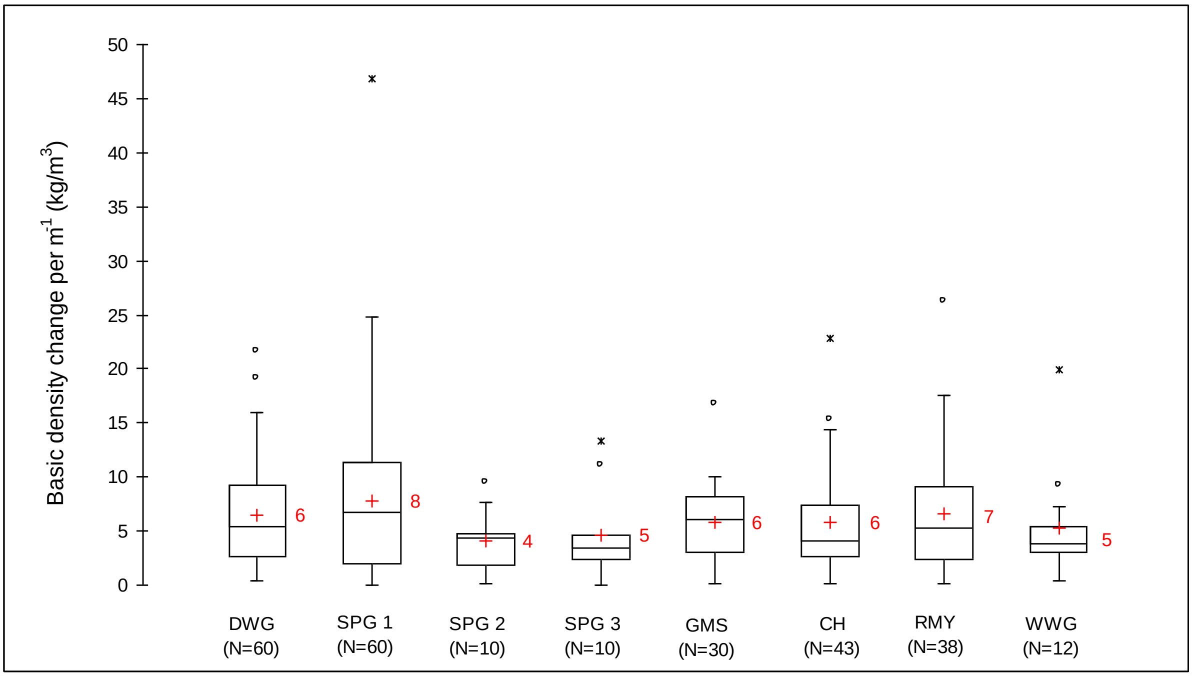


Figure 21. **Distribution of basic density variation up the tree**

4.2.2. Heartwood /sapwood proportions

Figures 22 and 23 illustrate the distribution of heartwood proportion and sapwood width respectively (measured from the butt disks) across the various species and sites. The measured properties are within the expected range for the included species and are similar to the results presented in the literature (Leggate et al. 2000, McGavin et al. 2006, Bailleres et al. 2008). The comparatively high heartwood proportion and low sapwood width displayed by Gympie messmate demonstrates a clear advantage over the other species for products where natural durability and natural heartwood colour is advantageous. The low sapwood width is also advantageous if preservative treatment is required to boost the sapwood durability for weather exposed products as minimal preservative chemical is used. Gympie messmate also has an advantage over many hardwood species with the sapwood not being lyctus susceptible therefore requiring no sapwood treatment for weather protected products.

In contrast, the spotted gums and spotted gum hybrid each measured the lowest heartwood proportion and highest sapwood width averages. The sapwood of these species is susceptible to lyctus attack. While this characteristic has minimal effect on mechanical properties, any sapwood contained on products manufactured from these species will require preservative treatment whether used in weather protected or weather exposed applications. The large volume of sapwood by comparison also increases the cost of treatment as more preservative chemical is required.

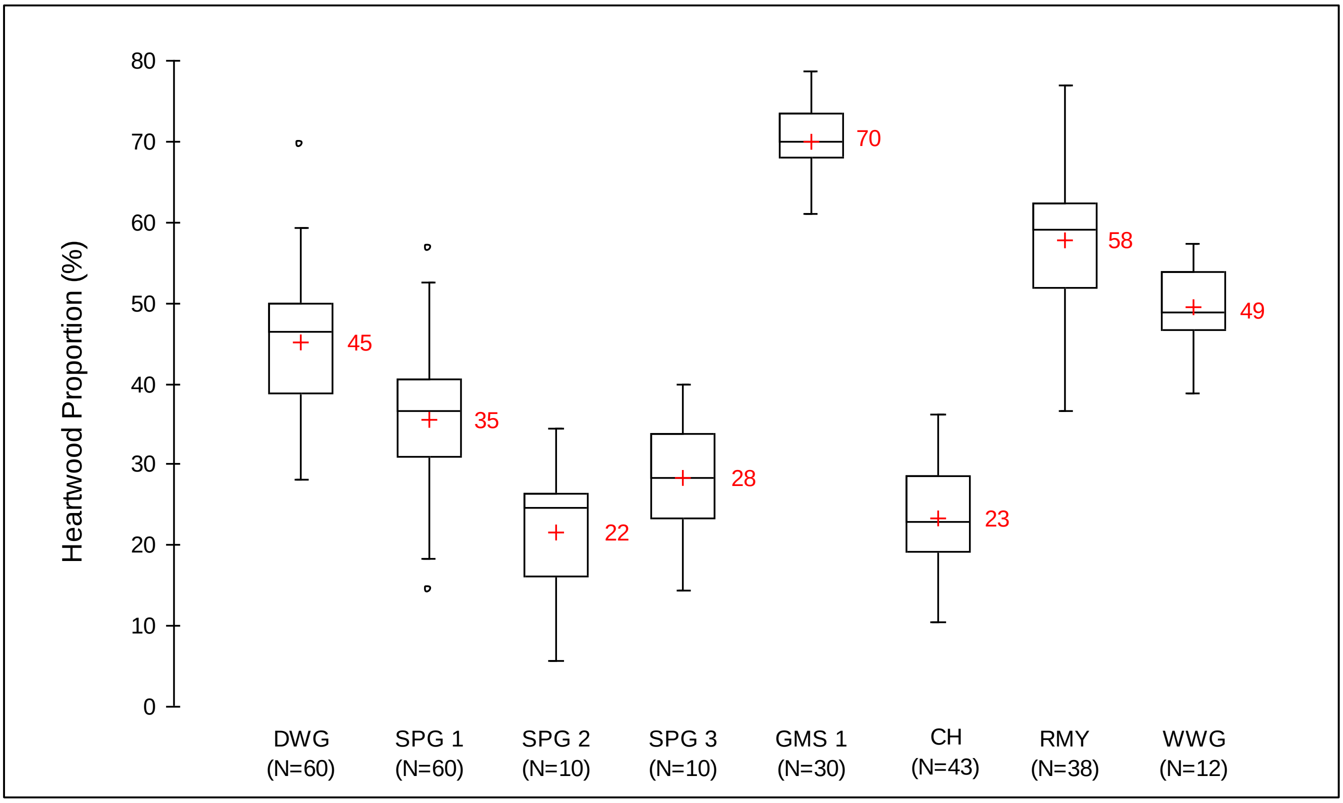


Figure 22. Distribution of heartwood proportion

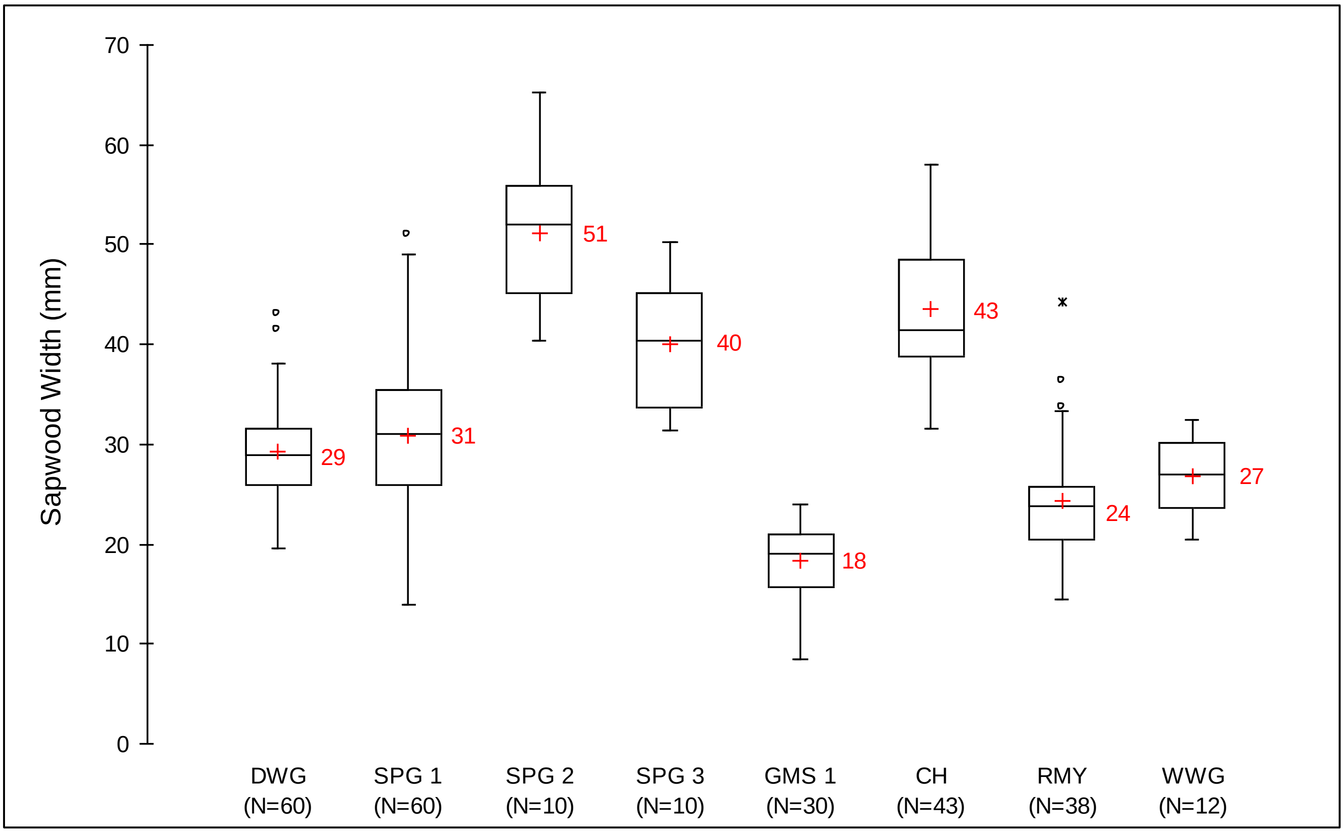


Figure 23. Distribution of sapwood width

4.3. Processing and veneer quality

4.3.1. Billet form and impact on recovery

The form of the billet will influence the recovery of veneer and the most impact will be the losses that occur in log volume during billet rounding where essentially no usable veneer is recovered. Factors such as billet straightness (i.e. sweep), taper (i.e. reduction in diameter from large end to small end) and billet roundness (i.e. ovality) would be expected to have the largest influence. To determine the reliability to predict or calculate the billet diameter that remains after roundup in the lathe from billet form characteristics, the following relationship was explored:

Calculated rounding diameter (billet smaller-end diameter – max billet sweep) versus actual diameter after rounding.

Figures 24 to 29 illustrate the relationship that exists for each species. While the relationship is very good it would be expected to be improved with the inclusion of a measure of billet roundness which wasn't measured within the trials. Given the positive relationship, the opportunity exists to use this methodology to assess the effect of using varying billet lengths (i.e. 1300 mm billets versus 2600 mm billets) and various log form qualities. These analyses were not undertaken as part of the trials.

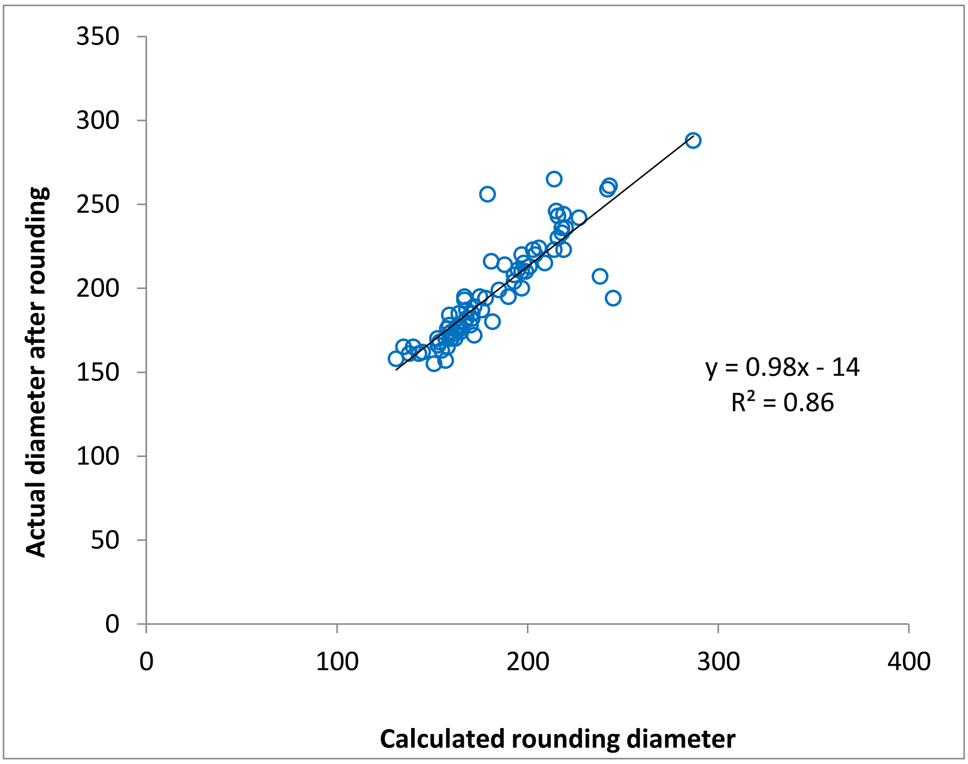


Figure 24. DWG actual billet diameter (mm) after round up versus calculated diameter (N=76)

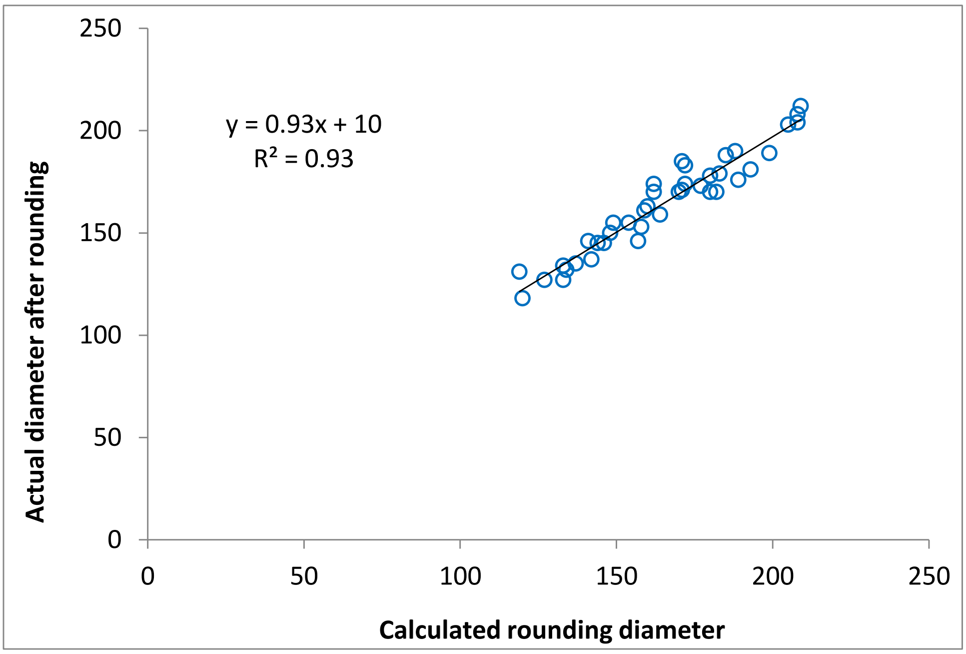


Figure 25. SPG actual billet diameter (mm) after round up versus calculated diameter (N=40)

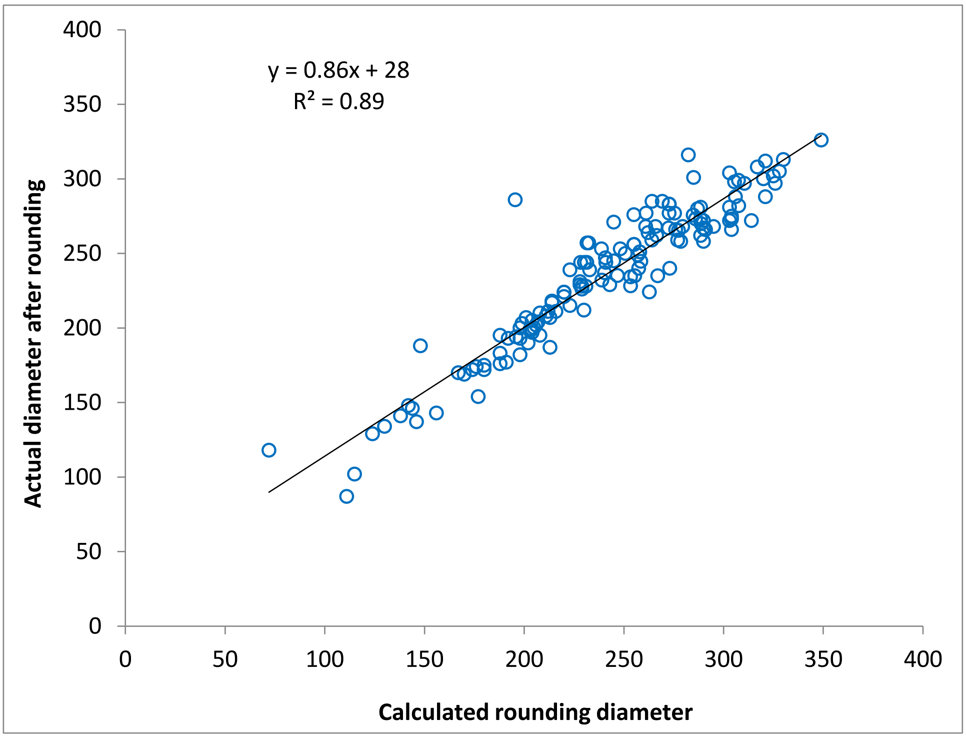


Figure 26. GMS actual billet diameter (mm) after round up versus calculated diameter (N=143)

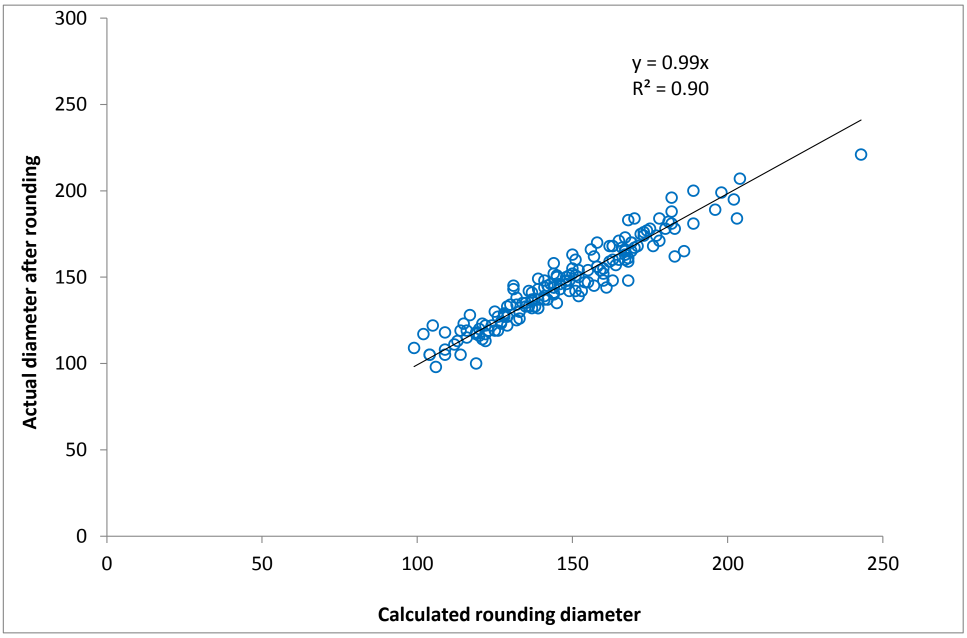


Figure 27. CH actual billet diameter (mm) after round up versus calculated diameter (N=166)

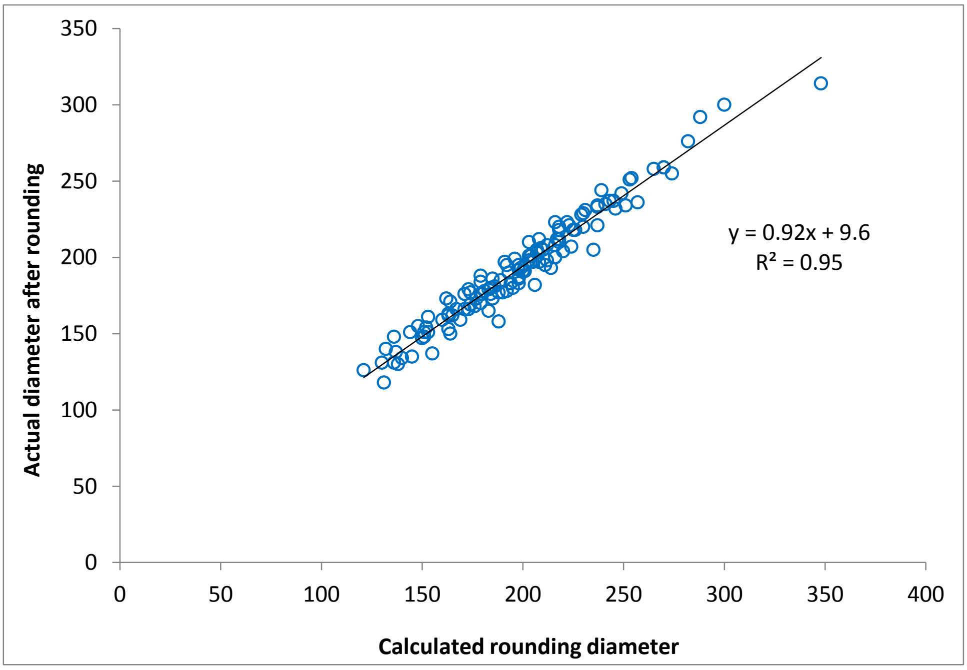


Figure 28. RMY actual billet diameter (mm) after round up versus calculated diameter (N=132)

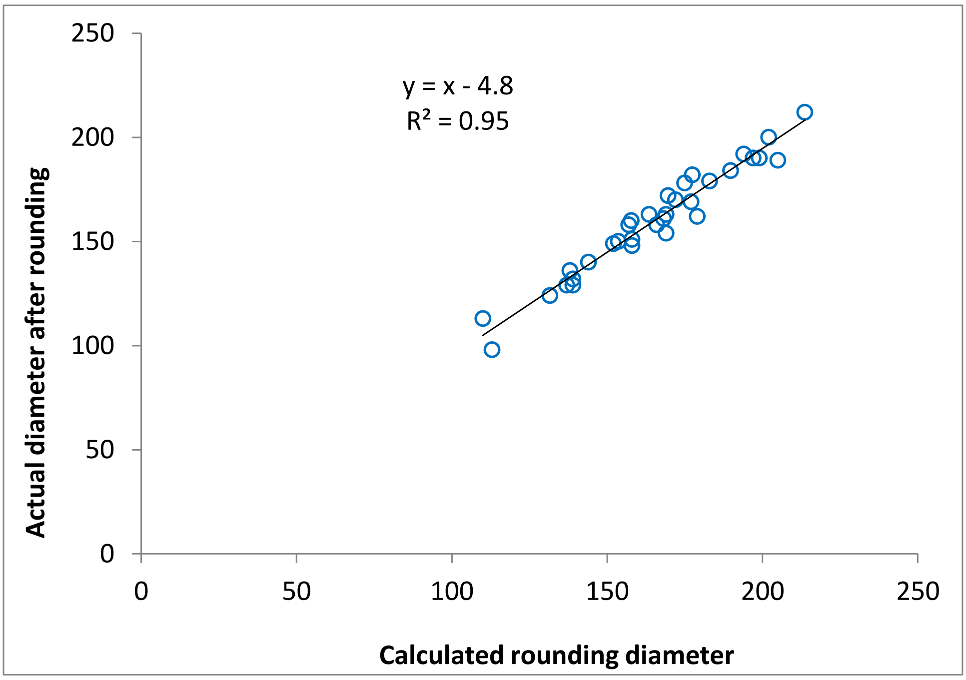


Figure 29. WWG actual billet diameter (mm) after round up versus calculated diameter (N=33)

4.3.2. Veneer recovery

Table 23 presents the recovery values for each processing trial. Green recoveries vary between 64% and 79% which is in the order of twice the comparable recovery (green-off-saw, GOS) for processing similar plantation resources using classical sawmilling techniques. For example Leggate et al. (2000) reported the green-off-saw recovering for solid wood processing (i.e. sawmilling) of six Queensland plantation sites (three species) as between 32.3 and 42.9%.

Net recovery, which indicates the saleable volume recovered, varied between 45% and 53%. By comparison to solid wood processing, Leggate et al. (2000) reported net grade recovery values of between 8% and 19% for six plantation sites (three species). This suggests that rotary veneer processing has the potential to recover up to six times the volume of saleable product from the young plantation species when compared to classical sawmilling techniques.

It is important to note that as the processing trials were conducted using billets that where approximately 1300 mm in length. Current industry standard practice is to process logs twice this length to enable one-piece long band veneers to be produced for the manufacture of standard sized 2400 mm x 1200 mm finished plywood panels. Billets sizes of 1300 mm are processed in some circumstances and used for cross band veneers where only 1200 mm finished veneer length is required in the longitudinal grain direction. Processing shorter logs has the potential to result in slightly inflated recovery rates as the impacts of log form (e.g. taper and sweep) have less impact (see Section 4.3.1). This will be more noticeable in green and gross recovery values.

The recovery of lower grade veneers dominates across all sites with D grade veneers contributing to over 80% (and up to 96%) of the net recovery in all sites with the exception of the Gympie messmate – Site 2 (which had 55% of the net recovery meeting the D grade requirements). Only a very low proportion of veneers meet the demanding grade requirements of A and B grade.

Gympie messmate – Site 2 produced the best overall recovery result and this performance can easily be contributed to the older age and quality of the plantation resource. The plantation management strategy for this plantation resulted in early and heavy thinning by comparison and also all trees were pruned to 6 m at age 4. The selected trees where in the order of twice the diameter at breast height (on average) than the other sites and the average billet small end diameters were approximately 30% larger when compared to other sites. The selection strategy also targeted the biggest diameters and best quality trees in the plantation.

While D grade is the lowest visual grade quality for structural veneer, the veneers are suitable for face veneers on non-appearance structural panels as well as the core material for the vast majority of appearance and non-appearance structural panels.

Table 23. Recovery summary of processed billets

Species - site	Green recovery (%)	Gross recovery (%)	Net recovery (%)	A grade recovery (%)	B grade recovery (%)	C grade recovery (%)	D grade recovery (%)
Dunn's white gum	67	62	49	0	<1	4	44
Spotted gum - Site 1	64	55	48	0	<1	7	41
Gympie messmate - Site 1	68	62	50	0	<1	8	42
Spotted gum hybrid	66	57	47	0	<1	9	38
Red mahogany	79	63	52	0	<1	6	46
Western white gum	73	57	46	0	<1	3	43
Spotted gum - Site 2	78	65	49	1	2	7	39
Spotted gum - Site 3	75	58	45	0	0	2	43
Gympie messmate - Site 2	77	65	53	<1	4	19	29

4.3.3. Visual grading

Figures 30 to 35 illustrate the distribution of visually assigned grades for each defect. In addition, at the bottom of each figure the proportion of veneer is illustrated within each assigned grade (taking into account the grade limiting defects). The construction of the tile graph is based on three variables with the x-axis representing the grades and the y-axis representing the defect and assigned grade. The colour and size of the bubbles represents the percentage of the total surface of the veneer produced for each defect and grade. For example, when the Dunn's white gum veneer was graded against manufactured splits (see Figure 24), more than 80% (as indicated by the large blue bubble) of the veneer met the criteria of A grade with the balance (less than 20% as indicated by the small red bubble) meeting the requirements of D grade. Similarly, when the Dunn's white gum was graded against resin pockets, between 60% and 80% of the veneer was limited to D grade (as indicated by the medium size dark green bubble) with the balance (between 20% and 40% as indicated by the small yellow bubble) meeting the requirements of A grade. Within the assigned grade category, Figure 24 clearly illustrates that the majority of veneer (more than 80% as indicated by the large blue bubble) met the requirements of D grade with a small portion (less than 20% as indicated by the small red bubble) meeting the requirements of C grade, and another small proportion (less than 20%) failing to make a structural grade (i.e. 'F' or fail grade).

Figures 30 to 35 clearly demonstrate that across all species, resin pockets have the most influence in restricting the veneers from attaining a grade higher than D grade. Given that

Australian and New Zealand standard *AS/NSZ 2269.0:2008* has been created with a significant focus towards softwood veneers, it is probable that the intent of the standard unnecessarily disadvantages plantation hardwood veneer especially given that the resin pockets that were present were often very small and would have in the majority of cases negligible effects on structural properties.

Two other defects that are common across all species and contribute to preventing veneers from attaining higher grades than D grade are roughness and encased knots. Veneer roughness is considered a manufacturing defect and therefore there is great opportunity to further optimise the process through more effective billet pre-conditioning, lathe setup etc. to reduce the effects. Bark encased knots are a common defect, given the trees are relatively young and small in diameter. In general, these knots are very small in diameter (e.g. usually less than 25 mm) and are scattered in distribution rather than concentrated, positive attributes compared to large knots or concentrated knots. Small and scattered knots will have the least amount of impact on structural properties (i.e. strength).

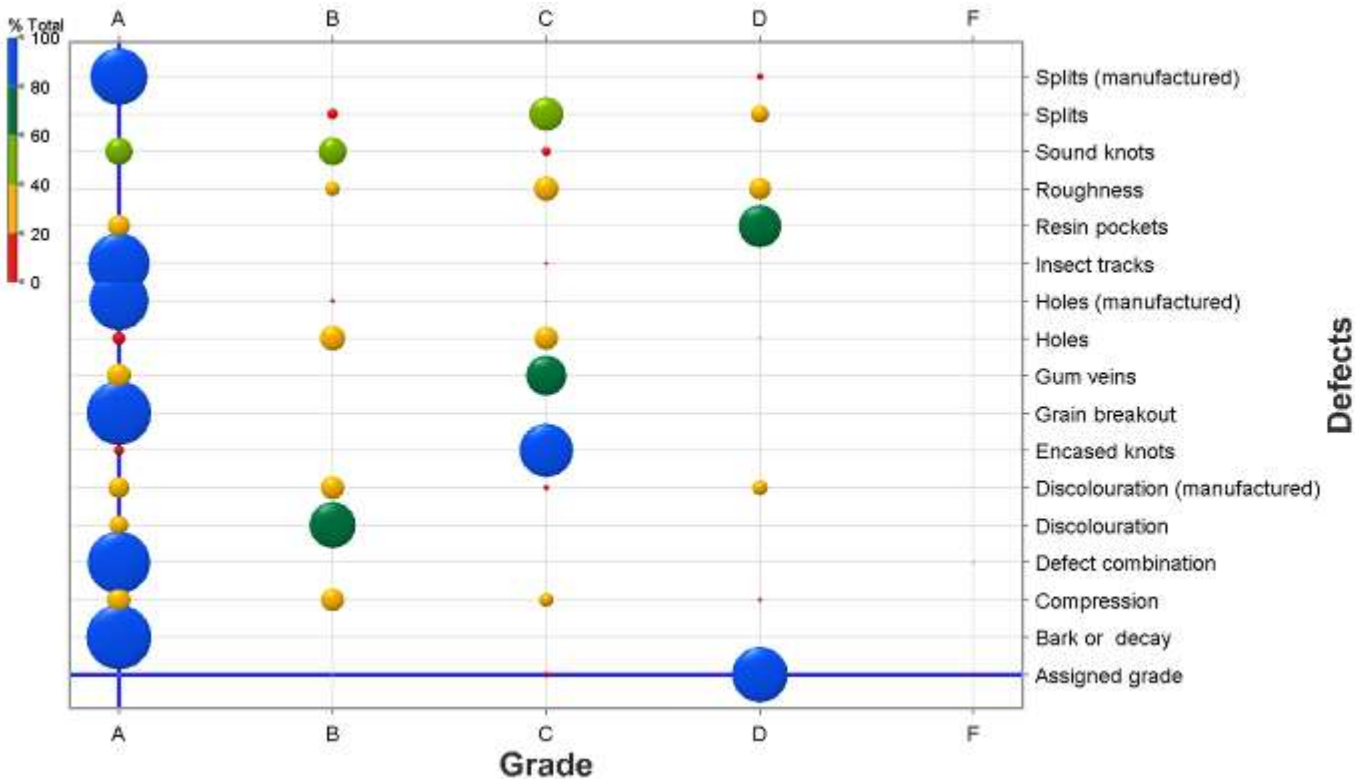


Figure 30. Distribution of grade quality and grade limiting features for Dunn's white gum

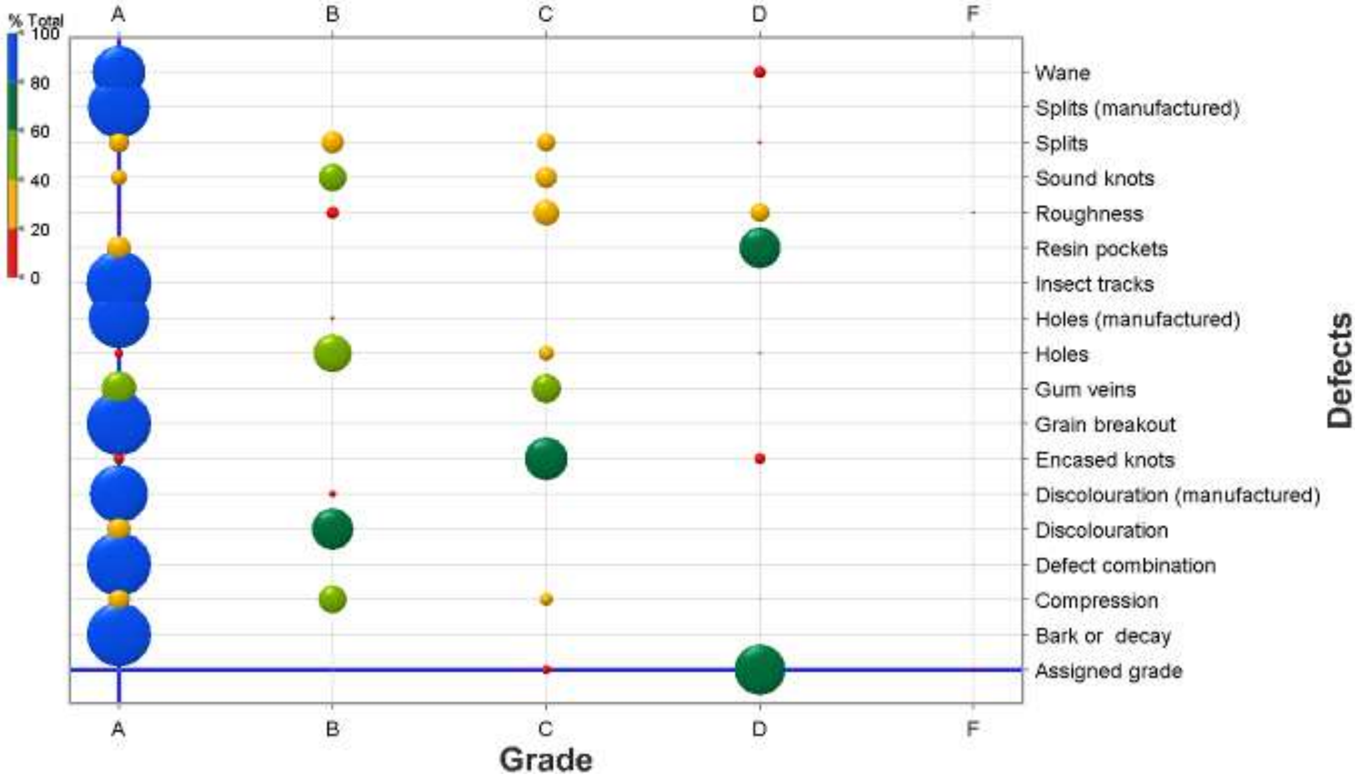


Figure 31. Distribution of grade quality and grade limiting features for spotted gum (all sites combined)

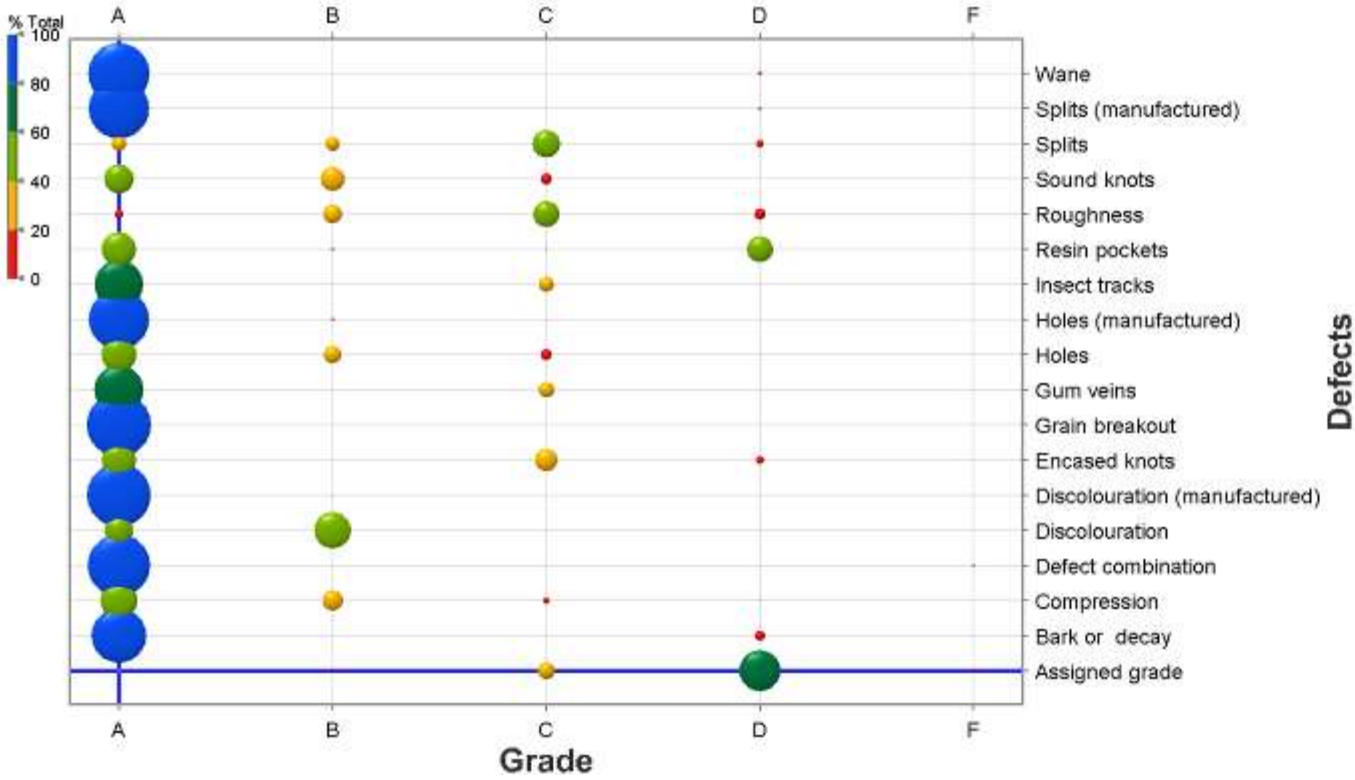


Figure 32. Distribution of grade quality and grade limiting features for Gympie messmate (all sites combined)

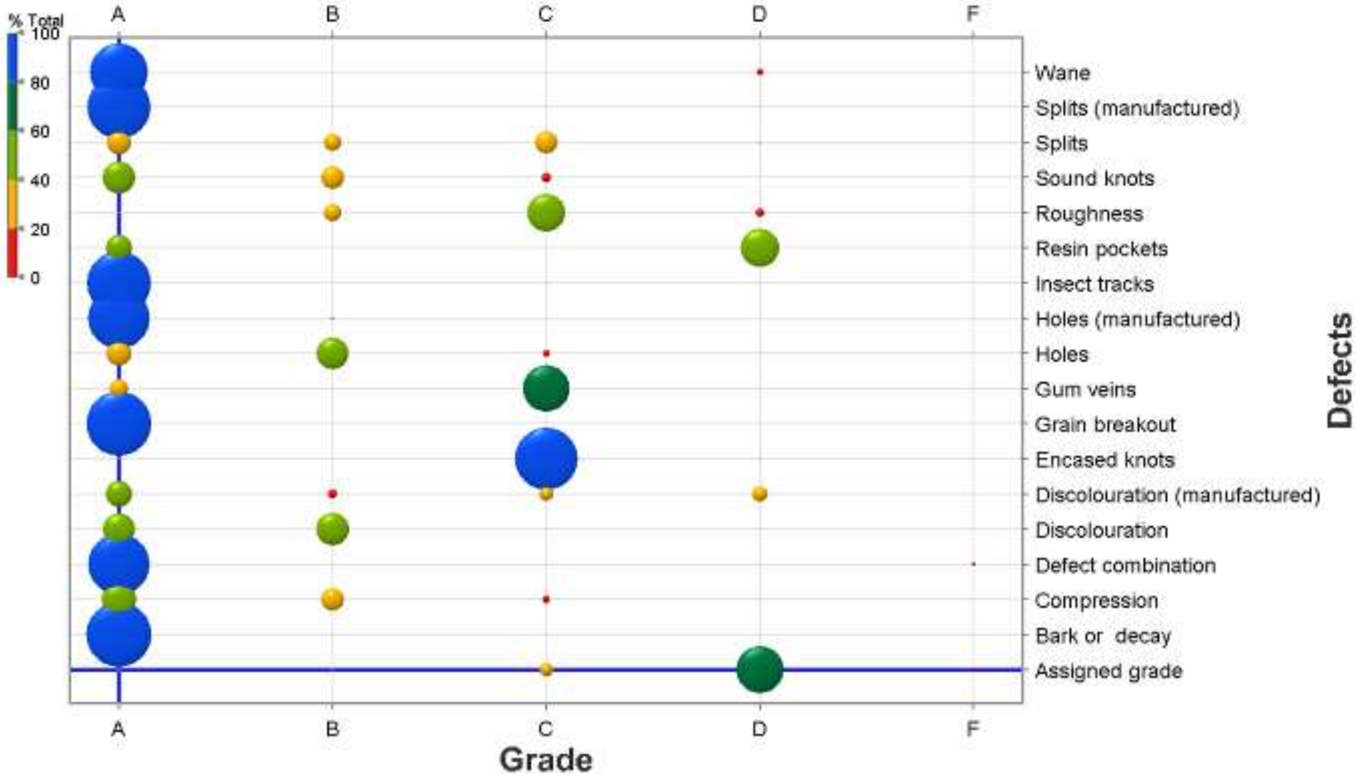


Figure 33. Distribution of grade quality and grade limiting features for spotted gum hybrid

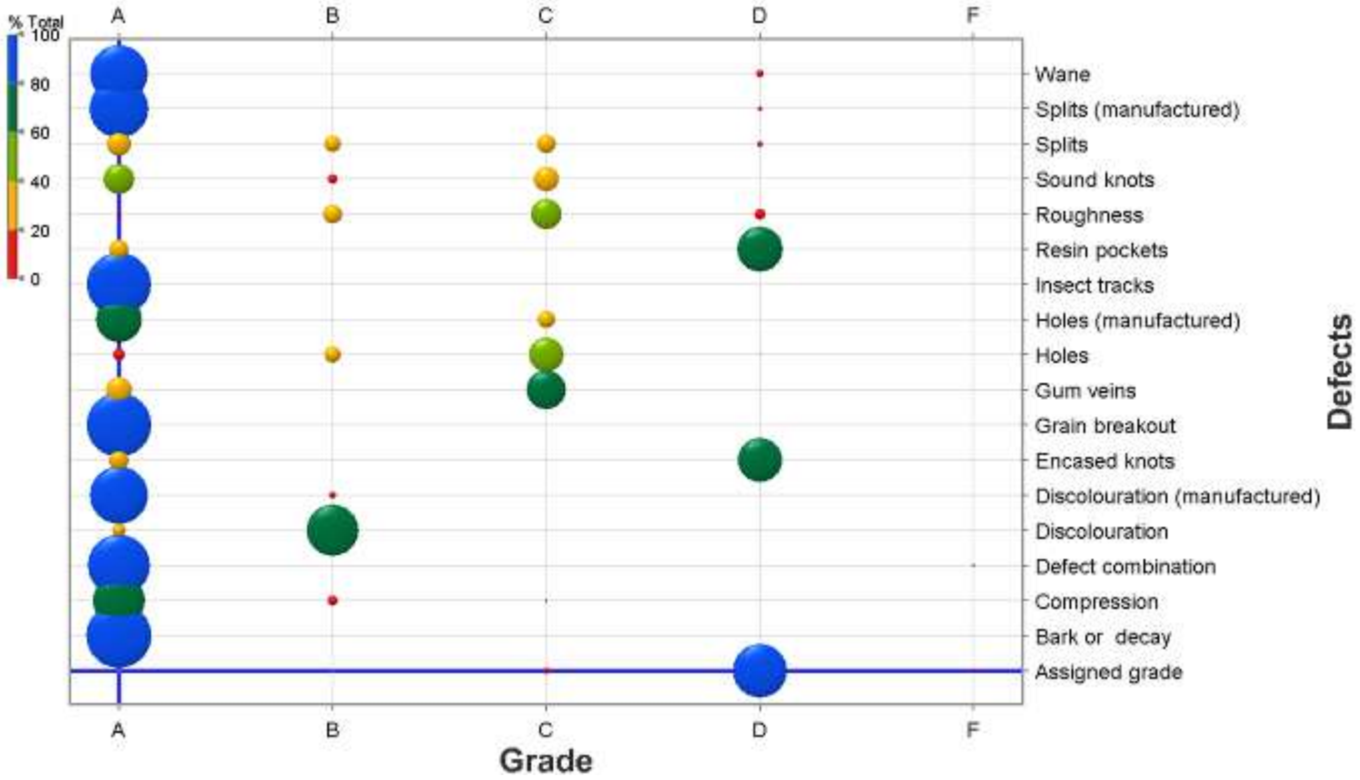


Figure 34. Distribution of grade quality and grade limiting features for red mahogany

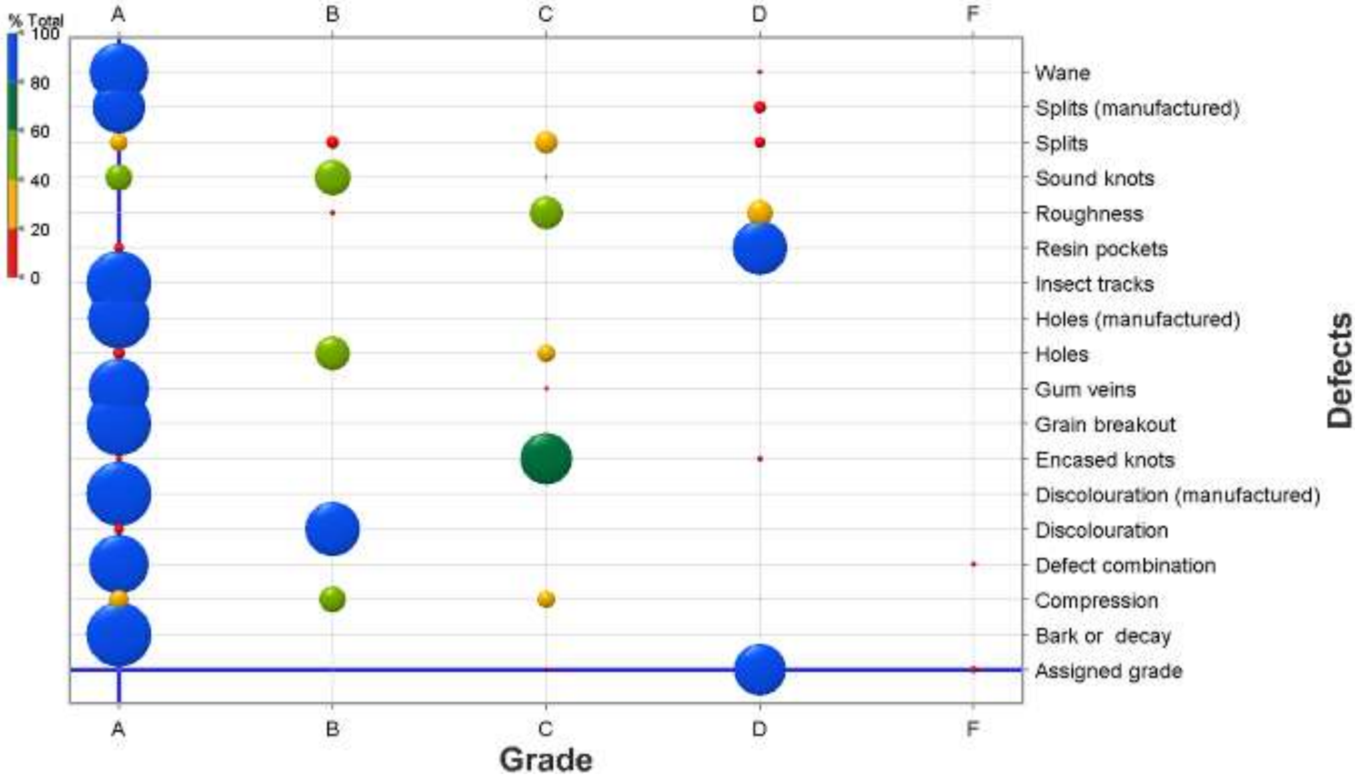


Figure 35. Distribution of grade quality and grade limiting features for western white gum

4.3.4. Visual grading scenarios

The adopted method of veneer grade quality data collection allows for a wide range of analysis and manipulation. For example, if a product was being commercially pursued and the veneer grade requirements differed from the Australian standard, it would be possible to calculate the expected grade recoveries from the trial material with alternative permissible defect rulings.

Figures 36 to 38 illustrate the impact on veneer recovery from Dunn's white gum, spotted gum and Gympie messmate respectively when resin pockets, gum veins and insect holes are no longer considered. While the permissible defect rulings for each of these defects may be considered inappropriate or too harsh for hardwood veneers (see also 4.3.3), in practise it would not be expected to be able to totally exclude a defect. Rather, permissible defect limits may be adjusted/relaxed. However the following scenario has been provided to demonstrate the capability and the implications of conducting grade recovery scenarios.

Figure 36 illustrates a change in assigned grades for Dunn's white gum from 8% C-grade, 87% D-grade and 5% fail (see Figure 30) to 23% C-grade, 73% D-grade and 5%. Given that 65% of the veneer that was originally assigned D-grade was due to resin pockets alone, it would be expected that the removal of these defects would have a much greater impact. This is not the case as the veneers contain a range of grade limiting defects and veneers may be restricted to a specific grade for more than one defect. The analysis of this complex interaction between grade limiting factors and many scenarios that can be conducted has great opportunities to not only guide recoveries targeting different products, but also guide forest management practices. For example, the decision to prune a plantation resource is often on the assumption of improved value due to reduced/eliminated knots. Assessing the impact through a grade quality scenario would provide the true impact of removing knots on grade recovering by taking into account all the non-knot defects that remain.

Figure 37 illustrates a change in assigned grades for spotted gum from <1% A-grade, 1% B-grade, 14% C-grade, 78% D-grade and 6% fail (see Figure 31) to from <1% A-grade, 2% B-grade, 33% C-grade, 59% D-grade and 6% fail. Similar to Dunn's white gum, the impact is small given that 63% of the veneer that was originally assigned D-grade was due to resin pockets alone.

Figure 38 shows the same trend for Gympie messmate with <1% A-grade, 5% B-grade, 27% C-grade, 63% D-grade and 5% fail (see Figure 32) to from <1% A-grade, 7% B-grade, 40% C-grade, 47% D-grade and 5% fail.

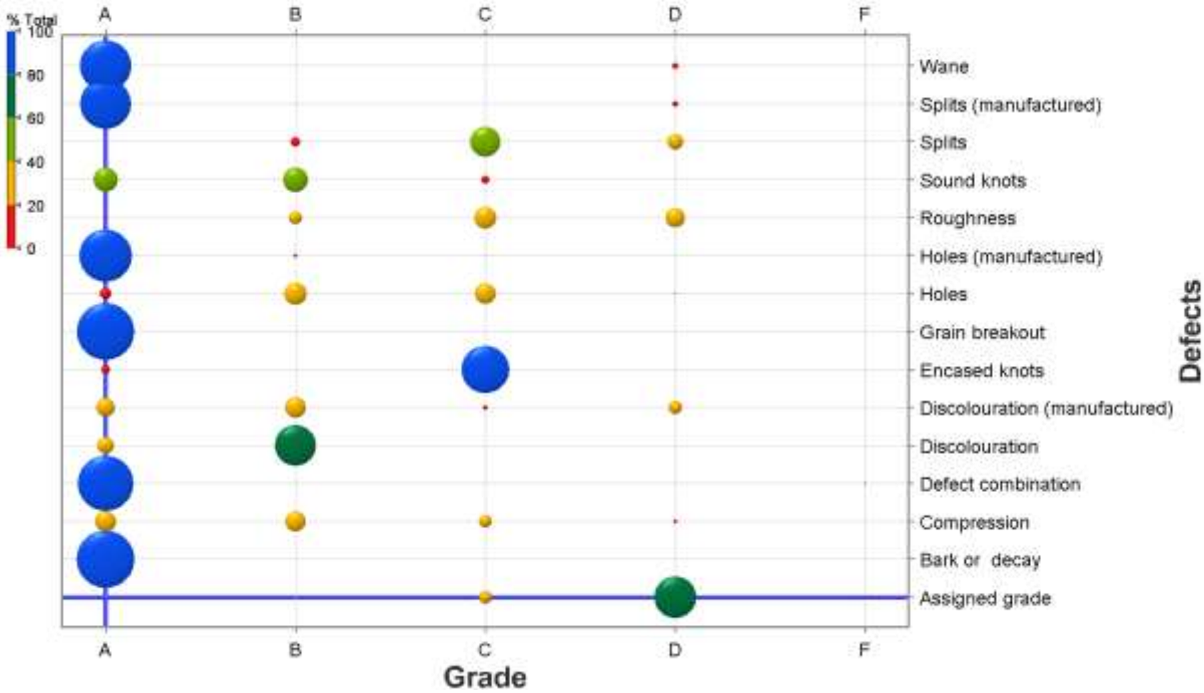


Figure 36. Impact on Dunn's white gum grade recovery if resin pockets, gum veins and insect holes are eliminated

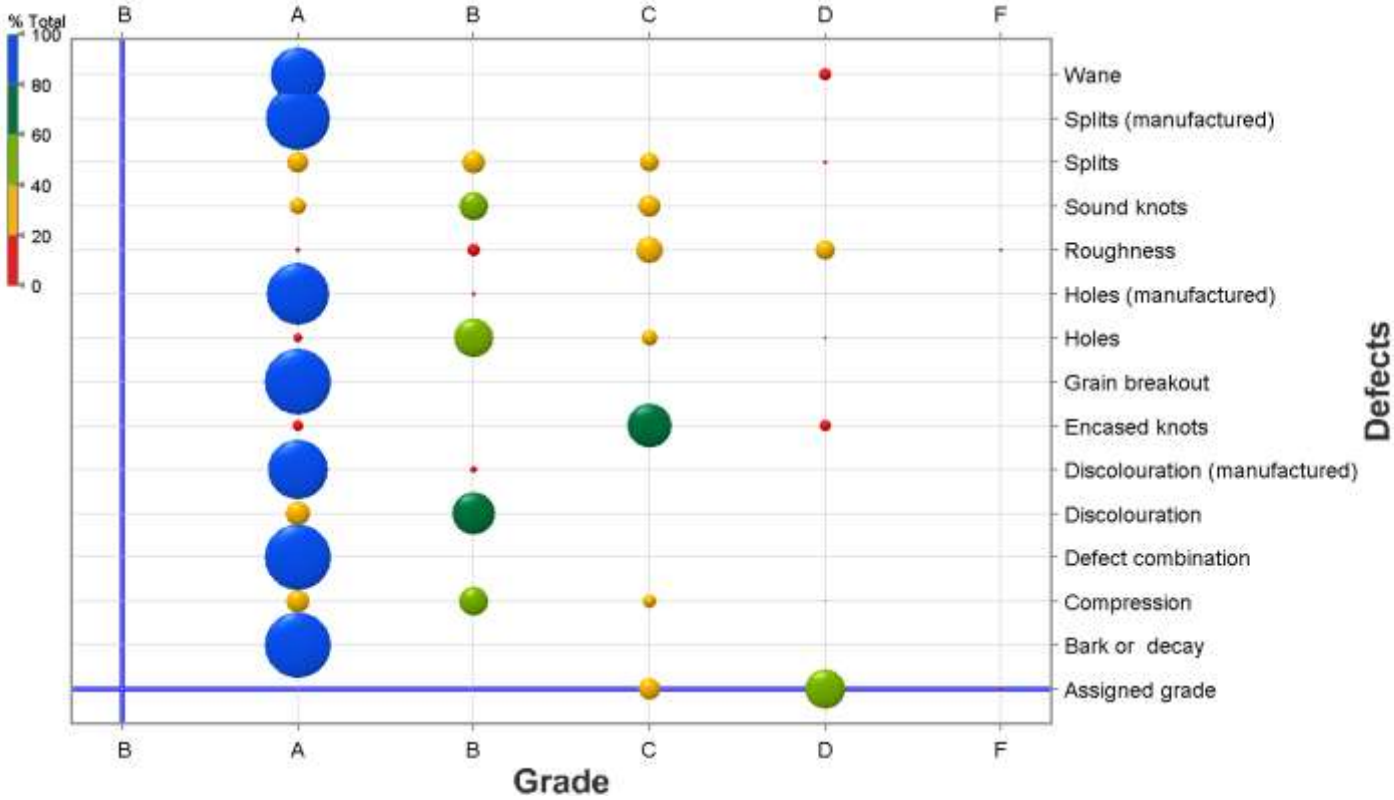


Figure 37. Impact on spotted gum grade recovery if resin pockets, gum veins and insect holes are eliminated

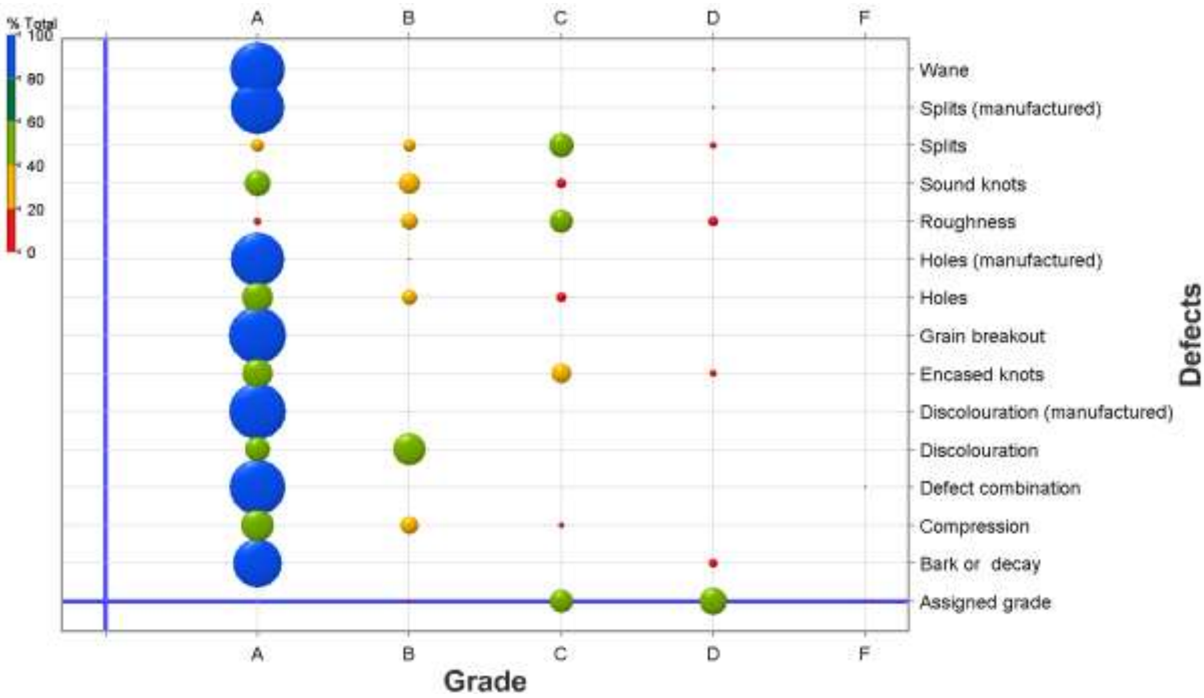


Figure 38. Impact on Gympie messmate grade recovery if resin pockets, gum veins and insect holes are eliminated

4.3.5. Log pre-treatment effect on veneer quality

The impact of log temperature prior to peeling was assessed through the measurement of veneer roughness and splits.

When the peeling parameters are optimum, roughness is mainly induced by a sharp variation of wood density and/or grain angle or by excessive forces on the knife. When the glass transition temperature is reached, the cutting forces decrease significantly thus roughness is expected to decrease.

Temperature also contributes to the release of internal stresses in the log with consequences on end split development.

4.3.5.1. Veneer roughness

To investigate the effect of billet temperature during the peeling process on veneer quality, an analysis of the veneer roughness in recovered grade quality against the billet temperature was conducted.

The roughness on Dunn's white gum veneers tends to decrease with increasing temperature (Figure 39). There is a significant statistical average temperature difference between D and A grades. Higher average temperature tends to produce a lower severity of roughness.

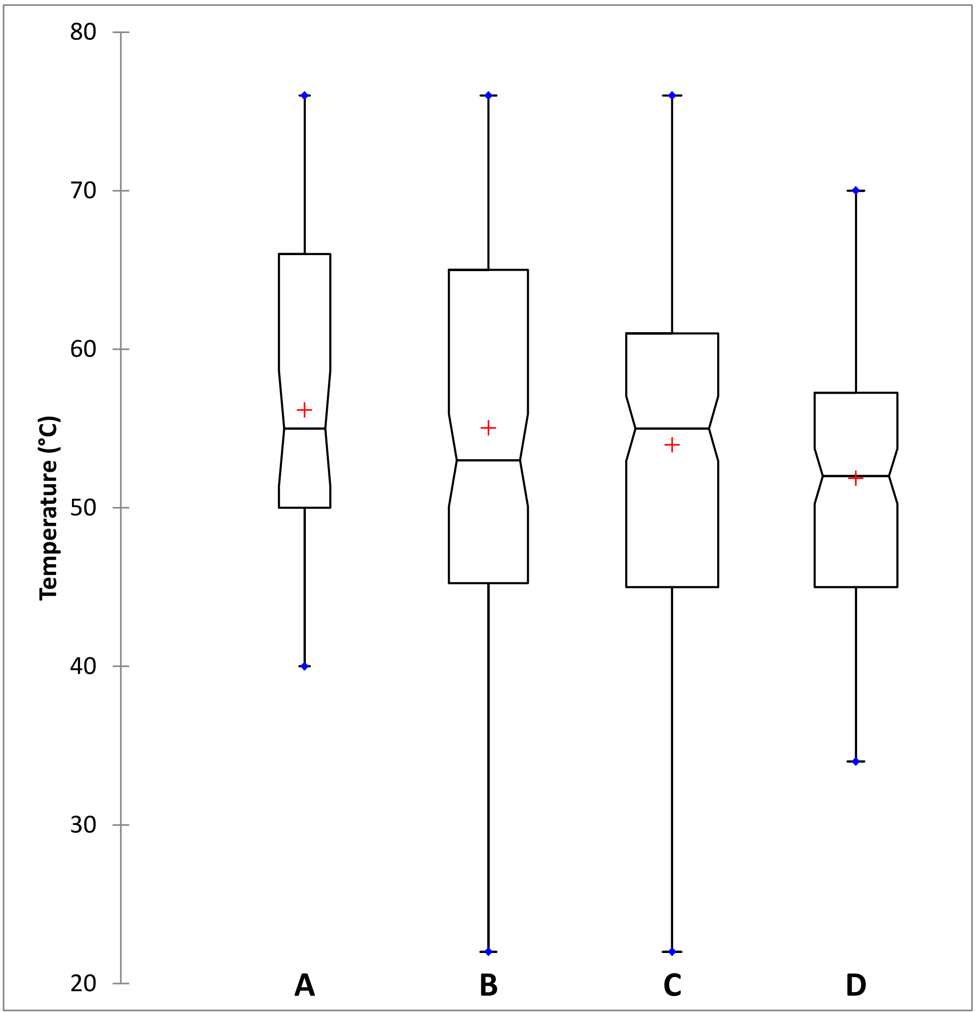


Figure 39. Impact of log pre-treatment on Dunn's white gum veneer roughness

Similar to Dunn's white gum, spotted gum D and F grades have statistically significant lower average temperature than A grade (Figure 40).

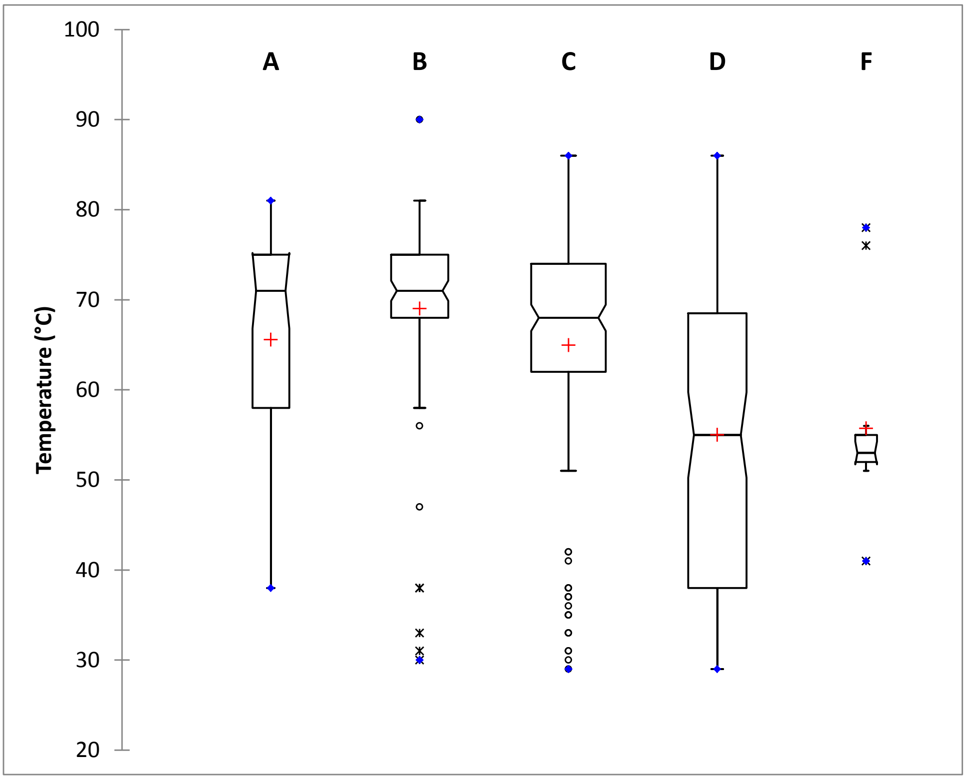


Figure 40. Impact of log pre-treatment on spotted gum veneer roughness

There is no statistical difference on average temperature between grades on Gympie messmate veneer (Figure 41).

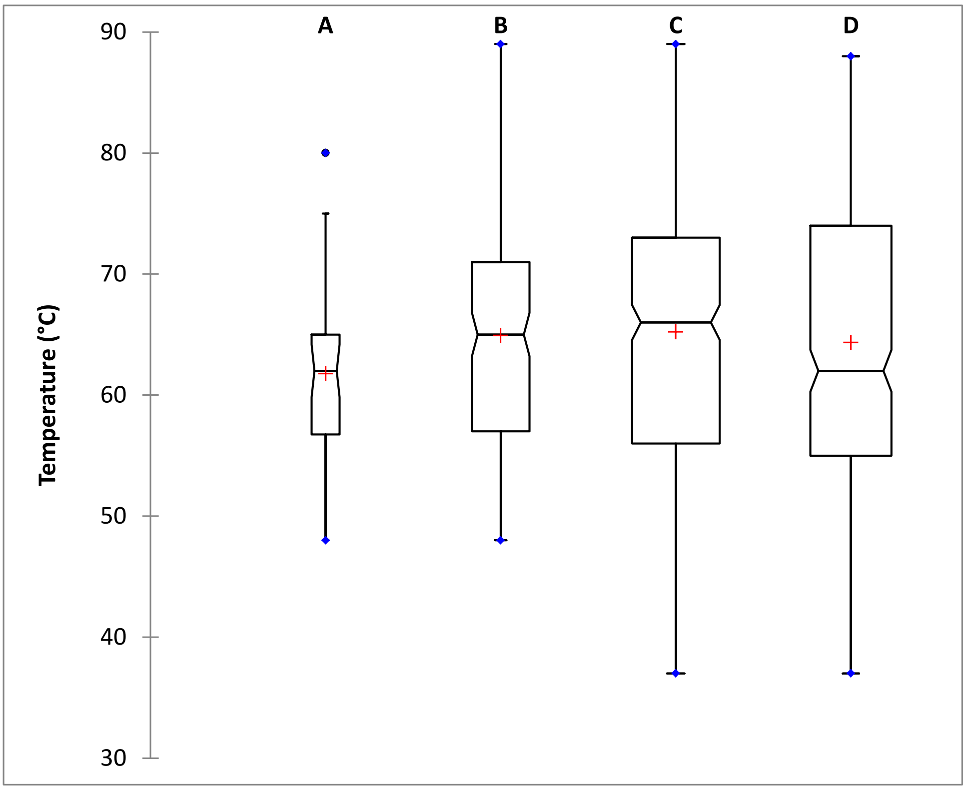


Figure 41. Impact of log pre-treatment on Gympie messmate veneer roughness

Spotted gum hybrid C and D grades for roughness displayed a significant lower average temperature than B grade.

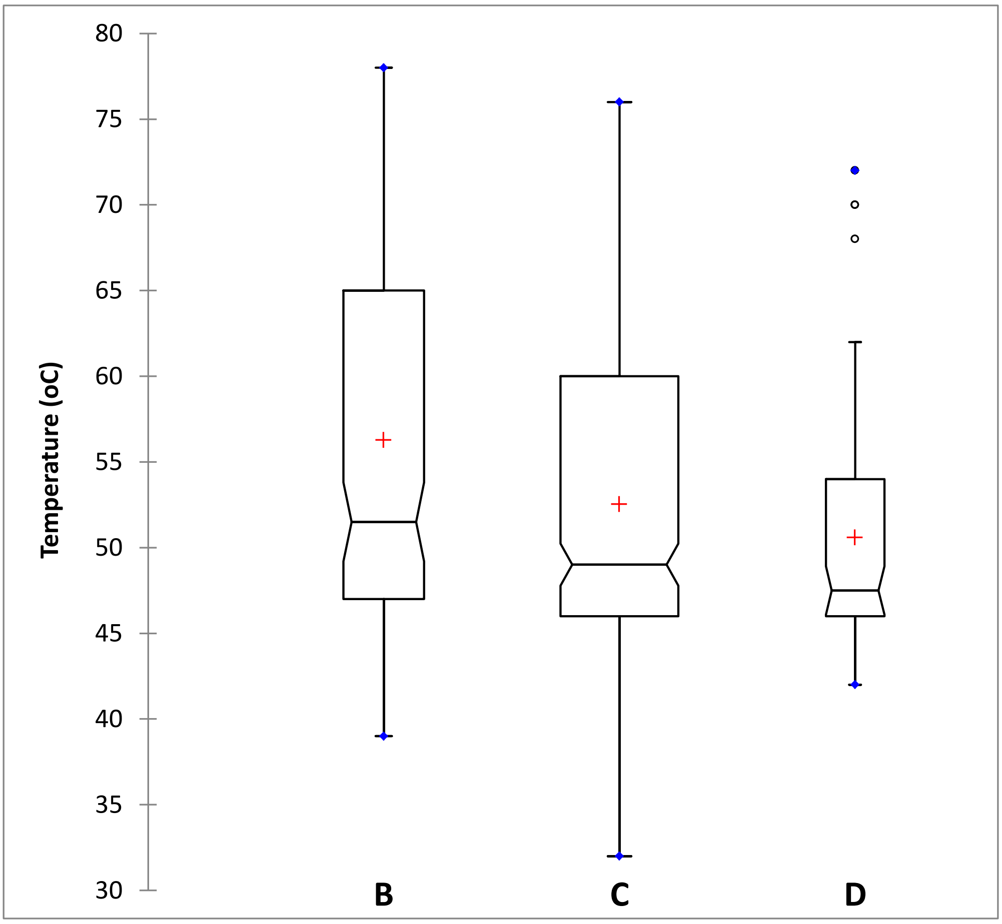


Figure 42. Impact of log pre-treatment on spotted gum hybrid veneer roughness

Figure 43 shows a clear decrease of average temperature from A grade to D grade veneers of red mahogany.

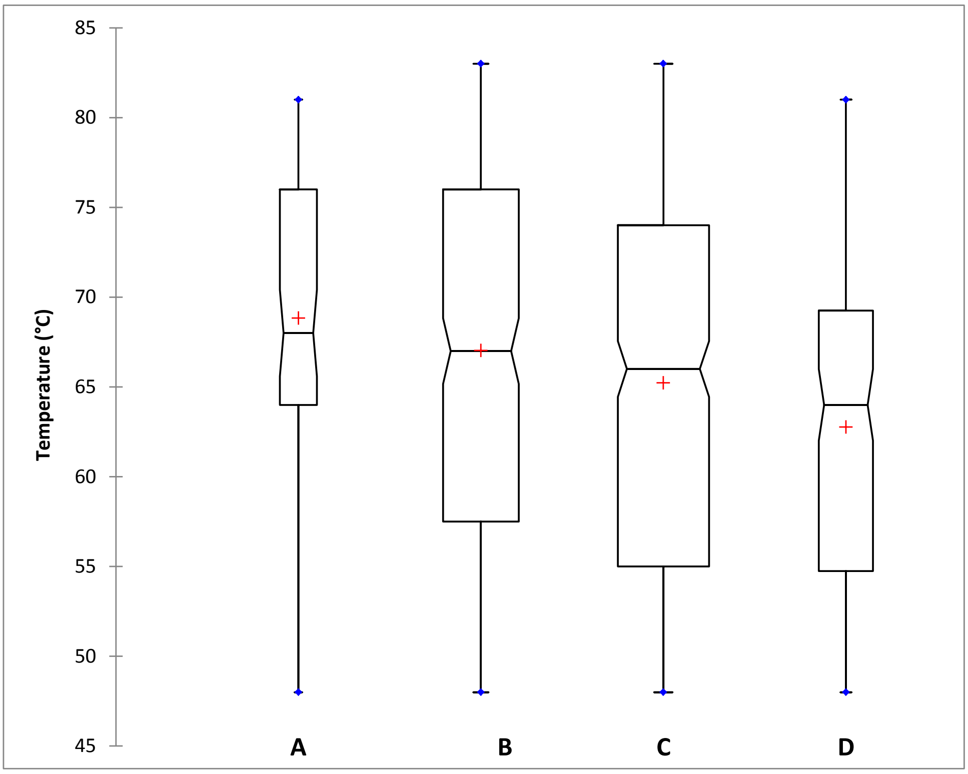


Figure 43. Impact of log pre-treatment on red mahogany veneer roughness

The average temperatures of C and D veneer grades are significantly lower than A and B grades of western white gum (Figure 44).

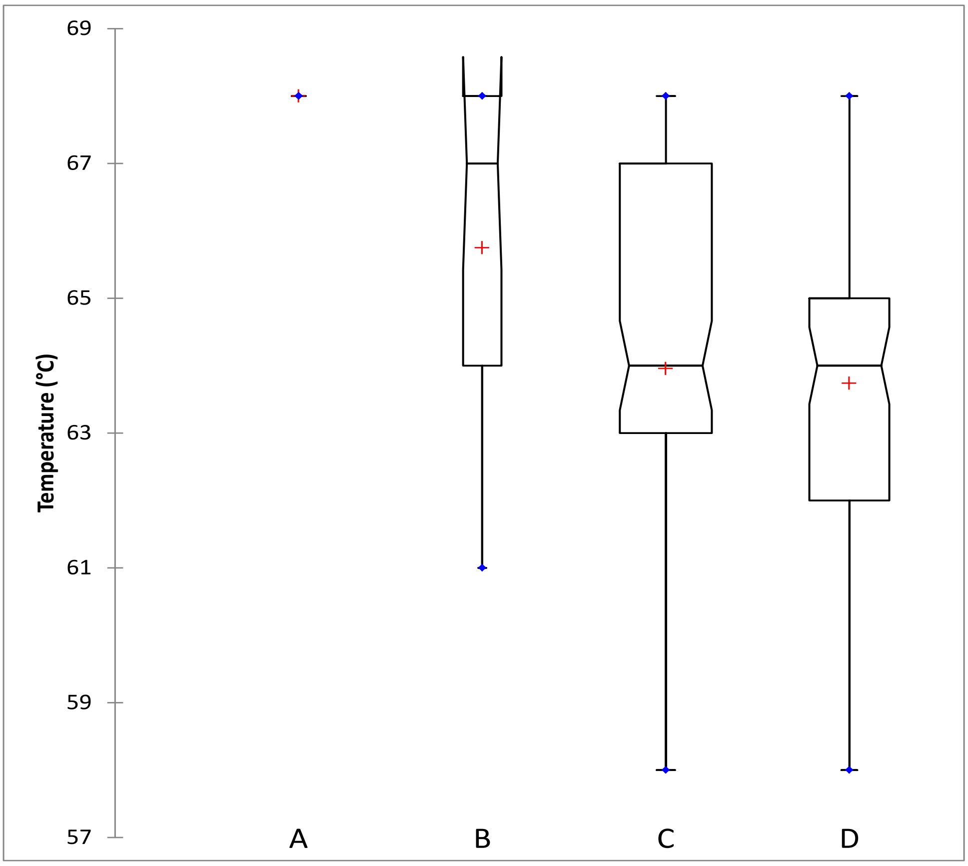


Figure 44. Impact of log pre-treatment on WWG veneer roughness

With the exception of Gympie messmate, there is a clear positive effect of temperature on roughness for all the species tested. The range of temperature tested was narrow consequently it wasn't possible to provide an accurate optimum level of temperature for peeling these species. As a preliminary guide, a temperature above 60°C is recommended.

4.3.5.2. Veneer splits

Figures 45 to 50 display the average temperature for each grade of each species relative to veneer splits. The figures indicate that log temperature doesn't have a clear effect on the extent splits. It should be noted that the logs were docked immediately before peeling consequently the extent of the splits on veneer was minimised. This procedure may explain the lack of clear tendency of split development due to temperature. In addition, the range of temperatures tested may not have been wide enough to induce significant splitting behaviour.

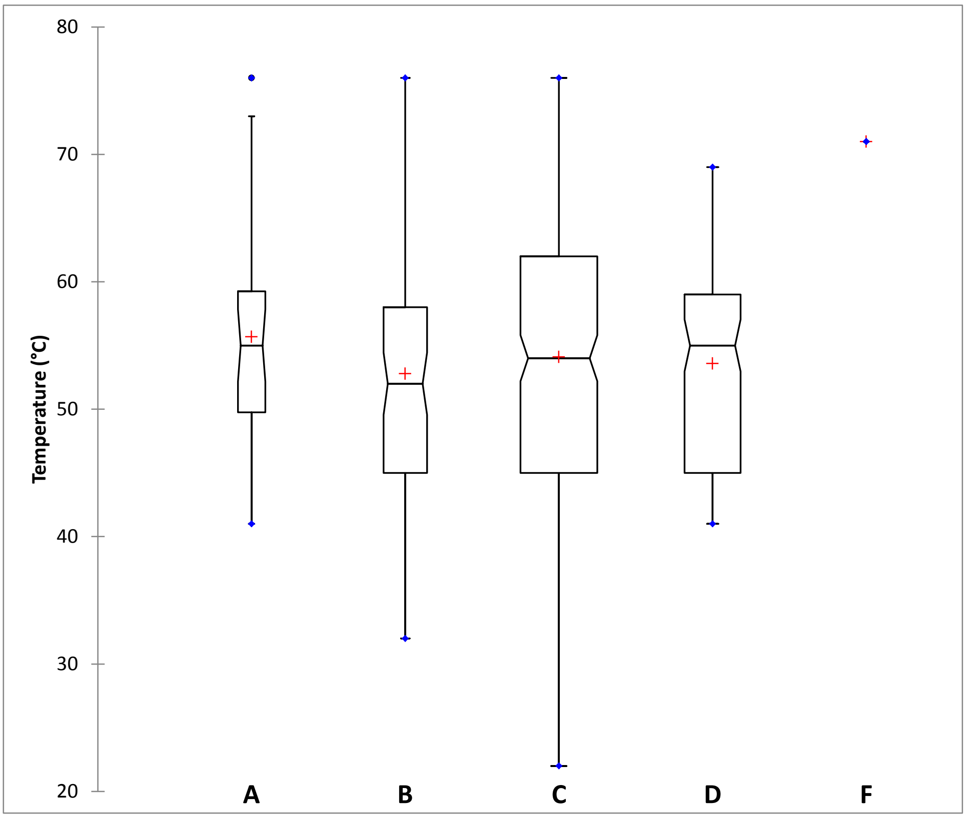


Figure 45. Impact of log pre-treatment on Dunn's white gum veneer splits

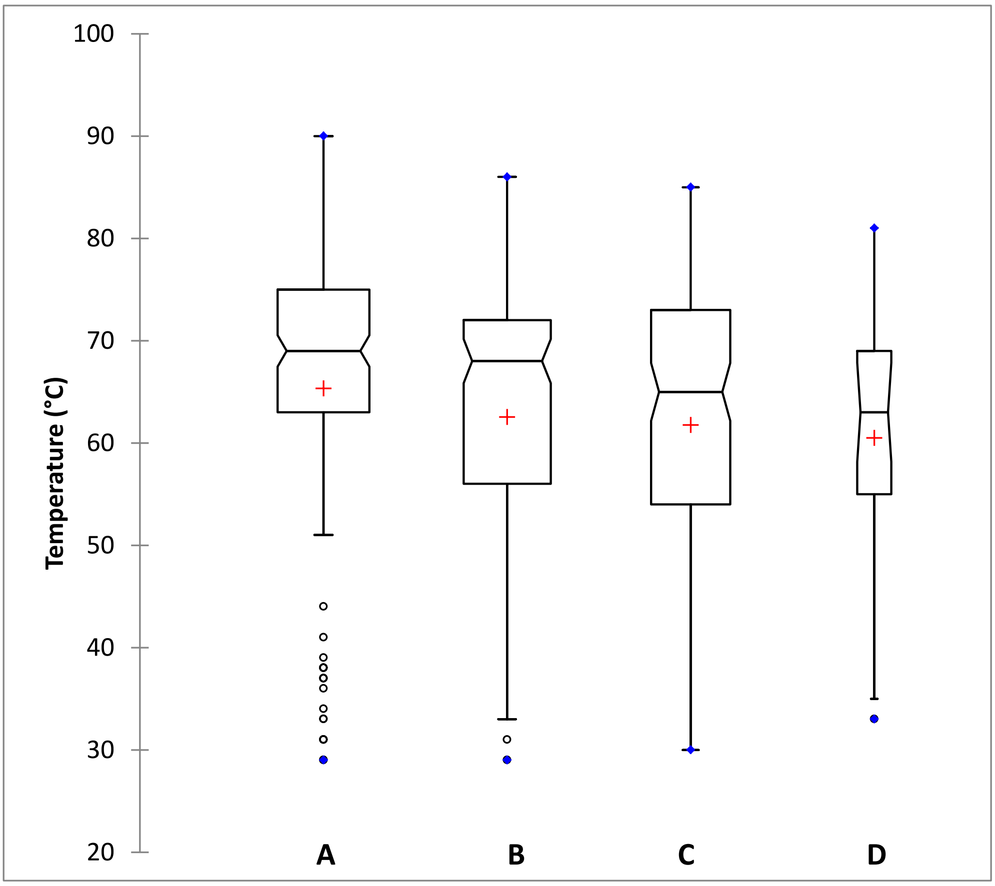


Figure 46. Impact of log pre-treatment on spotted gum veneer splits

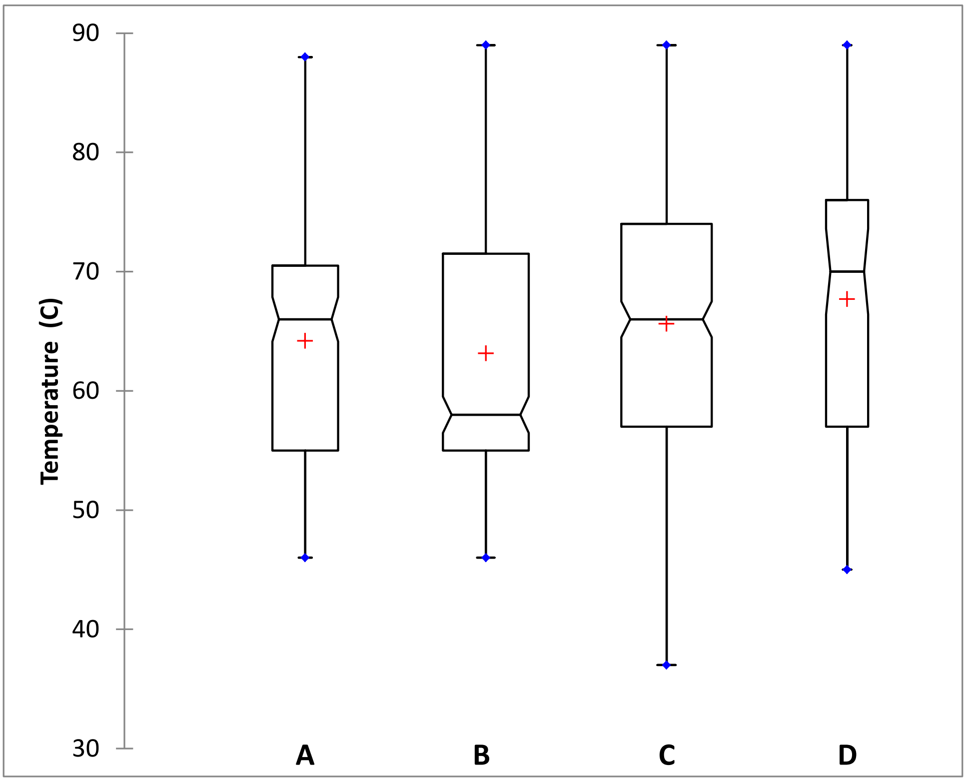


Figure 47. Impact of log pre-treatment on Gympie messmate veneer splits

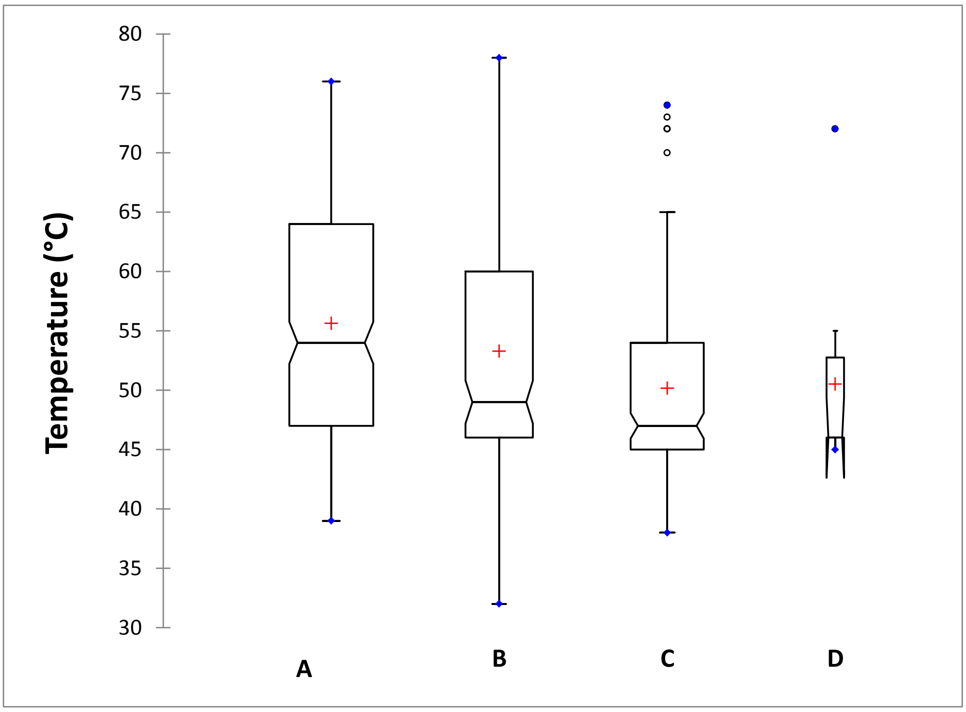


Figure 48. Impact of log pre-treatment on spotted gum hybrid veneer splits

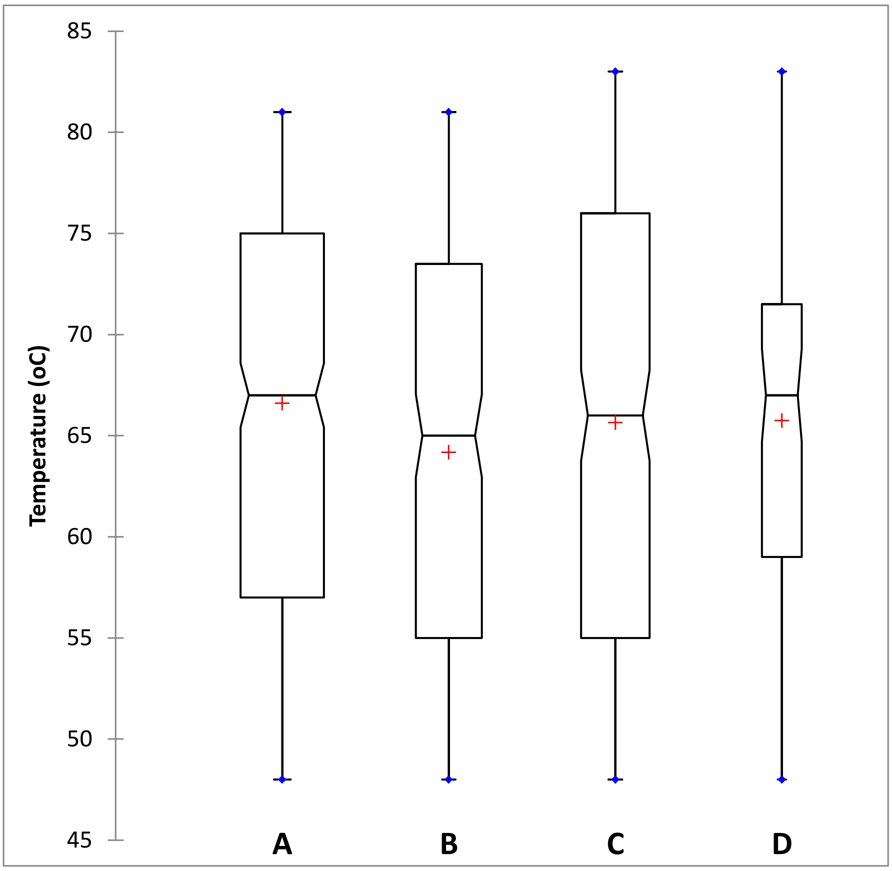


Figure 49. **Impact of log pre-treatment on red mahogany veneer splits**

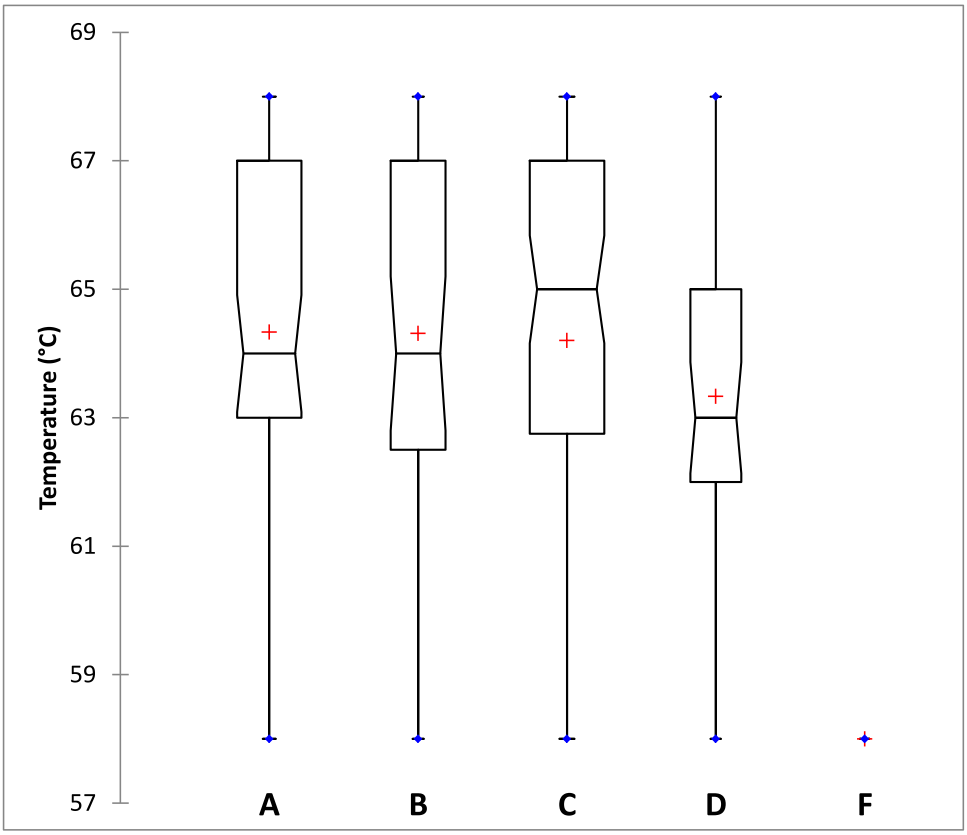


Figure 50. Impact of log pre-treatment on western white gum veneer splits

4.3.6. MOE variation between species

The average veneer MOE showed significant differences between species (Figure 51). Spotted gum has the highest average stiffness (16 200 MPa) followed closely by Gympie messmate (16 000 MPa). The third highest average MOE displayed by red mahogany is noticeably lower (13 700 MPa). It is slightly higher than western white gum (13 300 MPa). Dunn's white gum is in fifth position with an average veneer MOE of 12 300 MPa. Spotted gum hybrid displayed the lowest average veneer MOE (11 700 MPa).

The coefficient of variation from 22% for spotted gum hybrid to 29% for Dunn's white gum are relatively high due to the radial variation of stiffness caused by juvenile to mature transition.

By comparison, the average veneer stiffness range for the pine resource in Australia is usually between 8 000 to 12 000 MPa. All the species studied in this research display better stiffness than the Australian pine resources. This key observation has to be analysed in a context of suboptimal structural pine qualities for veneer based composites in Australia. A judicious strategic blend of these resources could be an avenue to improve their value.

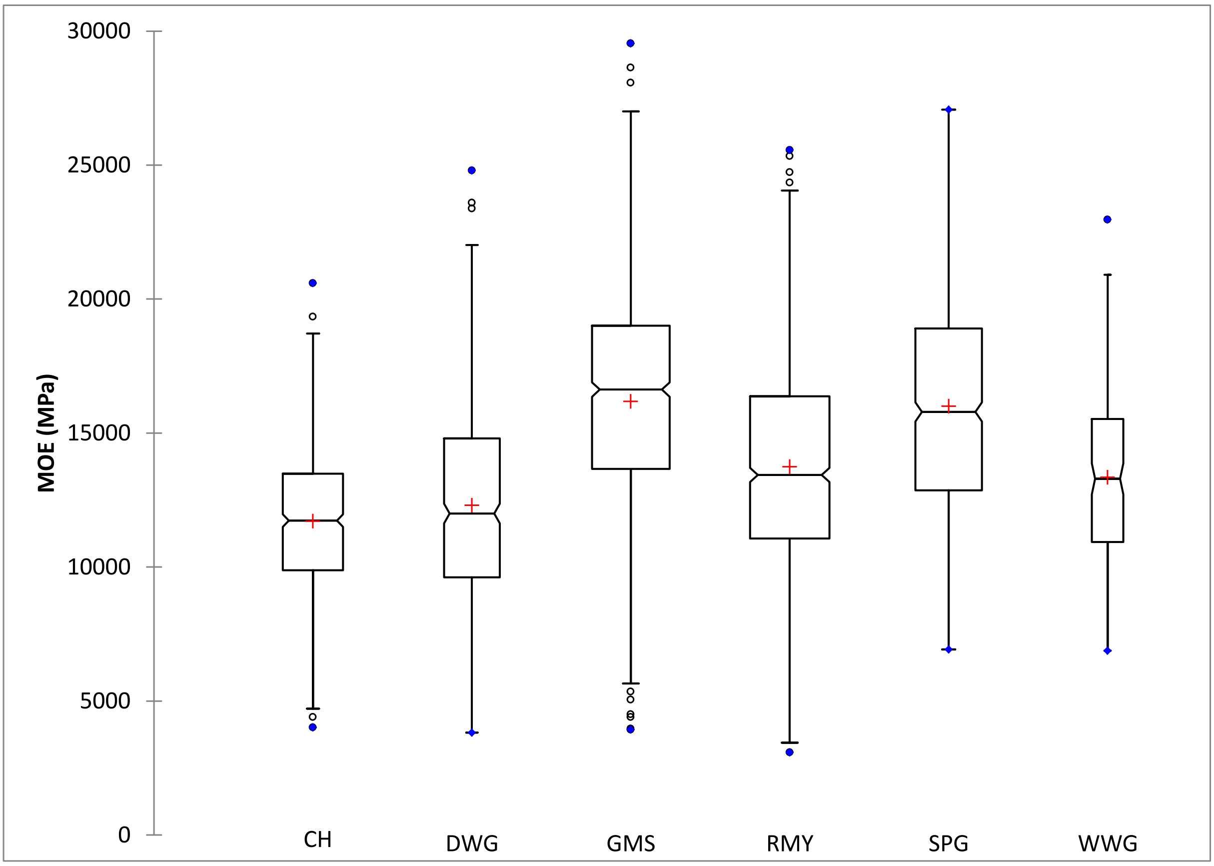


Figure 51. Acoustic measured veneer MOE for all species

4.3.7. Veneer stiffness variation across the log radius

The way to model the variation of wood properties from pith to bark has been extensively studied (e.g. Downes et al. 1997). Different approaches based on mathematical parametric or non-parametric fitting, have been explored.

The relatively simple approach adopted is to model the variation of MOE from pith to bark due to the transition from juvenile to mature wood is based on a sigmoidal function fitting.

A sigmoid function is a mathematical function having an "S" shape (sigmoid curve). Often, sigmoid function refers to the special case of the logistic function defined by the formula:

$$S(t) = \frac{1}{1 + e^{-t}}.$$

A sigmoid function is a bounded differentiable real function that is defined for all real input values and that has a positive derivative everywhere (http://en.wikipedia.org/wiki/Sigmoid_function).

It is used in modelling systems that saturate at large values of t. A wide variety of sigmoid functions have been used as the activation function of artificial neurons, including the logistic and hyperbolic tangent functions. Many natural processes, including those of complex system learning curves, exhibit a progression from small beginnings that accelerates and approaches a climax over time. When a detailed description is lacking, a sigmoid function is often used.

In general, a sigmoid function is real-valued and differentiable; having either a non-negative or non-positive first derivative which is bell shaped. There is also a pair of horizontal asymptotes which provide the lowest and the highest Y values when X tends to infinity. In our case this is a convenient way to model MOE variation from pith to bark since it tends to increase with increase in diameter due to cambial activity.

The sigmoid fitting is:

$$y = a + \frac{b}{(1+exp^{\frac{-(x-c)}{d}})}$$

With:

Transition height: b

Transition centre: c

Transition width: 2.197224578*d

Constraints: d<>0

Asymptote: a

4.3.7.1. *Variation with relative radius position*

Figures 52 to 57 display the veneer MOE versus the relative radial position calculated from the actual position of the veneer in the log relative to the small end diameter of the log. This representation provides a standard variation of veneer MOE at a given age of the stand. The red curve in the plots shows the sigmoid curve fitting.

The noticeable observation from the plots is the wide spread of the individual veneer MOE along the radius that can be explained by the impact of knots, the local and global grain angle and as well by the deviation between the position of the pith and the rotational axis of peeling. Depending on the extent of this deviation, the veneer at the same distance from the rotational axis can be more or less close to the pith, in other words more or less in juvenile wood. This deviation explains a large part of the variation observed at a given radius position.

Dunn’s white gum veneer MOE increased steadily with the radius (Figure 52). No MOE trend of stabilisation can be detected on the outer part of the log which indicates that the mature state is not yet reached.

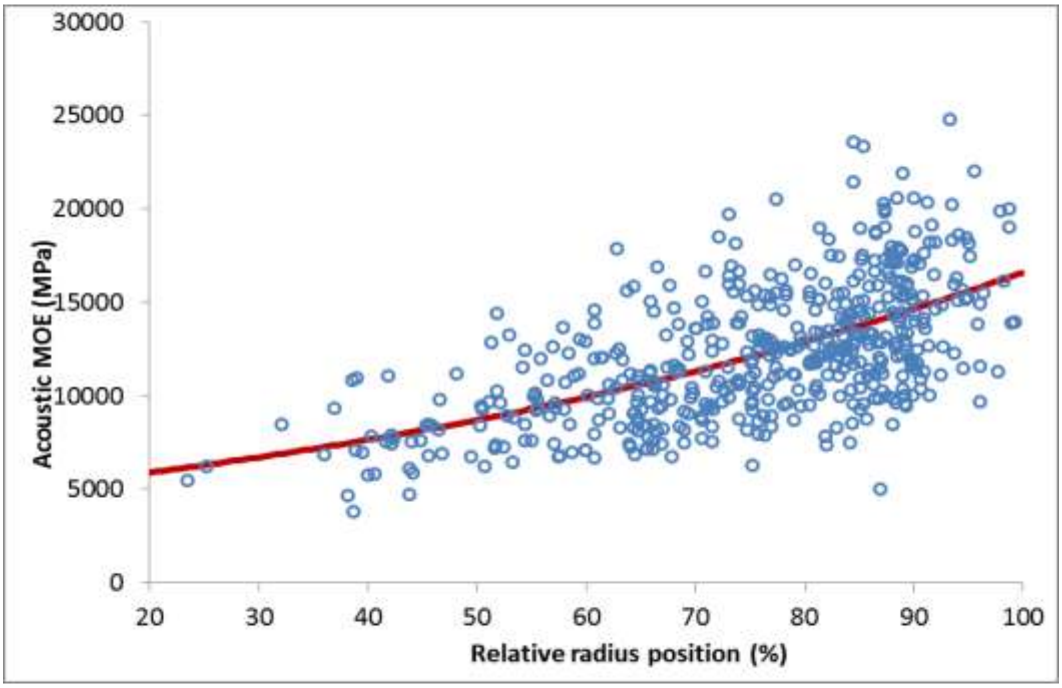


Figure 52. Variation of Dunn’s white gum veneer MOE with relative radius position (N= 500). The red curve in the plots shows the sigmoid curve fitting.

Spotted gum veneer MOE starts to stabilise at approximately 80% of the radius indicating that the mature state of the wood starts from this point (Figure 53).

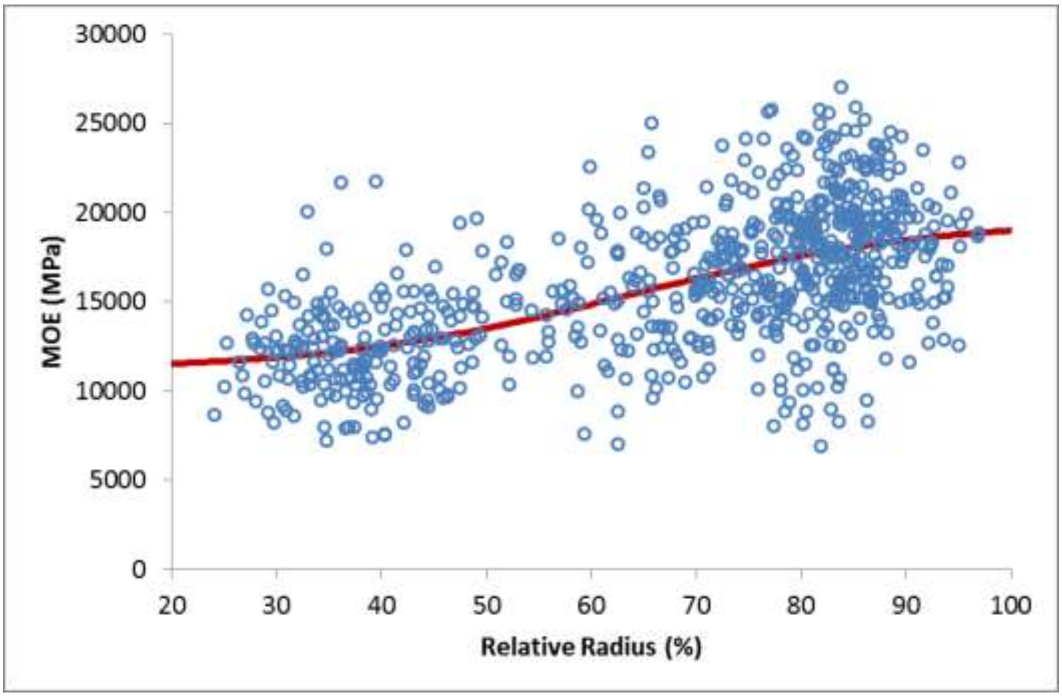


Figure 53. Variation of spotted gum veneer MOE with relative radius position (N= 712). The red curve in the plots shows the sigmoid curve fitting.

Gympie messmate veneer MOE starts to stabilise earlier than spotted gum at approximately 70% of the radius (Figure 54).

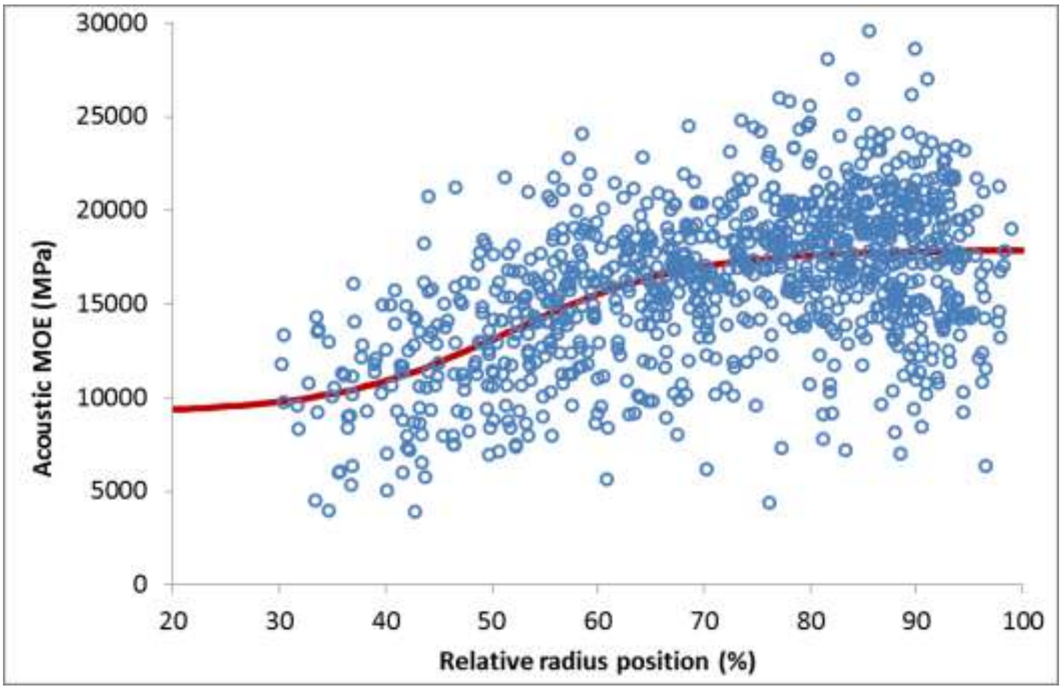
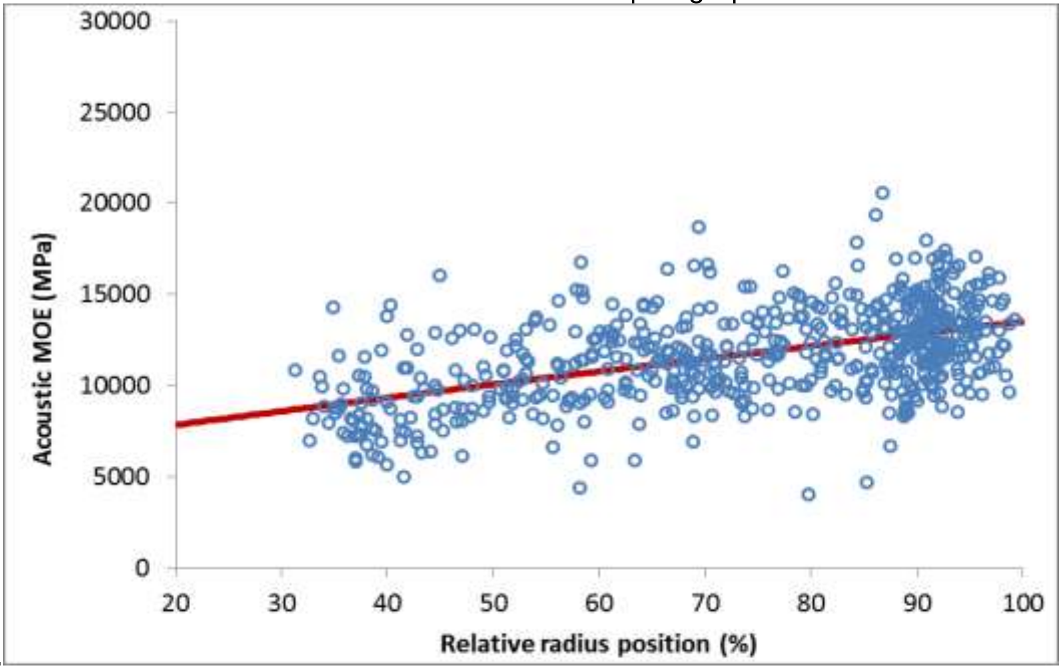


Figure 54. Variation of Gympie messmate veneer MOE with relative radius position (N= 967). The red curve in the plots shows the sigmoid curve fitting.

Similarly to Dunn's white gum, spotted gum hybrid veneer MOE increases steadily with the radius with no indication of stabilisation (Figure 55). Interestingly, the MOE dispersion at a given position along the radius is visibly less important than for the other species which is coherent with the coefficient of variation mentioned in paragraph



4.3.6.

Figure 55. **Variation of spotted gum hybrid veneer MOE with relative radius position (N= 582). The red curve in the plots shows the sigmoid curve fitting.**

Red mahogany veneer MOE seems to a stabilisation phase reach relatively quickly at around 70% of the radius (Figure 56).

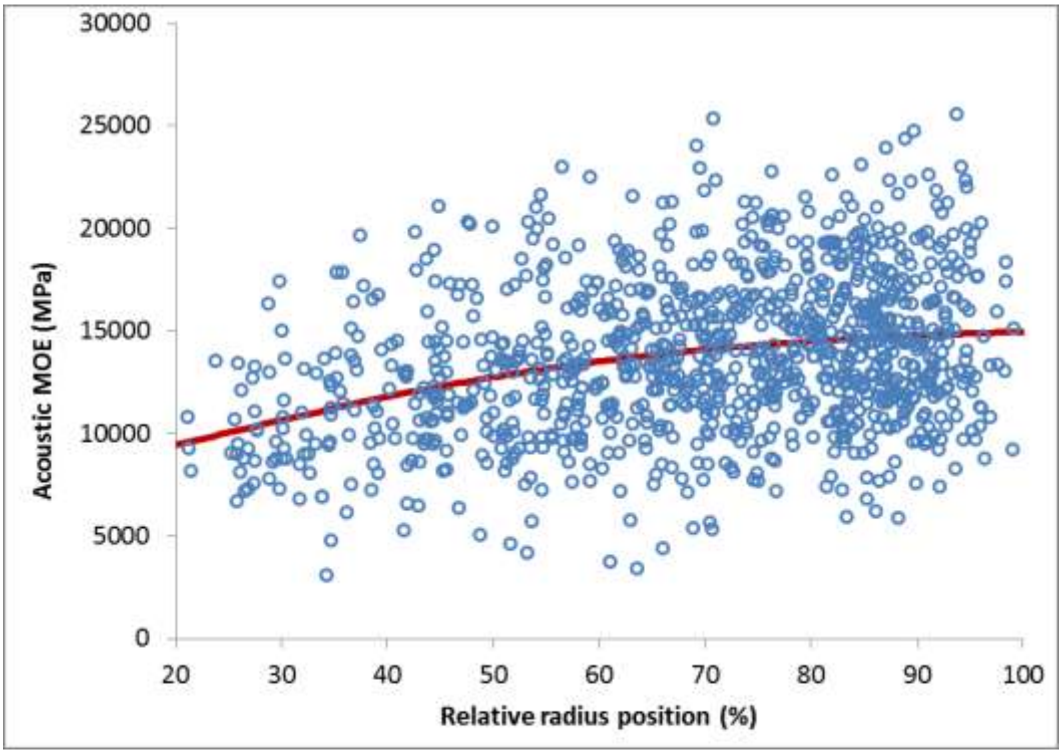


Figure 56. **Variation of red mahogany veneer MOE with relative radius position (N= 1013). The red curve in the plots shows the sigmoid curve fitting.**

Similarly to Dunn's white gum and spotted gum hybrid, western white gum veneer MOE increases steadily with the radius with no indication of stabilisation (Figure 57).

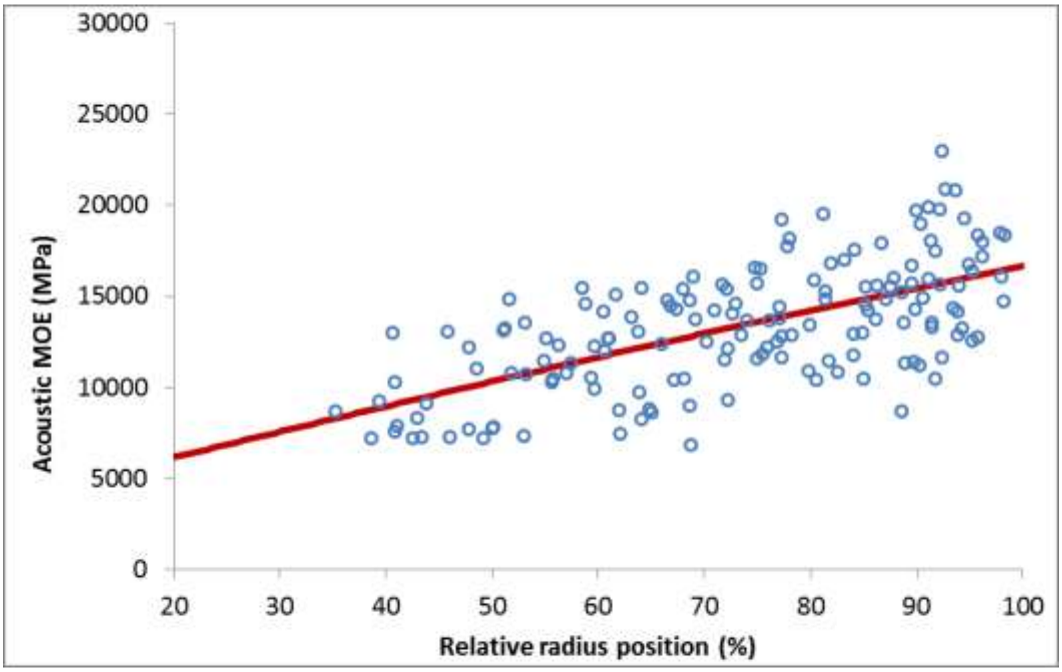


Figure 57. Variation of western white gum veneer MOE with relative radius position (N= 158). The red curve in the plots shows the sigmoid curve fitting.

4.3.7.2. Comparison on MOE variation along the radius between species

Figure 58 shows the sigmoid curve fittings for all species. This convenient representation gives at a glance, the pattern of MOE variation along the radius. Table 24 provides the sigmoid curve fitting parameters for all species.

The most noticeable observation is the spotted gum superiority in terms of veneer MOE (maximum 18 400 MPa) and early transition juvenile to mature (width of 22 mm) with a centre at 45 mm. Gympie messmate also displays high maximum veneer MOE (17 300 MPa) however the transition juvenile to mature is significantly larger than spotted gum (width of 44 mm) with a centre at 55 mm. Both species have similar minimum MOE around 11 200 MPa.

Another clear observation is the veneer MOE step (sharp "S" curve) for Dunn's white gum and spotted gum hybrid. These curve shapes are explained by the presence of a knotty core which diminishes along the radius. For spotted gum hybrid this pattern is probably due to the high initial stocking of approximately 1670 spha which promotes self-pruning when competition between trees is high. For Dunn's white gum the explanation lies in the combination of pruning impact and the early death of the branch. This phenomenon can be observed on veneers with high MOE (for this species) which displays many small dead knots and low local grain deviation.

Red mahogany displays a relatively high maximum MOE of 14 400 MPa despite a very low minimum MOE of 6 500 MPa near the centre of the log. This observation supports the findings of Bailleres et al. (2008) who reported compression failure and decay near the pith with adverse consequences on mechanical properties.

It was not possible to fit a typical sigmoid on the western white gum veneer MOE data. The curve on Figure 58 shows a very stretched "S" curve which doesn't really reflect the MOE trend along the radius. In order to approximate the real trend a sigmoid curve was "forced" to fit the data. This fitting is coherent with the curve displayed on Figure 57. Table 24 provides the parameters of the “forced” sigmoid. This indicates a very low MOE (5 000 MPa) near the centre and a relatively high MOE (15 000 MPa) on the periphery of the log. This pattern is similar to red mahogany and the veneers near the centre were probably affected by compression failure since no obvious trace of decay was detected.

These curves provide the potential MOE recovery of each species. For example, spotted gum exhibits high MOE wood at a smaller diameter than the other species which could be an important characteristic compared to other species. Further analysis of tree diameter and age would verify the trend of wood maturity against age.

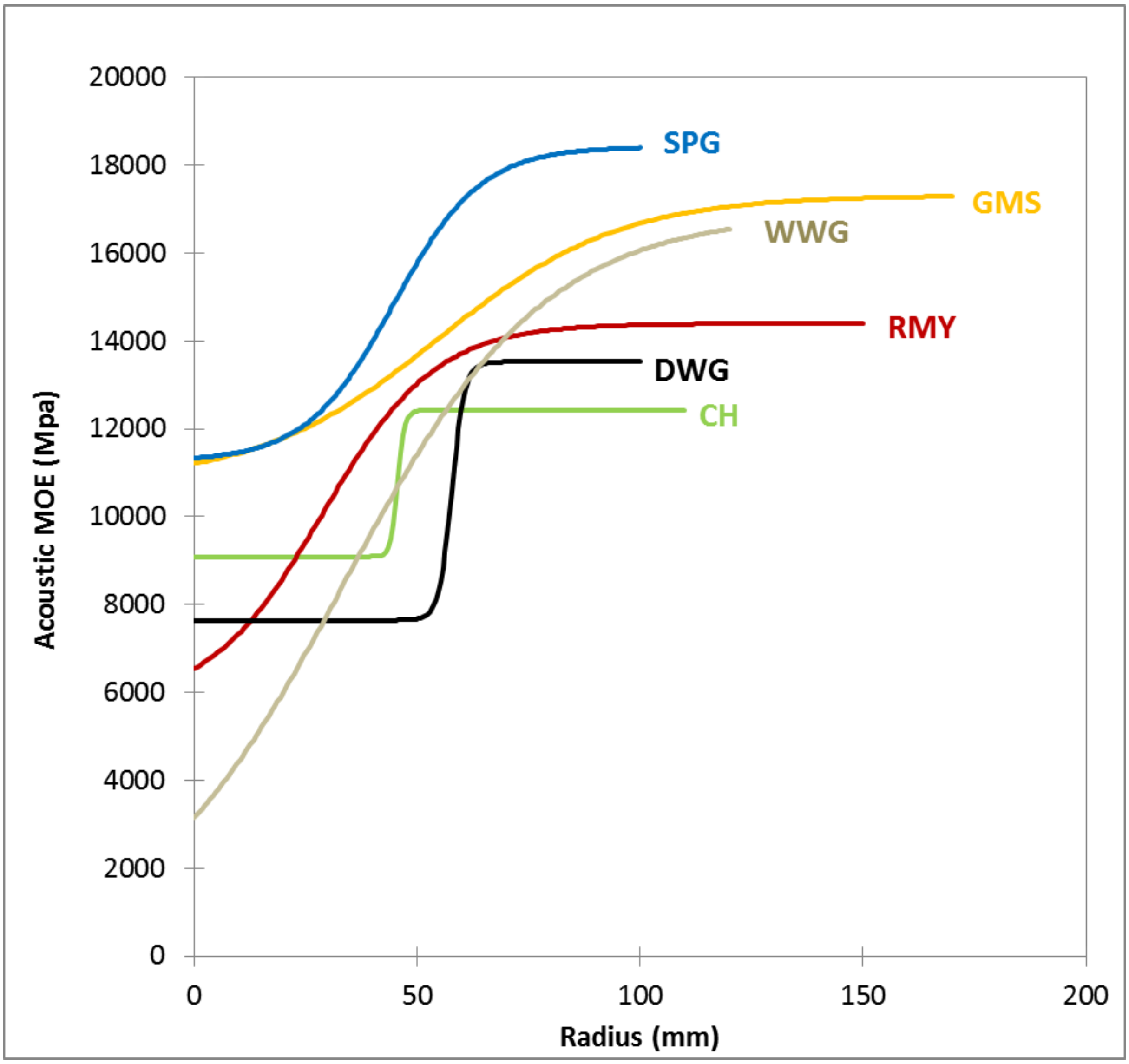


Figure 58. **Variation of veneer MOE along the radius between species from sigmoid curve fitting**

Table 24. Sigmoid parameters from acoustic MOE curve fitting versus radius for each species??

Species	Age (years)	MOE pith (MPa)	Max MOE (MPa)	Asymptote	MOE (MPa) Transition height	Radius (mm) Transition centre	Radius (mm) Transition width
GMS	12.4 / 15.6	11,200	17,300	YES	6500	55	44
SPG	12.3 / 10.4	11,300	18,400	YES	7200	45	22
CH	9	9100	12,400	YES	3300	46	2
RMY	13	6500	14,400	YES	8700	29	28
DWG	10.3	7600	13,500	YES	5900	58	3
WWG	12.1	5000	15,000	FORCED	8000	50	30

4.3.8. Veneer MOE variation with height (1 to 8 m)

For each species, there were no significant variations in MOE with height.

4.3.9. Veneer shrinkage and unit shrinkage

Figure 59 illustrates the results of unit shrinkage across the included species. The average unit shrinkage of Gympie messmate, spotted gum hybrid and red mahogany is lower than 0.4% with a relatively small distribution. Dunn’s white gum and western white gum have a unit shrinkage average of approximately 0.45% with a slightly larger distribution than the previous species. A larger population of spotted gum samples was assessed for unit shrinkage which resulted in spotted gum displaying the largest average unit shrinkage at above 0.5% and also the largest variation.

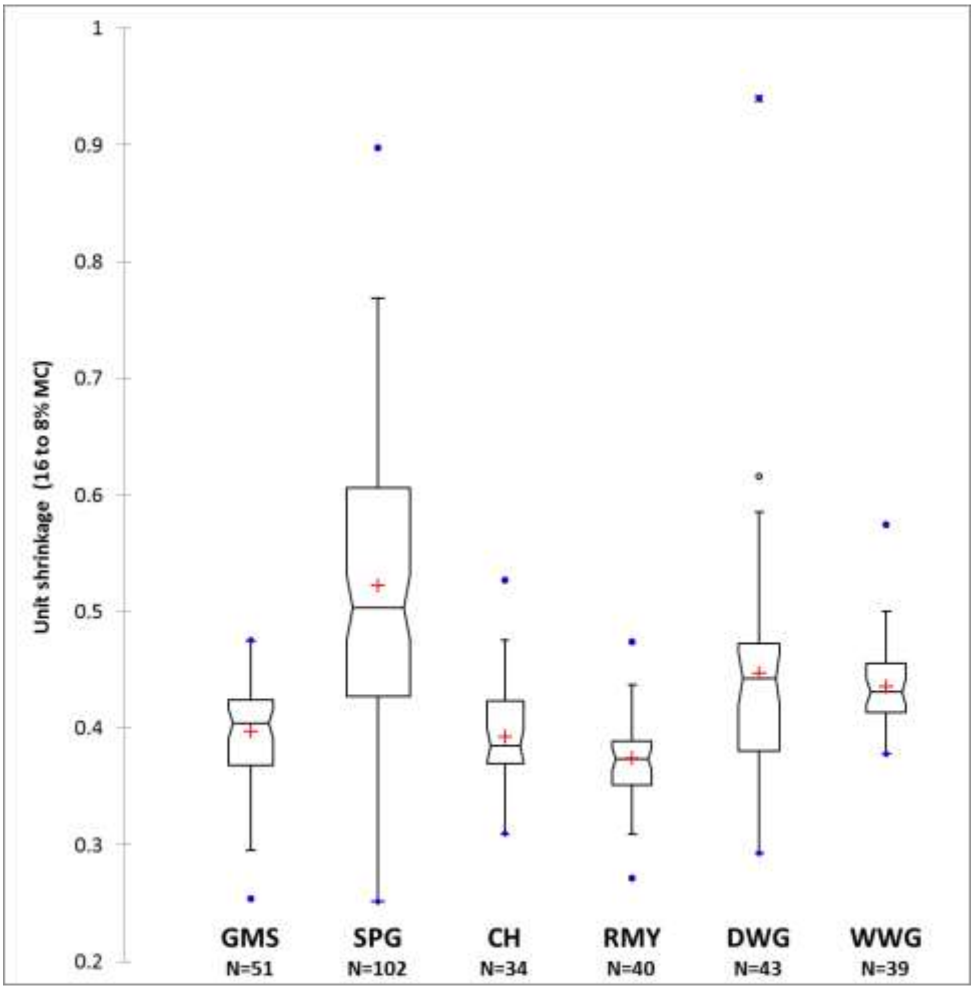


Figure 59. Veneer unit shrinkage (%)

Figure 60 displays the shrinkage that was measured from veneer produced from the stage two processing trials (i.e. spotted gum sites 2 and 3, and Gympie messmate site 2). Similar to the unit shrinkage measurements, spotted gum displays a wide variation in results with an average shrinkage from green to 8% moisture content of 7.6%. Gympie messmate displays a much more favourable narrower range with the average shrinkage value of 6.7%.

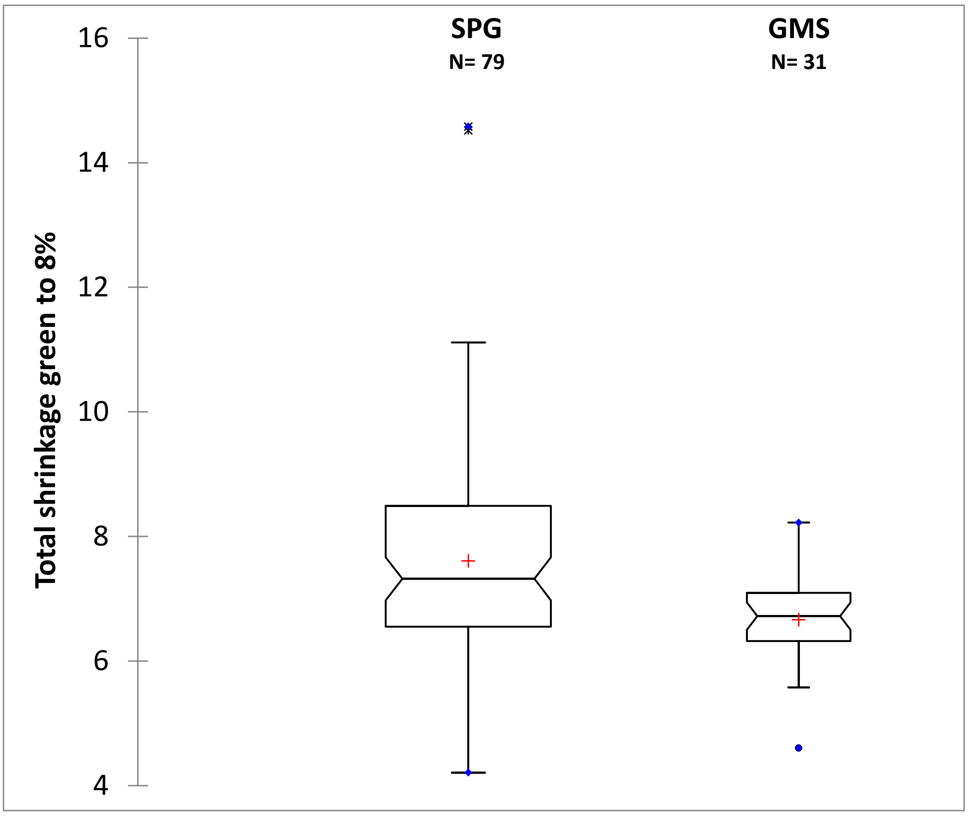


Figure 60. Veneer shrinkage

4.4. Adhesive performance

4.4.1. Phenol formaldehyde

A total of five trials were completed using PF adhesive systems. The resin systems were supplied predominately by Momentive Speciality Chemicals with Dynea supplying resins for two trials. Tables 25 and 26 provide a summary of each of the trials for plywood while Table 27 provides the summary results for the LVL samples. Within the tables, the average bond score is provided, with green shaded results indicating a bond average of five or greater or shaded pink where the bond average score was below five. The percentage of failed bonds is also presented with results shaded green indicating no failed bonds and pink if any failed bonds were present. Failed bonds were defined as a bond score of two or less.

Trial PF 1 demonstrated that there are benefits in applying the adhesive on both sides of each veneer opposed to the more commercially adopted strategy of applying adhesive to both sides of alternate veneers only. This strategy was continued for trial PF 2 but latter trials reverted back to applying adhesive on both sides of alternate veneers as a solution was being targeted that fit within standard commercial operations.

For the plywood samples, trial PF 2 resulted in good bonds being achieved for Dunn's white gum using both adhesive systems. This trend was not observed in the LVL samples. For the plywood samples, there was general trend for the other species to have improved bond results when veneer from the inner part of the billet was used. This may be attributed to different wood properties and chemistry including lower density, lower extractive contents etc. The same trend however was not observed in the LVL samples.

Trial PF 3 explored a range of PF adhesive systems available from Momentive Specialty Chemicals. While some variation existed between species, the only adhesive system that showed positive results across all species was Momentive's XB-91MO. This system was trialled in two formulations with the standard formulation (i.e. without additional catalyst added) demonstrated better performance. This adhesive system is currently not commercially available in Australia and only a very limited quantity was made available for this trial.

Trial PF 4 focused on the bonding performance of combining hardwood and softwood veneers using a commercially available traditional PF adhesive system developed for the softwood veneer industry. Samples that combined the hardwood faces (either Gympie messmate or spotted gum) and slash pine core produced good bonds. The samples that combined hardwood faces and long bands with slash pine cross bands produced marginal bonds.

Trial PF 5 used the same commercially available traditional PF adhesive system developed for the softwood veneer industry and used in trial PF 4. The trial included Gympie messmate and spotted gum only with satisfactorily average bonds being achieved. There were however a small number of individual glue lines (3% for both species) that were scored as two.

Across the trials completed, the only adhesive that demonstrated great potential across all species was Momentive's XB-91MO, however this adhesive system is not currently available commercially within Australia. The trial also only incorporated relatively low sample replication and further validation trials would be necessary to confirm these findings. From the locally available adhesive systems, Momentive's PP1158 showed reasonable promise although the trial was restricted to only Gympie messmate and spotted gum. Despite this trial limitation, reasonable results were achieved with spotted gum which has shown to be the most consistently problematic species to reliably bond.

Table 25. Results of PF adhesive trials on plywood samples (PF 1, PF 2, PF3 and PF 5)

	Trial No	Resin type	Pos.	CH			DWG			GMS			RMY			SPG		
				No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
Plywood	PF1/1	Momentive DPL 6381		20	7.2	0	20	6.6	5	20	8.7	0				20	4.2	35
	PF1/2			20	5.5	15	20	2.2	75	20	3.3	30				20	1.6	80
	PF2/1	Momentive DPL 6381	inner	12	5.6	0	12	6.2	0	12	8.0	0				12	6.6	0
			outer	12	6.8	8	12	7.3	0	12	6.7	0				12	5.6	0
	PF2/2	Dynea Prefere 14L004X	inner	20	6.7	0	4	8.5	0	12	8.6	0				12	6.2	0
			outer	12	8.0	0	12	8.3	0	12	5.9	8				12	2.6	58
	PF3/1	Momentive HL4645		4	5.3	0	4	7.5	0	4	5.0	25	4	5.8	0	4	1.5	75
	PF3/2	Momentive DPL6381		4	2.8	75	4	3.3	25	4	5.0	0	4	3.0	25	4	1.3	75
	PF3/3	Momentive XB-91MO		4	8.0	0	8	9.1	0	4	9.0	0	4	9.5	0	4	8.5	0
	PF3/4	Momentive XB-91MO + catalyst		4	7.3	0	4	8.5	0	4	8.0	0	4	9.0	0	4	6.8	0
	PF3/5	Momentive XB-91MO		20	6.9	5	20	7.9	0	20	9.2	0	19	8.3	0	20	4.3	45
	PF5	Momentive PP1158								30	7.6	3				30	6.4	3
	TOTAL / AVERAGE			**92**	**6.4**	**10**	**80**	**7.4**	**3**	**114**	**7.3**	**4**	**32**	**7.1**	**5**	**114**	**5.0**	**26**

Table 26. Results of PF adhesive trial PF 4 on mixed species plywood samples

	Trial No	Resin type	SPG/Slash pine			GMS/Slash pine		
			No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
Plywood	PF4/1	Momentive PP1158				18	7.1	6
	PF4/2		18	7.0	6			
	PF4/4					18	5.5	28
	PF4/5		18	5.7	17			
	TOTAL / AVERAGE		**36**	**6.3**	**11**	**36**	**6.3**	**17**

Table 27. Results of PF adhesive trials on LVL samples

	Trial No	Resin type	Pos.	CH			DWG			GMS			SPG		
				No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
LVL	PF2/1	Momentive DPL 6381	inner	30	5.8	10	10	5.3	30	10	8.7	0	20	4.6	15
			outer	20	6.9	0	30	6.3	3	30	6.3	7	10	6.3	0
	PF2/2	Dynea Prefere 14L004X	inner	30	6.5	0	30	7.5	0	30	7.4	0	40	6.0	3
			outer	30	6.6	0	40	7.6	3	30	5.2	13	40	5.3	13
	TOTAL / AVERAGE			**150**	**6.4**	**4**	**150**	**6.2**	**15**	**140**	**6.7**	**7**	**150**	**5.0**	**18**

4.4.2. Melamine urea formaldehyde

A total of seven trials were completed using MUF adhesives systems supplied by Momentive Speciality Chemicals. The adhesive system is produced commercially as being suitable for hardwood veneers and is believed to be used commercially in one operation within Australia for the manufacture of plywood from veneers sourced from native forest sub-tropical hardwood species. Tables 28 and 29 provide a summary for trials MUF 1 to MUF 3 and trials MUF 4 to MUF 7 respectively for plywood. Table 30 provides a summary for the LVL samples. Within the tables, the average bond score is provided, with green shaded results indicating a bond average of five or greater or shaded pink where the bond average score was below five. The percentage of failed bonds is also presented with results shaded green indicating no failed bonds and pink if any failed bonds were present. Failed bonds were defined as a bond score of two or less.

Despite the numerous trials and various process parameters adopted, there wasn't one trial that produced a bond average above five with individual bond scores above two across all species. While dry bonds[9] were often very good (results not reported), once samples were prepared in accordance with the standard test method, the bonds where in general, very poor. When the gluelines were assessed after testing, evidence of 'washout' was common. This was despite standard corrective options being adopted to counteract this problem through the various trials.

These poor results across all the MUF trials were surprising given the adhesive system is used commercially with similar species, albeit sourced from native forests. The trials were also conducted in close collaboration with the technical experts of Momentive Speciality Chemicals and a number of trials were conducted within Momentive's laboratories. While several theories exist, the cause of the problems is not clear and further investigations are necessary to understand the problem and develop a solution.

[9] Dry bond testing is a non standard test method that is often conducted to rapidly screen samples and provide an indication of bond quality. The sample treatment (e.g. steam or boiling) is bypassed meaning indicative results can be achieved much earlier.

Table 28. Results of MUF adhesive trials on plywood samples (MUF 1 to MUF 3)

	Trial No	Resin type	Pos.	CH			DWG			GMS			RMY			SPG		
				No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
Plywood	MUF1	Momentive BPly8166	inner	4	0.3	100	4	1.0	100	4	3.5	25	11	7.0	0	4	2.8	75
		Momentive BPly8166	outer	4	0.8	100	4	1.0	75				4	0.3	100	4	5.8	0
	MUF2	Momentive BPly8166	inner	12	1.5	83	12	5.8	17	12	6.0	8	12	6.2	0	12	4.4	25
		Momentive BPly8166	outer	12	4.3	17	12	5.3	25	12	4.2	42	12	4.2	33	12	4.8	0
	MUF3/1	Momentive BPly8166	inner	4	2.5	75	4	6.5	0	4	3.5	50	4	6.0	0	7	3.3	29
		Momentive BPly8166	outer	4	4.0	25	4	3.3	25	4	1.5	75	4	3.0	75	4	3.3	50
	MUF3/2	Momentive BPly8166	inner	4	3.8	25	4	6.0	25	4	6.3	0	4	5.5	0	4	3.8	25
		Momentive BPly8166	outer	4	4.5	0	4	4.5	0	4	3.8	25	4	4.8	25	4	1.3	75
	MUF3/3	Momentive BPly8166	inner	4	5.3	0	4	8.5	0	4	6.5	0	4	7.8	0	4	5.0	25
		Momentive BPly8166	outer	4	4.3	25	4	6.8	0	4	7.0	0	3	5.0	0	4	4.3	50
	TOTAL / AVERAGE			**56**	**3.1**	**45**	**56**	**4.9**	**27**	**52**	**4.7**	**25**	**62**	**5.0**	**23**	**59**	**3.9**	**35**

Table 29. Results of MUF adhesive trials on plywood samples (MUF 4 to MUF 7)

	Trial No	Resin type	GMS			SPG		
			No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
Plywood	MUF4/ 1	Momentive BPly8166	20	4.4	35			
	MUF4/ 2	Momentive BPly8166	20	4.5	20			
	MUF4/ 3	Momentive BPly8166	20	5.9	10			
	MUF4/ 4	Momentive BPly8166	20	5.3	20			
	MUF4/ 5	Momentive BPly8166	20	6.4	5			
	MUF4/ 6	Momentive BPly8166	20	5.4	10			
	MUF5/ 1	Momentive BPly8166	38	5.5	16			
	MUF5/ 2	Momentive BPly8166	28	6.7	7			
	MUF5/ 3	Momentive BPly8166	12	5.3	33			
	MUF6/ 1	Momentive BPly8166				80	5.7	8
	MUF6/ 2	Momentive BPly8166				80	5.6	9
	MUF7/ 1	Momentive BPly8166				40	3.4	43
	MUF7/ 2	Momentive BPly8166				80	4.6	30
	TOTAL / AVERAGE		**198**	**5.5**	**17**	**280**	**4.8**	**22**

Table 30. Results of MUF adhesive trials on LVL samples

	Trial No	Resin type	Pos.	CH			DWG			GMS			RMY			SPG		
				No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
LVL	MUF1	Momentive BPly8166	inner	10	1.7	60	10	3.7	30	10	3.0	50	10	9.3	0	10	5.5	20
		Momentive BPly8166	outer	10	8.6	0	10	3.2	30	10	4.3	30				10	6.5	0
	MUF2	Momentive BPly8166	inner	30	5.2	13	21	2.0	67	21	2.7	57	30	6.2	3	30	5.2	17
		Momentive BPly8166	outer	30	5.9	7	30	6.4	0				14	3.6	29	30	6.0	7
	MUF3/1	Momentive BPly8166	inner	10	4.5	20	10	5.6	10	10	7.8	0	10	7.0	10	10	6.2	0
		Momentive BPly8166	outer	10	5.4	0	10	5.1	0	10	4.9	20	10	7.6	10	10	5.1	10
	MUF3/2	Momentive BPly8166	inner	10	5.6	0	10	5.9	0	10	6.4	0	10	6.8	0	10	3.6	20
		Momentive BPly8166	outer	10	5.5	0	10	4.0	30	10	5.2	0	10	6.7	0	10	4.1	10
	MUF3/3	Momentive BPly8166	inner	10	5.4	10				10	7.0	0	10	6.7	0	10	7.5	0
		Momentive BPly8166	outer	10	7.0	0	10	6.7	0	10	6.7	0	10	7.9	0	10	6.2	10
	TOTAL / AVERAGE			**140**	**5.5**	**11**	**121**	**4.7**	**19**	**101**	**5.3**	**17**	**114**	**6.9**	**6**	**140**	**5.6**	**9**

4.4.3. Polyurethane

Of the 150 plywood samples prepared for testing, all samples delaminated during the pre-treatment stage resulting in 100% failure before any shear testing could be conducted.

Table 31 displays the results of the LVL lap shear tests which indicate that bonding Dunn's white gum and spotted gum were successful. It is noted however that even with Dunn's white gum which performed the best, three of the nine tests failed when analysed individually. Similarly, two of the nine individual tests for spotted gum also failed. Two of the red mahogany tests failed during pre-treatment preventing them for being tested further.

Table 32 displays the results of the LVL delamination testing. Half of the Dunn's white gum and spotted gum samples failed while 25% of the Gympie messmate samples failed. The cause of each failure was heavily influenced by one individual glueline within each sample. All spotted gum hybrid and red mahogany samples passed.

Table 31. Lap shear results for polyurethane bonded LVL

Species	No of samples	No of tests	Average (MPa)	Fibre fail (%)	Result
Dunn's white gum	1	9	0.36	81	Pass
Spotted gum	1	9	0.72	56	Pass
Gympie messmate	1	9	0.58	26	Fail
Spotted gum hybrid	1	9	0.56	49	Fail
Red mahogany	1	9	0.58	32	Fail

Table 32. Delamination results for polyurethane bonded LVL

Species	Sample No.	No. of gluelines	No. of failed gluelines	Ratio of delamination - Total glueline	Result
Dunn's white gum	1	10	1	8%	Fail
	2	10	1	8%	Fail
	3	10		3%	Pass
	4	10		3%	Pass
Spotted gum	1	10	1	8%	Fail
	2	10	1	8%	Fail
	3	10		2%	Pass
	4	10		2%	Pass
Gympie messmate	1	10		3%	Pass
	2	10		2%	Pass
	3	10		2%	Pass
	4	10	1	5%	Fail
Spotted gum hybrid	1	10		1%	Pass
	2	10		0%	Pass
	3	10		2%	Pass
	4	10		2%	Pass
Red mahogany	1	10		2%	Pass
	2	10		2%	Pass
	3	10		0%	Pass
	4	10		1%	Pass

4.4.4. Overlaid plywood

The samples produced during overlay trials OL 1 and OL 2 were considered to have greater than 50% wood plus overlay paper failure and therefore pass the requirements of the bond quality and durability testing in accordance with *AS6669:2007*.

4.5. Veneer product performance

4.5.1. Plywood (single species)

4.5.1.1. Mechanical properties

All the mechanical tests were performed according to AS/NZS 2269.1:2008. The data were collected from all the plywood construction strategies (HHH, HLH, LLL, LHL). It should be noted that the results for each panel depends on the selection of veneers that constitute it. As a consequence since only 12 specimens have been tested for each property, the statistics are sensitive to the choice of the veneers that constitute individual panels. This choice was based on random selection of veneers within the two stiffness groups (low and high stiffness) and their availability at the time of panel manufacture.

Flexure parallel to the grain

Figure 61 shows the MOE and MOR distributions for five species. For both properties spotted gum is clearly superior to the other species. However it is important to note that average MOE of the face veneers for Gympie messmate (15 900 MPa) is significantly lower comparatively to average MOE of the face veneers for spotted gum (17 400 MPa) despite an average MOE of 15 900 MPa for internal veneers for both Gympie messmate and spotted gum. Red mahogany comes in third position followed by Dunn’s white gum and spotted gum hybrid which display similar average MOEs, the latter having a smaller distribution than Dunn’s white gum.

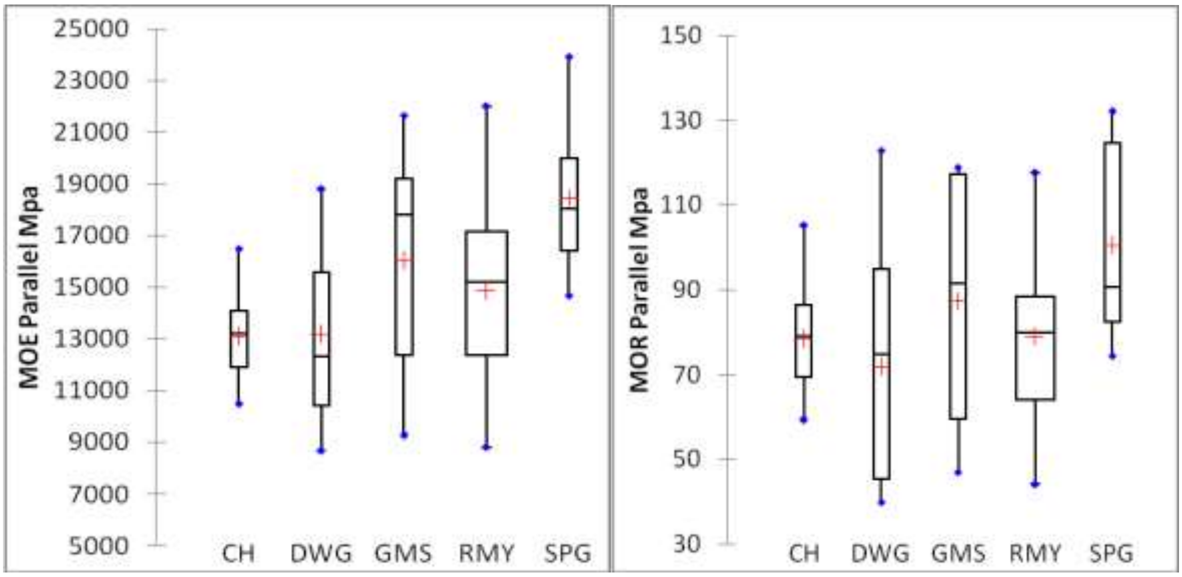


Figure 61. Plywoods MOE and MOR in flexure parallel to the grain for five species. N= 72 for RMY. N=12 for each species.

Flexure perpendicular to the grain

The same MOE and MOR trends are observed in flexure perpendicular and parallel to the grain (Figure 62).

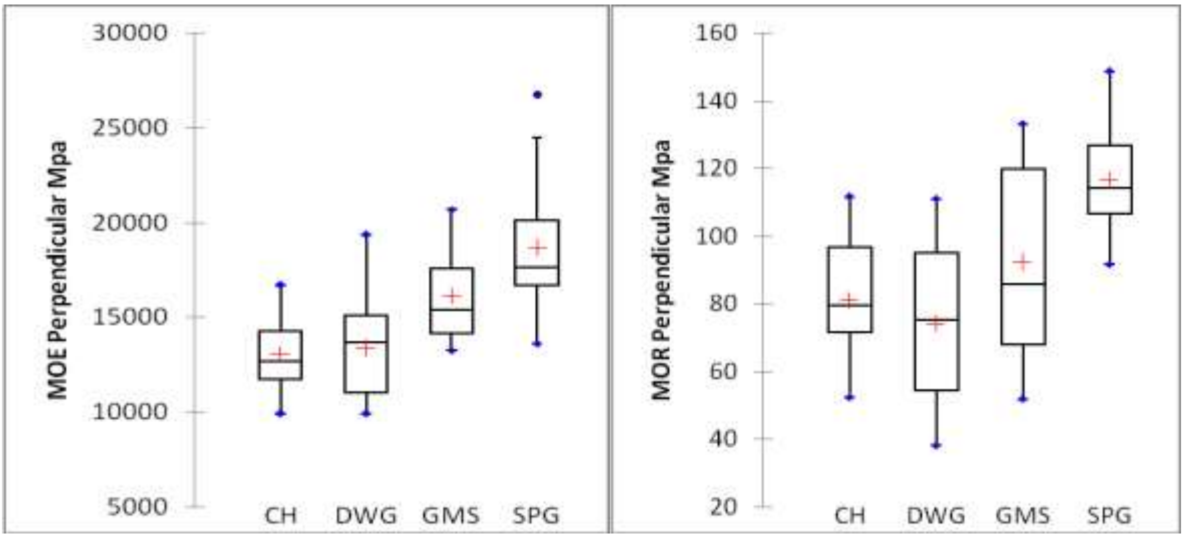


Figure 62. Plywood MOE and MOR in flexure perpendicular to the grain for four species. N=12 for each species.

Tension strength

Figure 63 shows the tension strength distributions parallel and perpendicular to the grain for four species. Spotted gum displays the highest mean tension strength closely followed by Gympie messmate. The latter shows a larger strength distribution. Spotted gum hybrid has the third highest mean tension strength significantly above Dunn's white gum. This low strength is partly due to the high proportion of knots in Dunn's white gum.

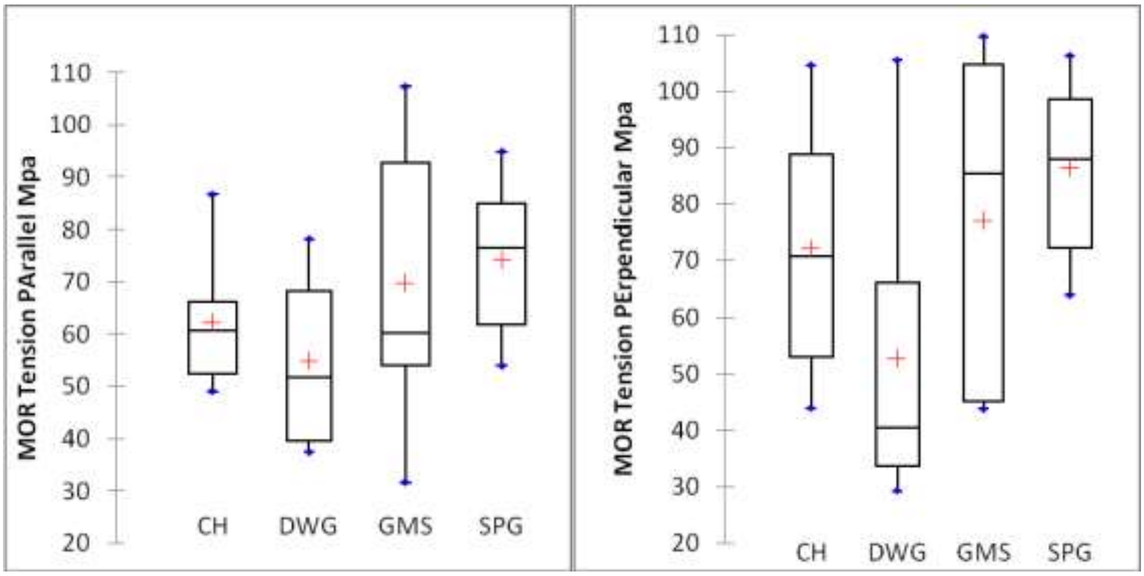


Figure 63. Plywood MOR in tension parallel and perpendicular to the grain for four species. N=12 for each species.

Compression strength

Figure 64 shows the compression strength distributions parallel and perpendicular to the grain for four species. Dunn's white gum displays the lowest strength partly attributable to the high proportion of knots in the veneers. In compression parallel spotted gum hybrid has strength similar to spotted gum and Gympie messmate whereas in compression perpendicular to grain Gympie messmate and spotted gum are noticeably superior.

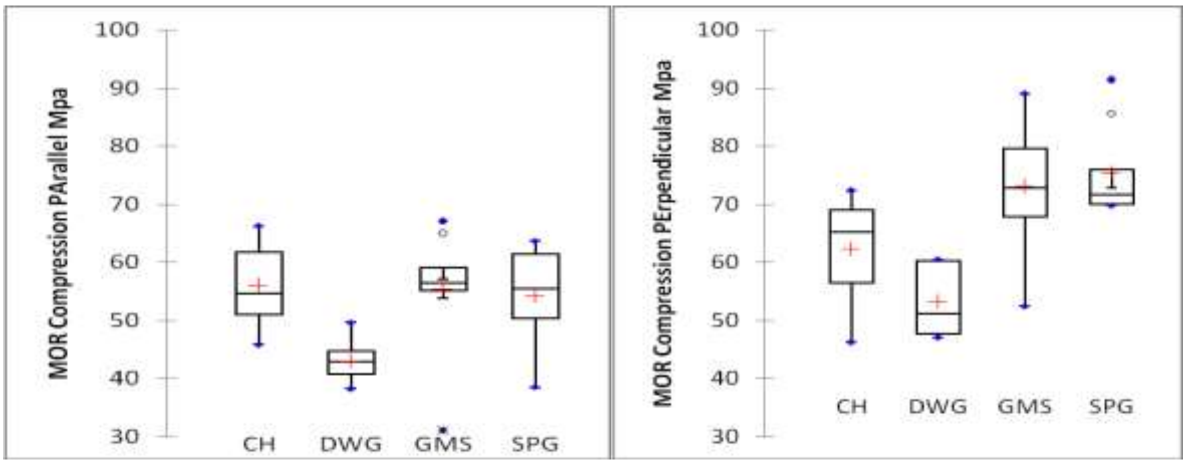


Figure 64. Plywood MOR in compression parallel and perpendicular to the grain for four species. N=12 for each species.

Shear strength

Figure 65 shows the shear strength distributions parallel and perpendicular to the grain for four species. Again Dunn's white gum displays the lowest strength partly attributable to the high proportion of knots in the veneers. Gympie messmate and spotted gum have the same level of strength and they are markedly higher than spotted gum hybrid.

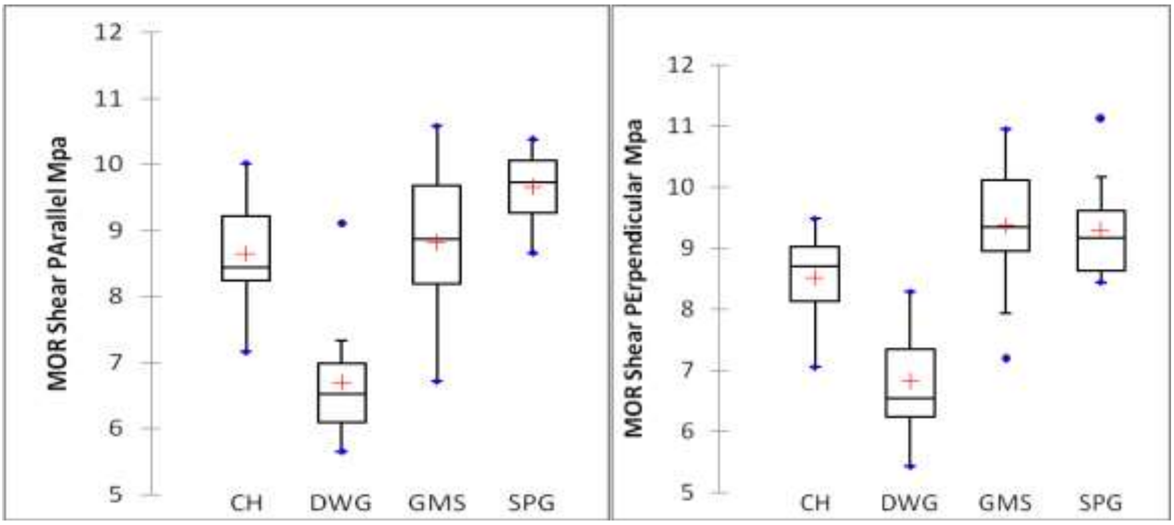


Figure 65. Plywood MOR in shear parallel and perpendicular to the grain for four species. N=12 for each species.

Plywood standard properties (AS/NZS 2269)

The correlation between MOE and MOR on plywood parallel or perpendicular to the grain is relatively high on a wide range of values (Figure 66). Apart from red mahogany (R^2=0.64 in flexure parallel to the grain), this correlation is even better with a coefficient of determination above 0.80 for each species. The quality of the correlation is partly due to the construction strategy which deliberately provided a wide range of mechanical properties.

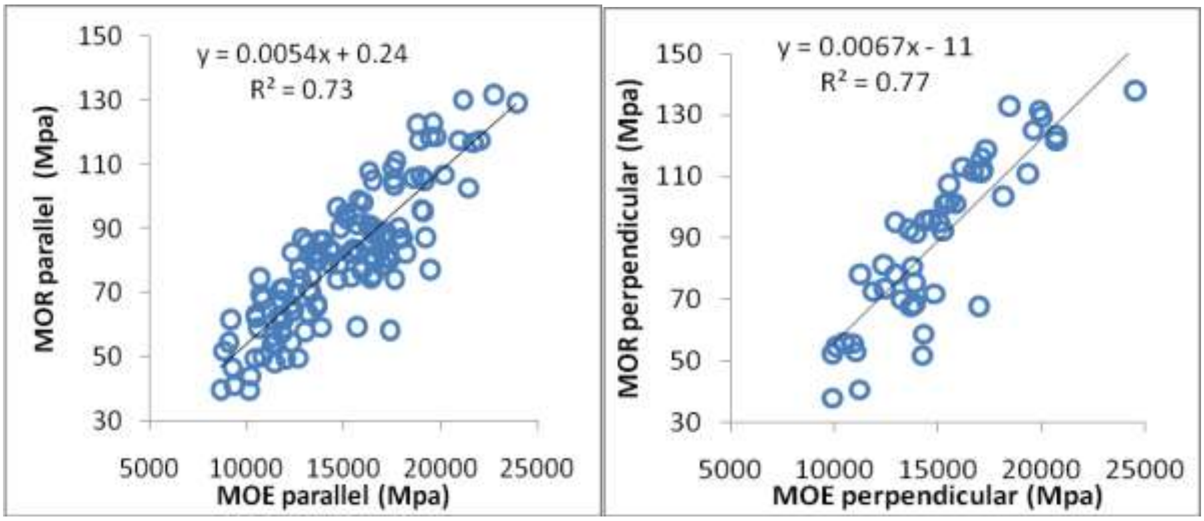


Figure 66. Plywood flexure parallel and parallel to the grain for five species. N=12 for CH, DWG, GMS and SPG. N= 72 for RMY.

4.5.1.2. Assigned F grades for all plywood construction strategies

Structural plywood engineering properties are given for eight standard stress grades. The characteristic strength and stiffness values of structural plywood are allocated a stress grade via the F- grade classification system:

- F7, F8, F11, F14, F17, F22, F27 or F34.

It should be noted that although the F-grade characteristic strength and stiffness values of structural plywood and structural timber are the same for bending, tension, compression and modulus of elasticity; shear capacity of structural plywood is superior and modulus of rigidity is marginally reduced.

The I values of each test were adjusted to accommodate the actual panel thickness, rather than the nominal 15 mm. The mean standard deviation and Coefficient of Variation were calculated using formulae from *AS/NZS 2269.0:2012*. The sampling factor ks, 5th percentile (E 0.05 / Tp 0.05 / Psp 0.05), and characteristic parameters (Ek, mean/ Tpk / Pspk) were calculated using *AS/NZS 4063.2*, method 1 (lognormal) in the absence of an evaluation method in *AS/NZS 2269.0:2012*.

The calculations for determining the assigned grades are based on eight to 12 samples per mechanical property and per species, however the standard specifies at least 30 samples per property and panel configuration. The small number of samples results in a penalising sampling factor calculation to determine the characteristic values. A larger number of samples would provide more accurate F-grades.

In addition, the panels were designed to cover the worst and the best case lamination scenarios (or construction strategies) in order to validate the analytical mechanical model described above which predicts the panel mechanical properties from the veneer stiffness. Veneer selection for high and low stiffness was performed randomly within a selection of high and low acoustic MOE. Obviously this strategy is not what a normal run of the mill should target since the objective is to optimise the construction design of the plywood. These elements have contributed to produce significantly lower F-grades than would be expected from a normal run of a mill with similar resources. An upgrade of one to three F-grades may be expected by using more samples and optimising the lamination design.

Flexure module of elasticity

Spotted gum displays the best assigned F-grades, attaining F22 for both plywood perpendicular and parallel to the face grain (Table 33). Gympie messmate is two and one grade respectively below spotted gum. Spotted gum hybrid is two grades below spotted gum for both plywood orientations. Dunn's white gum is three grades and two grades below spotted gum, parallel and perpendicular respectively. These results are coherent with the veneer MOE distribution given in paragraph 4.3.7.2.

Table 33. Bending MOE distribution parameters, characteristic properties and assigned grades

Species	Average MOE (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Ek, mean (MPa) from AS/NZS 4063.2		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	**Para**	**Perp**
Dunn's white gum	13 200	13 200	8 500	9 200	11 500	12 600	24.99	20.43	**F11**	**F14**
Spotted gum	18 400	18 700	14 500	13 300	17 900	17 900	14.11	19.75	**F22**	**F22**
Gympie messmate	16 000	16 100	9 820	12 520	13 230	15 600	28.05	14.82	**F14**	**F17**
Spotted gum hybrid	13 600	13 100	10 200	10 000	13 100	12 700	16.56	15.78	**F14**	**F14**

Flexure modulus of rupture

Spotted gum displays the best flexure strength assigned F-grades attaining F22 parallel and F27 perpendicular to the face grain (Table 34). Gympie messmate is two and three grades respectively below spotted gum. Spotted gum hybrid is three grades below spotted gum for both plywood orientations. Dunn's white gum is four grades and three grades below spotted gum, face grain parallel and perpendicular respectively.

Table 34. Bending MOR distribution parameters, characteristic properties and assigned grades

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	**Para**	**Perp**
Dunn's white gum	72	72	38	38	30	33	41	36	**F8**	**F11**
Spotted gum	100	117	69	91	64	87	21	14	**F22**	**F27**
Gympie messmate	90	94	47	46	41	40	36	39	**F14**	**F14**
Spotted gum hybrid	81	81	58	55	54	51	20	23	**F17**	**F17**

Tension strength

Spotted gum shows the highest tension strength assigned F-grades, F27 parallel and F34 perpendicular to the face grain (Table 35). Gympie messmate is two and three grades respectively below spotted gum. Spotted gum hybrid is only one and two grades below spotted gum for parallel and perpendicular face grain orientation respectively. Dunn's white gum is three grades and five grades below spotted gum, face grain parallel and perpendicular respectively.

Table 35. Tension strength distribution parameters, characteristic properties and assigned grades

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Par	Perp	Para	Perp	Para	Perp	**Para**	**Perp**
Dunn's white gum	63	52	30	22	26	19	42	48	**F14**	**F11**
Spotted gum	74	86	51	61	48	58	21	20	**F27**	**F34**
Gympie messmate	70	77	33	36	29	32	42	42	**F17**	**F17**
Spotted gum hybrid	62	72	45	41	42	37	19	32	**F22**	**F22**

Compression strength

Spotted gum hybrid shows the highest compression strength assigned F-grades, F22 parallel and F27 perpendicular to the face grain (Table 34). Spotted gum has similar grade for perpendicular orientation but is one grade below for parallel orientation. Gympie messmate is two grades and one grade below spotted gum hybrid, face grain parallel and perpendicular respectively. Dunn's white gum is one grade and two grades below spotted gum, face grain parallel and perpendicular respectively.

Table 36. Compression strength distribution parameters, characteristic properties and assigned grades

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade From 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	**Para**	**Perp**
Dunn's white gum	43	53	38	44	37	42	8	11	**F17**	**F17**
Spotted gum	54	75	41	64	38	61	16	10	**F17**	**F27**
Gympie messmate	55	73	38	56	34	53	22	15	**F14**	**F22**
Spotted gum hybrid	56	62	46	49	43	46	12	14	**F22**	**F27**

Panel shear strength

Spotted gum hybrid, Gympie messmate and spotted gum have F-grades for panel shear strength of F34 parallel and perpendicular to the face grain (Table 37). This is the maximum F-grade for panel shear strength. Dunn's white gum is four grades below these species face grain parallel and perpendicular.

Table 37. Panel shear strength distribution parameters, characteristic properties and assigned grades

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade From 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	**Para**	**Perp**
Dunn's white gum	6.7	6.8	5.5	5.5	5.2	5.3	12.5	12.7	**F17**	**F17**
Spotted gum	9.6	9.3	8.8	8.1	8.6	7.9	5.5	8.0	**F34**	**F34**
Gympie messmate	8.8	9.4	7.1	7.7	6.9	7.4	12.2	11.7	**F34**	**F34**
Spotted gum hybrid	8.7	8.5	7.4	7.4	7.2	7.2	9.1	8.5	**F34**	**F34**

Note: The maximum published characteristic strength for panel shear is 6.0 MPa, meeting 'greater than F34' (*AS/NZS2269.0:2012*).

Summary- assigned F grades

Spotted gum clearly demonstrated the highest grades (Table 38). Spotted gum hybrid is ranked second before Gympie messmate. This result is not consistent with the findings in paragraph 4.3.7.2. were Gympie messmate had a better overall veneer MOE distribution than spotted gum hybrid. Unfortunately the selection of the veneers for the plywood manufacture didn't reflect closely the overall quality of each species. This selection bias along with the F-grade calculation sensitivity due to the small number of specimen makes direct comparison of the results problematic. For this reason, the use of a predictive model like the one described in chapter 3.8 may prove extremely useful.

Table 38. Assigned F-grades on plywood face grain parallel and perpendicular

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

4.5.1.3. *Assigned F grades for plywood construction with high MOE veneer position optimised*

Given the impact of veneer selection and construction strategies had on assigned F-grades (Section 4.5.1.2), additional analysis was conducted with stress grades being calculated from panel constructions which more accurately reflect what would be adopted commercially i.e. maximising the mechanical properties. For this analysis, data from the following construction strategies were used:

- Flexure MOE & MOR: only HHH and HLH data, usually leaving six values per species.
- Tension & compression: only HHH, HLH and LHL data, leaving six values per species
- Panel shear: HHH, HLH, LHL, leaving nine values per species.

As stated above, the calculations for determining the assigned grades are based on a limited number of specimens per mechanical properties and per species. Consequently the F-grades indicated in tables below provide only a tendency of improvement when optimising the plywood construction strategy.

Where the grade increased, the grade is shown in orange. Conversely where the grade decreased, it is shown in blue. Note that 5th percentiles calculated from only six values are approximate at best.

Flexure modulus of elasticity

Spotted gum hybrid wasn't affected by inclusion of restricted construction strategies. Spotted gum and Gympie messmate F-grades improved by one to three grades, both parallel and perpendicular to the grain (Table 39). Dunn's white gum improved by two grades face parallel to the grain but lost a grade perpendicular to the grain. In perpendicular grain direction, the F-grade is less important because of the low correlation between longitudinal and transverse MOE on veneer. The latter combined with the sensitivity of the calculation can lead to a loss in stress grade.

Table 39. Bending MOE distribution parameters, characteristic properties and assigned grades with HHH, HLH plywood construction strategies only

Species	Average MOE (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Ek, mean (MPa) from AS/NZS 4063.2		Coefficient of Variation (%)		Assigned F grade From 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	16 400	13 500	13 900	8 300	15 900	11 000	10 000	28 000	F17	F11
Spotted gum	20 600	20 400	16 800	15 600	19 900	19 500	12 000	16 000	F27	F27
Gympie messmate	19 400	17 000	17 300	12 300	19 100	16 100	7 000	19 000	F27	F22
Spotted gum hybrid	14 100	12 600	11 800	9 700	13 700	12 600	11 000	19 000	F14	F14

Flexure Modulus of Rupture

The grades in MOR face grain parallel were all significantly improved by one to four grades (Table 40). In perpendicular grain direction, the results are contrasted for the reasons mentioned above.

The low assigned stress grade for Gympie messmate (F11, blue in the table) is as well partly due to low average MOE of the face veneers for Gympie messmate (15 900 MPa). This is significantly lower than the average MOE of the face veneers for spotted gum (17 400 MPa) despite an average MOE of 15 900 MPa for internal veneers for both Gympie messmate and spotted gum plywoods. This can be explained by the random selection of the veneers which in this case doesn't reflect the higher MOE values of Gympie messmate and consequently probably doesn't reflect the intrinsic value of the species.

Table 40. Bending MOR distribution parameters, characteristic properties and assigned grades with HHH, HLH plywoods only

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	90	72	75	31	67	25	16	43	F22	F8
Spotted gum	115	124	80	100	72	94	21	13	F27	F34
Gympie messmate	112	95	95	41	91	32	9	45	F34	F11
Spotted gum hybrid	87	85	70	56	65	50	13	24	F22	F17

Tension strength

Tension strength follows a similar trend as for bending strength and is displayed in Table 41.

Table 41. Tension strength distribution parameters, characteristic properties and assigned grades with LLL plywoods excluded

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Par	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	61	59	37	23	31	18	29	53	F17	F11
Spotted gum	81	91	64	65	60	59	14	20	F34	F34
Gympie messmate	80	90	47	46	40	37	31	39	F22	F22
Spotted gum hybrid	55	53	46	50	39	34	21	28	F22	F17

Compression strength

The improved construction strategy didn't significantly impact the F-grade rating with results displayed in Table 42.

Table 42. Compression strength distribution parameters, characteristic properties and assigned grades with LLL plywoods excluded

Species	Average MOR (MPa)		5th Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade from 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	44	53	38	43	36	41	9	12	F17	F17
Spotted gum	56	77	45	63	43	60	13	12	F17	F27
Gympie messmate	60	75	52	54	50	49	8	19	F22	F22
Spotted gum hybrid	58	63	48	46	45	43	12	18	F22	F17

Panel shear strength

The shear strength values of spotted gum, Gympie messmate and spotted gum hybrid were appreciably above the threshold of the higher grade (6.0 MPa). Consequently there were obviously no improvements in F-grades for these species (Table 43).

Table 43. Panel shear strength parameters, characteristic properties and assigned grades with LLL plywoods excluded

Species	Average MOR (MPa)		5^{th} Percentile (MPa) from AS/NZS4063.2		Rk (from AS/NZS 4063.2) (MPa)		Coefficient of Variation (%)		Assigned F grade From 2269.0 2012	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Dunn's white gum	6.9	7.1	5.6	5.7	5.4	5.4	12.5	12.6	F17	F17
Spotted gum	9.8	19.5	9.0	8.4	8.8	8.1	5.2	7.8	F34	F34
Gympie messmate	9.0	9.7	7.7	8.2	7.4	7.9	9.7	9.5	F34	F34
Spotted gum hybrid	8.8	8.7	7.3	7.8	7.0	7.7	10.9	6.4	F34	F34

Note: The maximum published characteristic strength for panel shear is 6.0 MPa, meeting 'greater than F14'.

4.5.1.4. Summary assigned F grades

With the exception of panel shear strength and to a lesser extent compression strength, most of the stress grades have increased. Bending and tension F-grades were the most improved. Understandably some of the perpendicular bending ones did not improve, sometimes the contrary, mainly because of the poor correlation between transversal and longitudinal mechanical characteristics on veneer. The veneer checks that result from processing are possibly another adverse factor on face grain perpendicular properties. Table 44 displays the recalculated assigned F grades based on the restricted construction strategies.

Table 44. Assigned F-grades on plywood face grain parallel and perpendicular with improved construction strategy

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	F17	F11	F22	F8	F17	F11	F17	F17	F17	F17
Spotted gum	F27	F27	F27	F34	F34	F34	F34	F34	F17	F27
Gympie messmate	F27	F22	F34	F11	F22	F22	F34	F34	F22	F22
Spotted gum hybrid	F14	F14	F22	F17	F22	F17	F34	F34	F22	F17

4.5.1.5. Bond quality

The single species plywood panels were manufactured using an MUF adhesive system supplied by Momentive Speciality Chemicals and is the same adhesive system used in the MUF adhesive trials (Section 4.4.2). Table 45 provides a summary of the bond qualities from the manufactured plywood panels. Within the table, the average bond score is provided, with green shaded results indicating a bond average of five or greater or shaded pink where the average bond scores were below five. The percentage of failed bonds is also presented with results shaded green indicating no failed bonds and pink if any failed bonds were present. Failed bonds were defined as a bond score of two or less.

Dunn's white gum was the only species that provided a satisfactorily result although with an average bond score of 5.3, the result is still marginal. The results are in-line with the MUF adhesive results provided in Section 4.4.2.

Table 45. Bond quality of single species plywood

Trial No	CH			DWG			GMS			RMY			SPG		
	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %
PLY1	24	3.5	42	20	5.3	0	16	5.3	6				19	3.9	16
PLY2										48	5.4	19			

4.5.2. Laminated Veneer Lumber

4.5.2.1. Mechanical properties

There are no generic grades for LVL. Each LVL manufacturer has designed and tested their products in accordance with AS/NZS 4063.2 Timber - Stress-graded - In-grade strength and stiffness evaluation to determine their design properties. This engineering data is available from the relevant manufacturer, together with span tables for common applications.

Flexure on flat: MOE and MOR

Figure 67 shows the MOE and MOR distributions for four species. For both properties spotted gum is clearly higher than the other species, just above Gympie messmate. The differences between these two species on the average MOE is 1300 MPa and 18 MPa on average MOR. Dunn's white gum and spotted gum hybrid display similar average MOE, but Dunn's white gum has a lower MOR than spotted gum hybrid with a difference of 16 MPa observed.

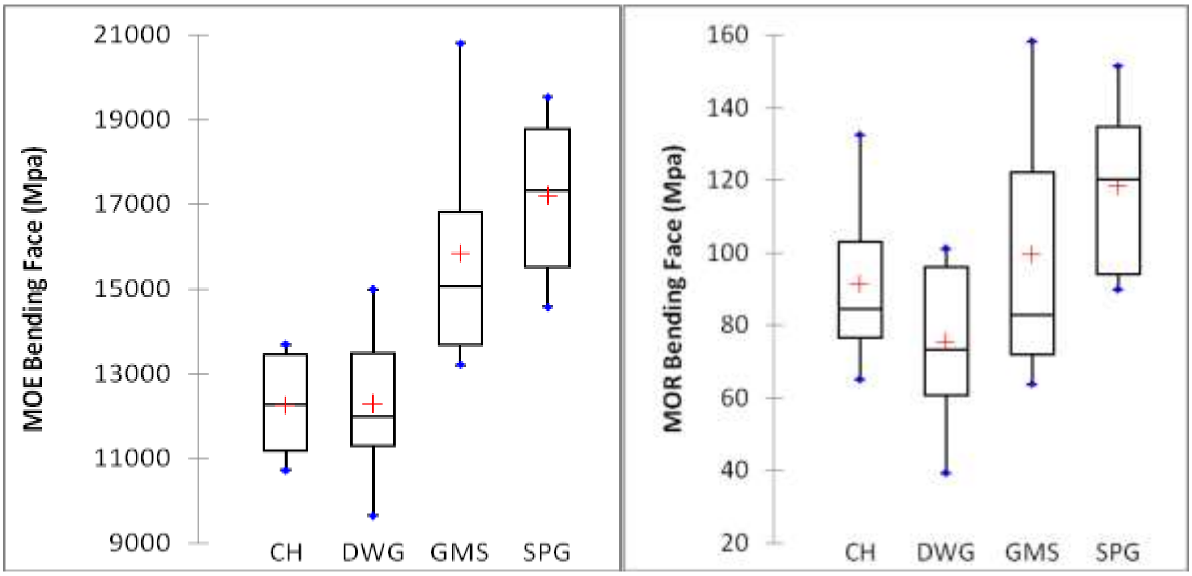


Figure 67. LVL MOE and MOR flexure on flat for four species. N=8 for each species.

Flexure on edge: MOE and MOR

Similar trends are observed on MOE and MOR between flexure on edge (Figure 68) and flat (above).

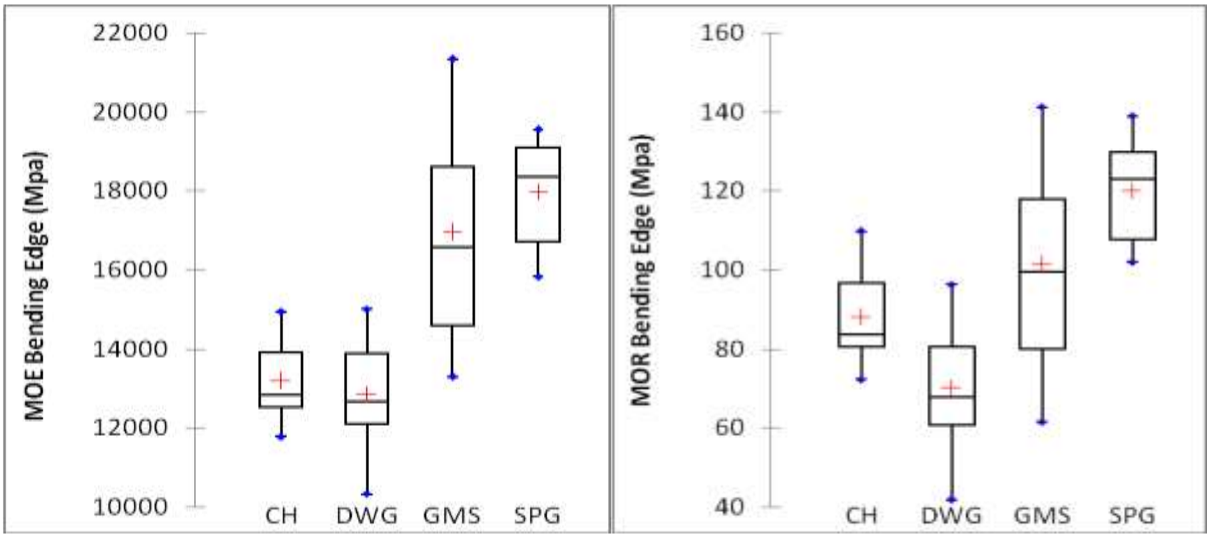


Figure 68. LVL MOE and MOR on edge flexure for four species. N=8 for each species.

Tension and compression strength

The rank of the species is the same as MOR in flexure for compression and tension strength (Figure 69).

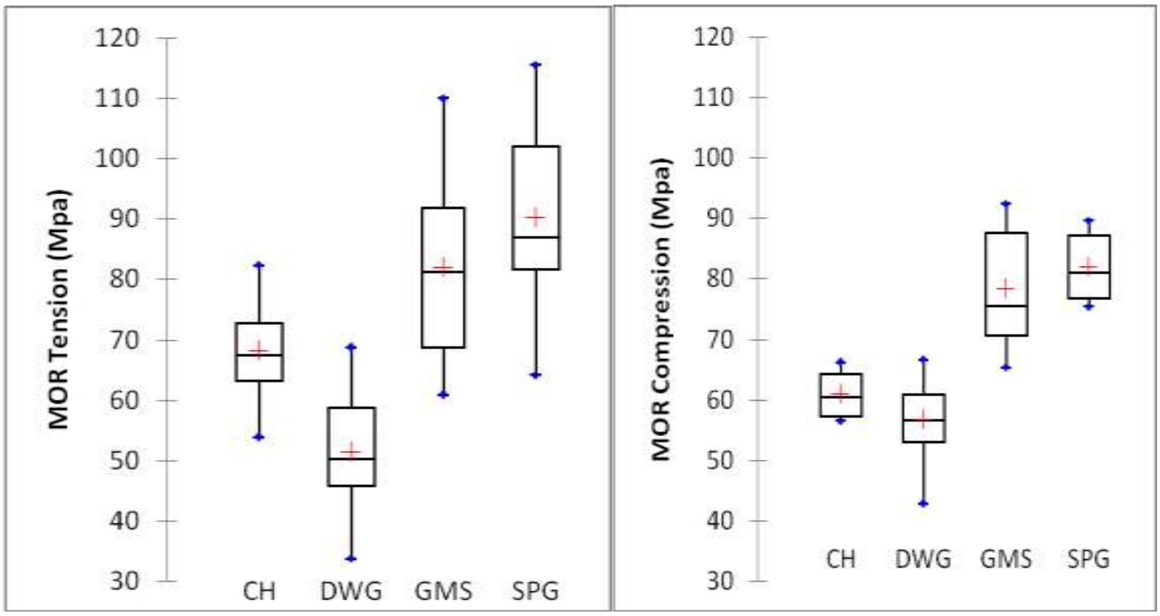


Figure 69. LVL tension and compression MOR for four species. N=8 for each species.

Shear strength

Although the shear strength on face ranked similarly as MOR in tension, compression and flexure on flat and on edge, the shear strength on edge is similar for spotted gum hybrid, Gympie messmate and spotted gum. Dunn's white gum shows slightly lower shear strength.

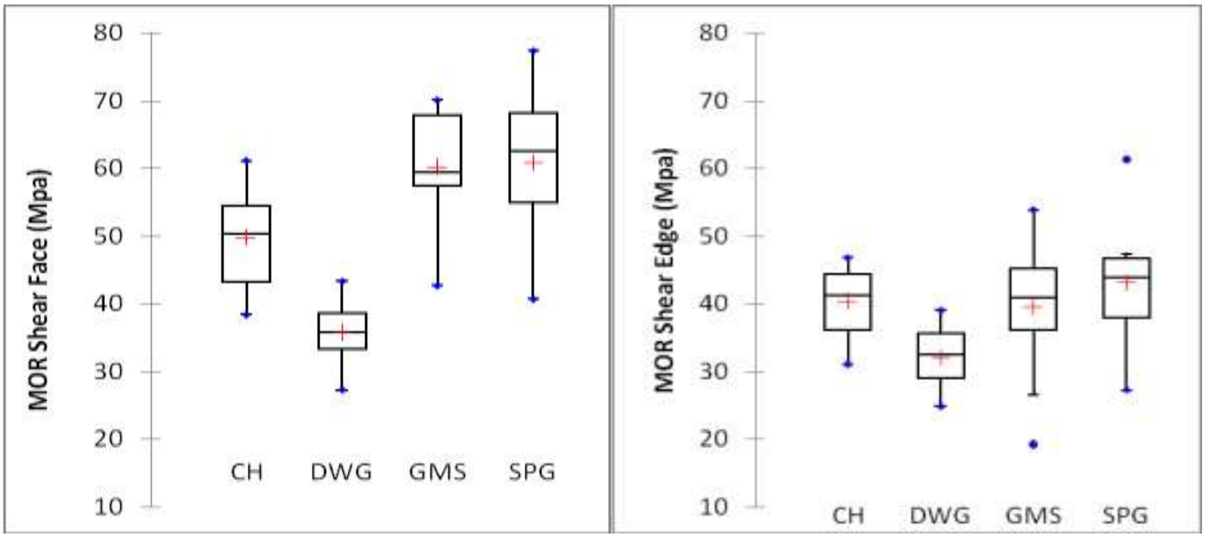


Figure 70. LVL shear MOR on face and edge for 4 species. N=8 for each species.

The correlation between MOE and MOR for LVL on edge or on face is quite high on a wide range of values (Figure 71 and Figure 72). This correlation is even better with a coefficient of determination around 0.90 for each species. The quality of the correlation is partly due to the construction strategy which deliberately provided a wide range of mechanical properties.

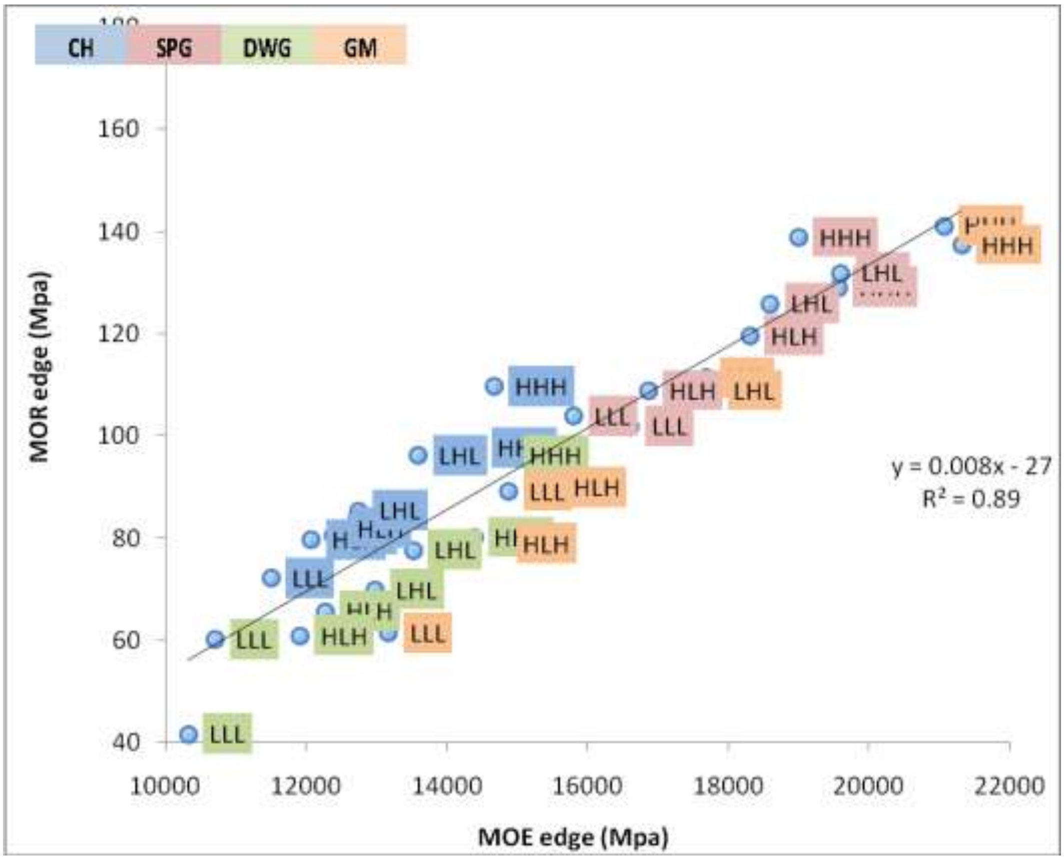


Figure 71. Correlation MOE versus MOR for LVL flexure on edge for four species. N=12 each for spotted gum hybrid, Dunn's white gum Gympie messmate and spotted gum.

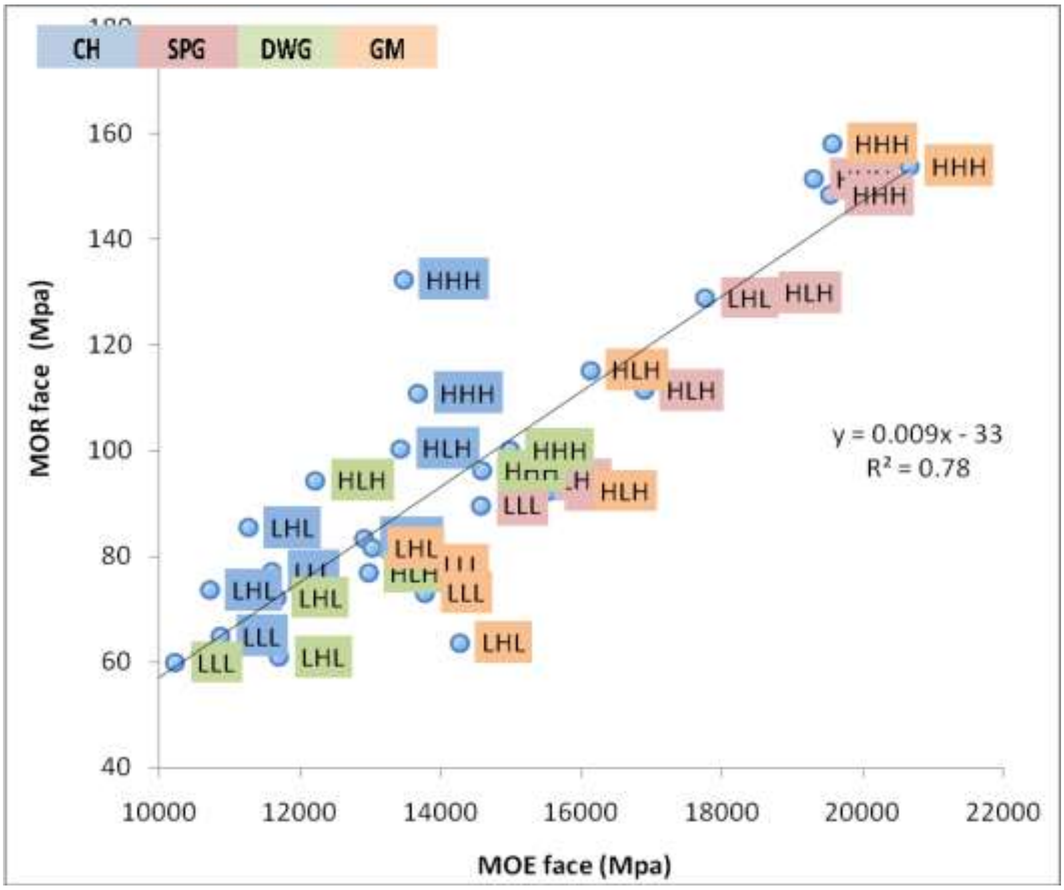


Figure 72. Correlation MOE versus MOR for LVL flexure on face for four species. N=12 each for spotted gum hybrid, Dunn's white gum Gympie messmate and spotted gum

4.5.2.2. Bond quality

The single species LVL panels were manufactured using an MUF adhesive system supplied by Momentive Speciality Chemicals and is the same adhesive system used in the MUF adhesive trials (Section 4.4.2). Table 46 provides a summary of the bond qualities from the manufactured LVL panels. Within the table, the average bond score is provided, with green shaded results indicating a bond average of five or greater or shaded pink where the average bond scores were below five. The percentage of failed bonds is also presented with results shaded green indicating no failed bonds and pink if any failed bonds were present. Failed bonds were defined as a bond score of two or less.

While no species provided an excellent bond quality result, both Dunn's white gum and Gympie messmate demonstrated much better performance that either spotted gum or the spotted gum hybrid. While the bond average for Dunn's white gum and Gympie messmate were both higher than five, there were 6% of individual gluelines that scored two or less. Spotted gum and spotted gum hybrid had average bond scores of 3.7 and 3.0 respectively with 42% and 33% of individual gluelines respectively scoring two or less, suggesting the adhesive performance is far from satisfactory.

Table 46. Bond quality of single species LVL

Trial No	CH			DWG			GMS			SPG		
	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %	No of glue-lines	Bond average	Failed bond %
LVL1	36	3.7	33	36	5.8	6	36	6.2	6	36	3.1	42

4.5.3. Plywood (mixed species)

4.5.3.1. Mechanical properties

There was a dramatic improvement in bending MOE and MOR parallel to face grain by replacing the face veneer from pine to Gympie messmate (Figure 73). This improvement was 13 900 to 19 600 MPa for MOE and 78 to 118 MPa for MOR. This corresponds to improvements of three stress grades for MOE and one stress grade for MOR (Table 47).

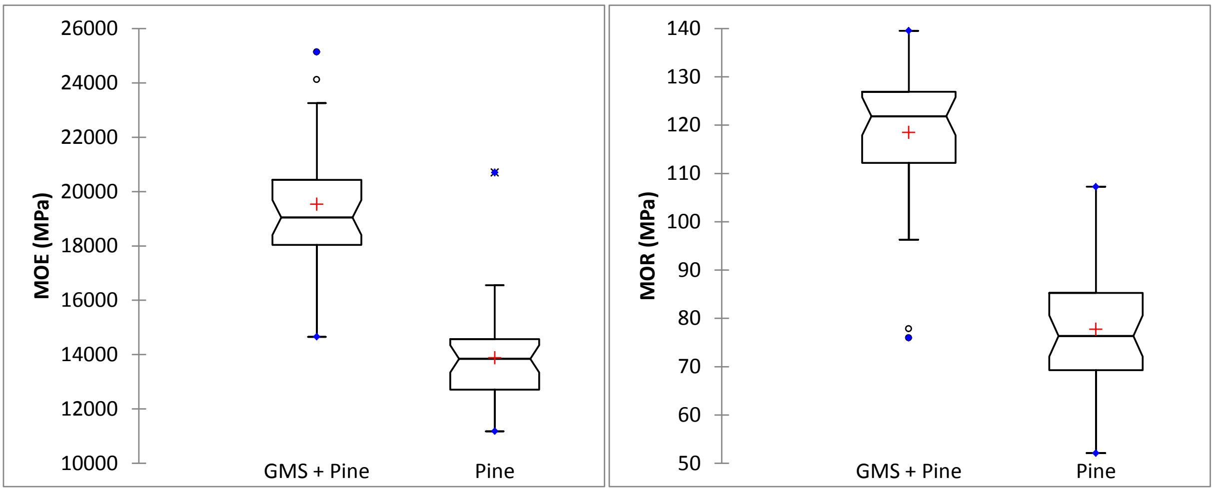


Figure 73. MOE and MOR face parallel to the grain on pine with Gympie messmate faces and pine only plywoods

The improvement is not statistically significant in bending MOE and MOR perpendicular to face grain as the veneers which predominantly contribute to stiffness and strength are made of pine (figure 74 and Table 47).

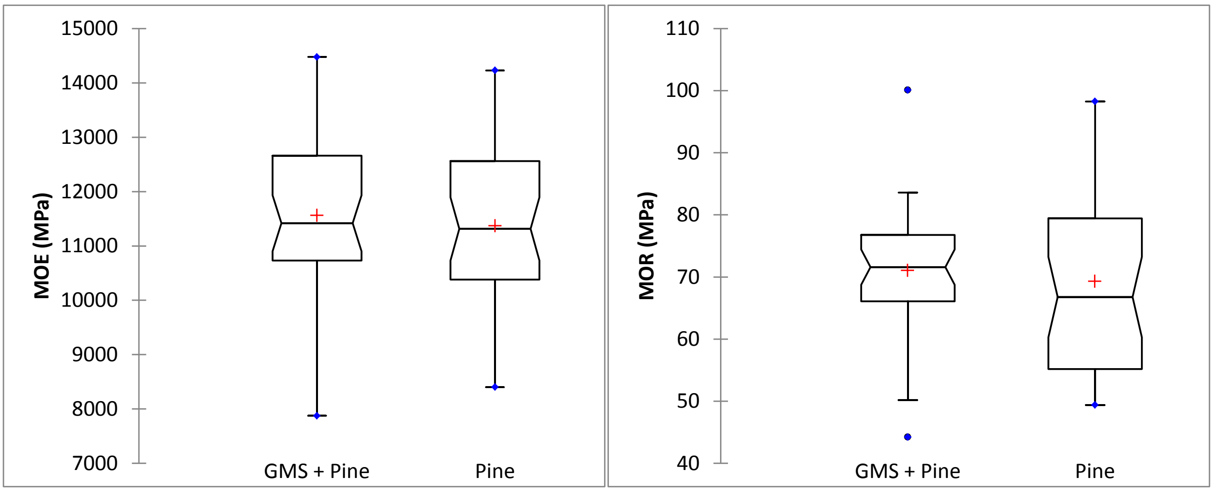


Figure 74. MOE and MOR face perpendicular to the grain on pine with Gympie messmate face and pine only plywoods

Unless hardwood cross-bands are combined in the plywood, the limiting F-grade will remain F11 in both construction strategies (Table 47).

Table 47. Bending MOE and MOR distribution parameters, characteristic properties and assigned grades

Plywood type & direction	MOE (MPa)	Ek (MPa)	F grade	MOR (MPa)	Rk (MPa)	F grade	Limiting F grade
Pine parallel	13 900	13 700	F14	78	57	F17	F11
Pine perpendicular	11 400	11 200	F11	69	47	F17	
GMS+pine parallel	19 600	19 300	F27	118	92	F34	F11
GMS+pine perpendicular	11 600	11 400	F11	71	53	F17	

Notes:
1 Standard MOE & MOR calculated using nominal I & Z values as AS/NZS 2269
2 Assumed construction = 12-24-5 except GMS where I & z allows for actual face veneer thickness
3 Ek & Rk calculated as per AS1720.1

4.5.3.2. Bond quality

The mixed species plywood panels were manufactured using Momentive Speciality Chemicals PP1158 PF adhesive and is the same adhesive system used in the PF adhesive trials four and five (Section 4.4.1). Table 48 provides a summary of the bond qualities from the manufactured plywood panels. Within the table, the average bond score is provided, with green shaded results indicating a bond average of five or greater or shaded pink where the average bond scores were below five. The percentage of failed bonds is also presented with results shaded green indicating no failed bonds and pink if any failed bonds were present. Failed bonds were defined as a bond score of two or less.

The results indicate a satisfactory average bond score and a very low occurrence of individual glueline bond scores of two or less. The results are in-line with the MUF adhesive results provided in Section 4.4.2.

Table 48. Bond quality of mixed species plywood

Resin type	GMS / Radiata pine			Radiata pine		
	No of gluelines	Bond average	Failed bond %	No of gluelines	Bond average	Failed bond %
Momentive PP1158	44	6.8	2	40	7.2	3

4.5.4. Overlay plywood

An assessment of the surface quality of the manufactured samples indicated that even with the thinner overlay systems (45/130 and 60/150), commonly occurring defects such as small tight knots could be adequately covered (Image 13). Additional testing including field trials (e.g. concrete pour trials) would be necessary to validate these preliminary observations. The surface quality assessments did also identify an irregularity or waviness in the surface flatness which was more pronounced in the lower quality face veneers (those that contained small tight knots). It is suspected that the waviness is a result of veneer thickness variation which is more prominent in veneer which originated close to the billet centre (also where knots are more frequent).

Image 13: Overlay systems adequately covered commonly occurring defects

4.6. Alternative method of grading

4.6.1. Plywood parallel and perpendicular

4.6.1.1. Four species

As expected, the correlation between acoustic MOE and static MOE is very high for the tested four species regardless of the plywood grain direction (Figure 75). The acoustic MOE is slightly higher than the static MOE (4 to 6%) due to the viscoelastic nature of wood.

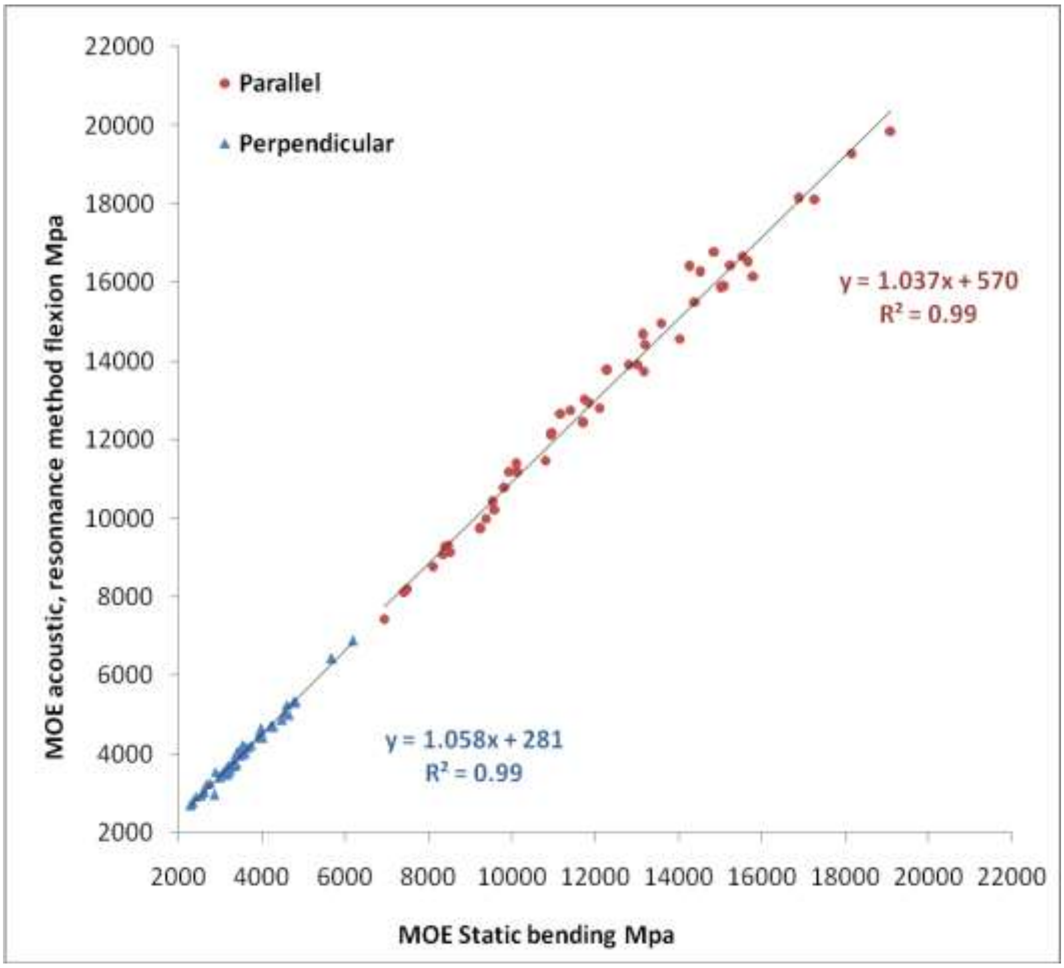


Figure 75. Correlation between acoustic MOE versus static bending MOE on plywood parallel and perpendicular to the grain for four species. N=12 each for CH, DWG, GMS and SPG.

4.6.1.2. Red mahogany plywood (parallel only)

Figure 76 displays the very high correlation (R2=0.96) that is achieved when comparing acoustic MOE and static MOE for red mahogany plywood. The use of a more complex mechanical model based on Timoshenko's equations which takes into account the shear stress to calculate the MOE doesn't improve the correlation. Indeed the introduction of shear effect in the model is only useful when the length-to-depth ratio of the specimen is lower than 25 (Brancheriau and Bailleres, 2002). In the case of plywood the first frequency of the vibration spectrum provides an accurate measurement of the MOE.

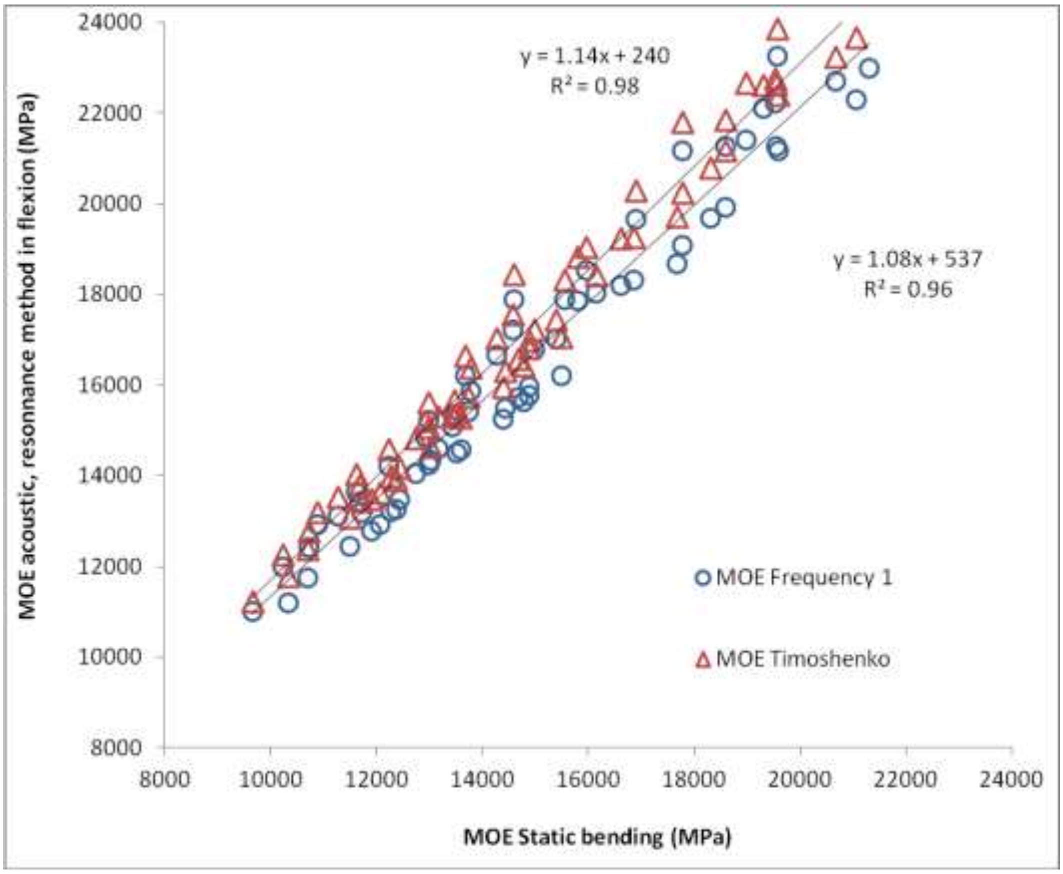


Figure 76. Correlation for acoustic MOE versus static bending MOE on plywood parallel to the grain for red mahogany. N=72.

4.6.2. LVL edge and flat

On LVL the correlation between acoustic and static MOE on four species, flat and edge combined, is very high (Figure 77). The use of a more complex mechanical model based on Timoshenko's equations which takes into account the shear stress to calculate the MOE improves slightly the correlation from R^2=0.96 to R^2=0.98 since the length-to-depth ratio is close to 25 (Brancheriau and Bailleres, 2002). The MOE prediction is marginally higher for the Timoshenko model than for the first frequency based model.

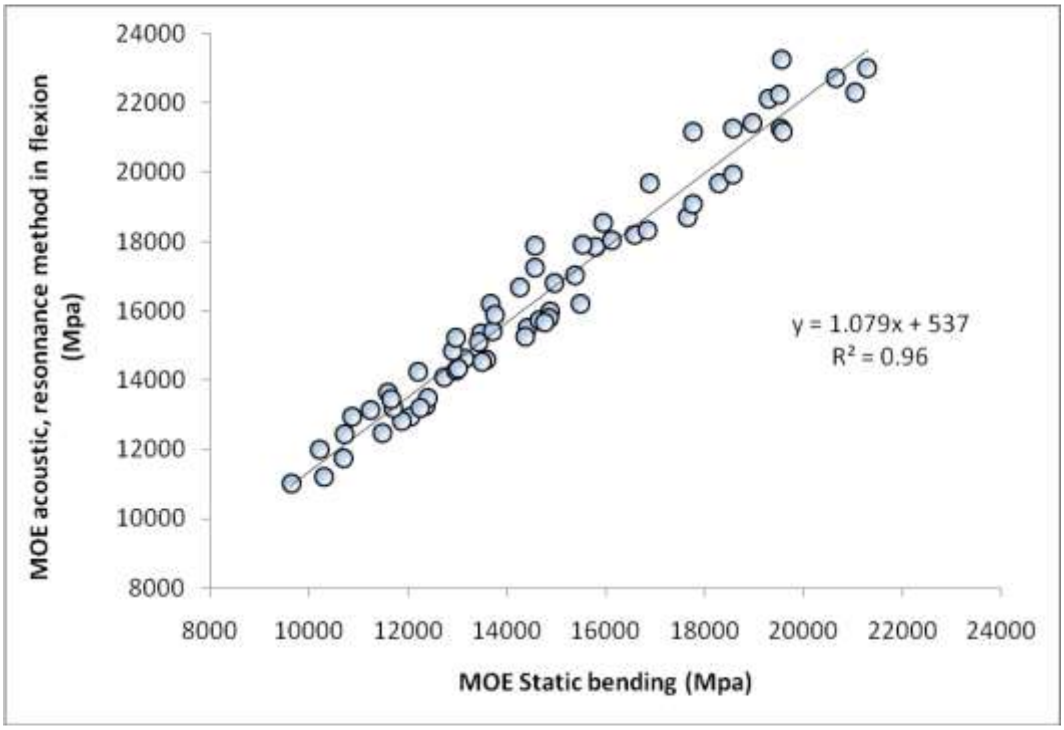


Figure 77. Correlation for acoustic MOE versus static bending MOE on LVL, flat and edge position for four species. N=8 each for spotted gum hybrid, Dunn's white gum, Gympie messmate and spotted gum.

4.7. Product mechanical modelling

All the plywood panels were tested in flexure according to *AS/NZS 2269.1:2008*. However, in order to match the model MOE computation method, the static MOE and MOR were calculated based on the total inertia of the panel whereas the standard specified the inertia to be calculated from the inertia of each ply.

4.7.1. Plywood: veneer longitudinal MOE deduced from adjacent veneers

In this trial, the MOE was measured on a veneer sample adjacent to the veneer used to manufacture the panel. The measurement wasn't performed directly on the veneers used for the panel fabrication but instead measured from the sampling strips (B or BS, Section 3.4.3). Twelve panels (1.3 x 1.3 m) per species (spotted gum hybrid, spotted gum, Gympie messmate and Dunn's white gum) were manufactured. A total of 47 panels were tested in flexure parallel and perpendicular to the face veneer grain (Section 4.5.1).

Figure 78 displays the correlation between the model and the experimental data with the grain of the face veneer parallel to the main flexure axis of the specimen. The correlation is quite satisfactory with regard to the numerous hypotheses and simplifications applied in the model. In particular, the longitudinal MOE was measured from adjacent veneer, not directly on the veneers that made up the panel.

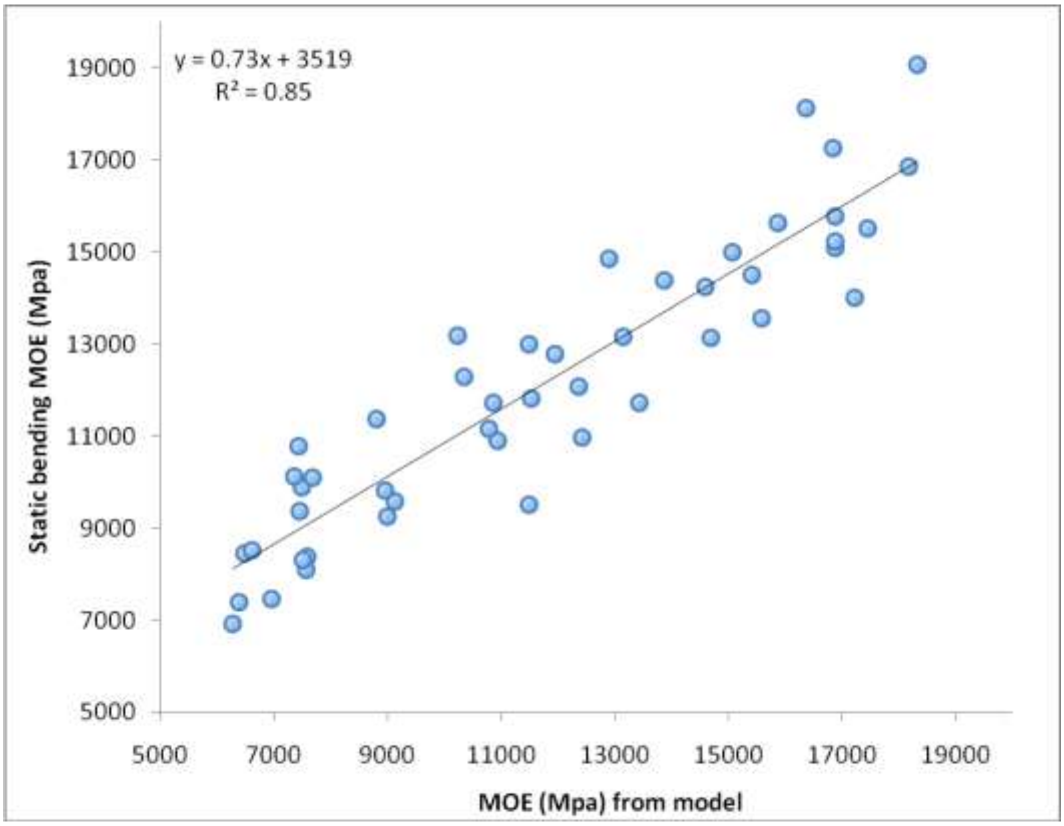


Figure 78. Plywood MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia). The grain of the face veneer is parallel to the main flexure axis of the specimen. N= 47.

The slope of the linear regression equation is significantly lower than one, which indicates that the model tends to under-predict the low stiffness panels and conversely it tends to over-predict the higher stiffness panels as shown by the regression trend line with intercept set to 0 (thick straight line on Figure 79). The transition is approximately at 12 000 MPa.

A possible explanation for this phenomenon lies in the type of straight, fixed and linear supports used by standardised Australian experimental method that do not release anticlastic curvature and bending-torsion coupling when load is applied on the sample. The consequence is an increase in apparent stiffness due to torsional interference induced during bending. This effect is more likely to occur on plywood where the faces enclose the grain deviation and/or significant defects. This is more frequent on low stiffness veneers which originate from the centre of the logs. Consequently, the MOE of plywood with low stiffness is systematically over-estimated by the static bending procedure. It should be noted that ASTM D 3043 for structural wood-based panels partially takes this phenomenon into account in the MOE measurement protocols and devices. In addition, the acoustic MOE measured on 150 mm strips is more sensitive to defect than the measurement on a 300 mm wide panel in static bending and the thickness was set at 2.4 mm despite variation in veneer thickness in the panel which couldn't be accurately measured. This thickness variation is most probably the main cause of the discrepancy between the model and the experimental data as demonstrated below. All these effects combined with measurement errors and model hypothesis explain the level and quality of the correlation observed.

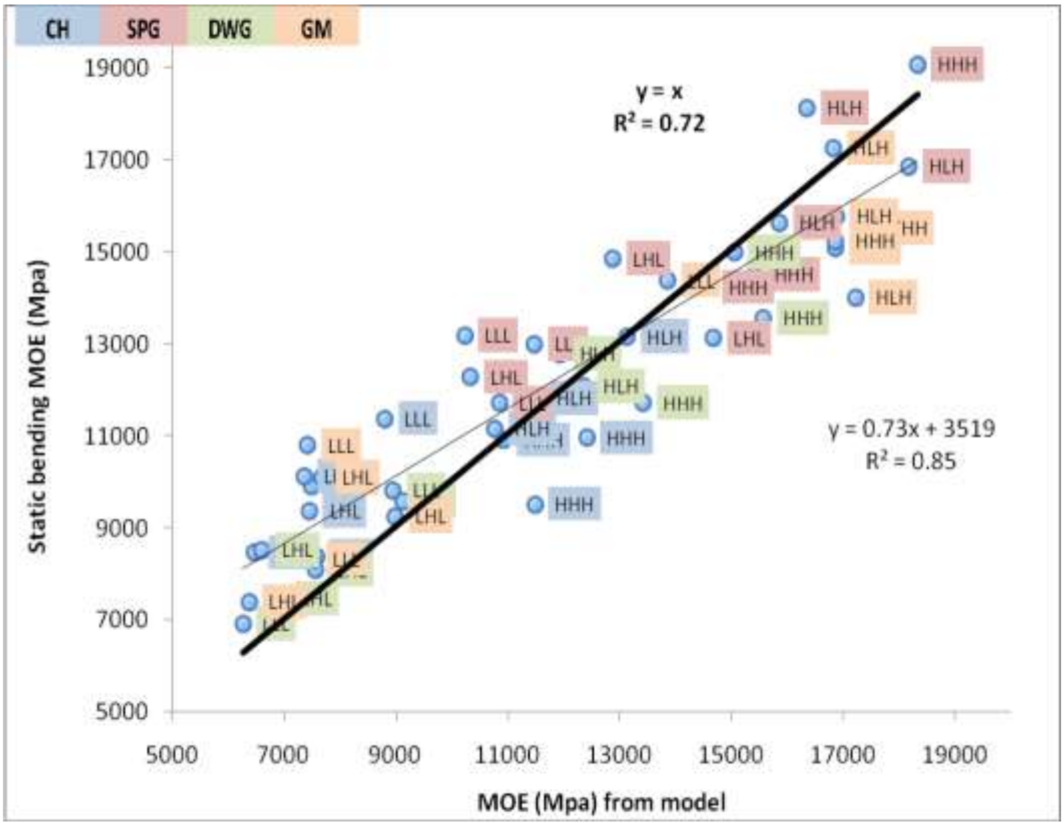


Figure 79. Plywood MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia). The grain of the face veneer is parallel to the main flexure axis of the specimen. Species (colour) and construction strategies (letters) are indicated. N= 47 for all four species.

Figure 80 displays the correlation between the model and the experimental data with the grain of the face veneer perpendicular to the main flexure axis of the specimen.

In this experiment the transverse MOE of the veneers was only assessed through density and experimental correlations (Guitard and El Amri, 1987). This approximation process explains the decline in correlation level comparatively to the results from the plywood with the face grain parallel to the main flexure axis of the specimen. In addition, the MOE variation across the test panels was smaller than in the bending test parallel to the grain and consequently a decline in correlation quality is expected. Furthermore, the same phenomenon described above in relation to mechanical test design applies. Nevertheless, despite these combined inaccuracies the prediction is considered acceptable for ranking the mechanical properties.

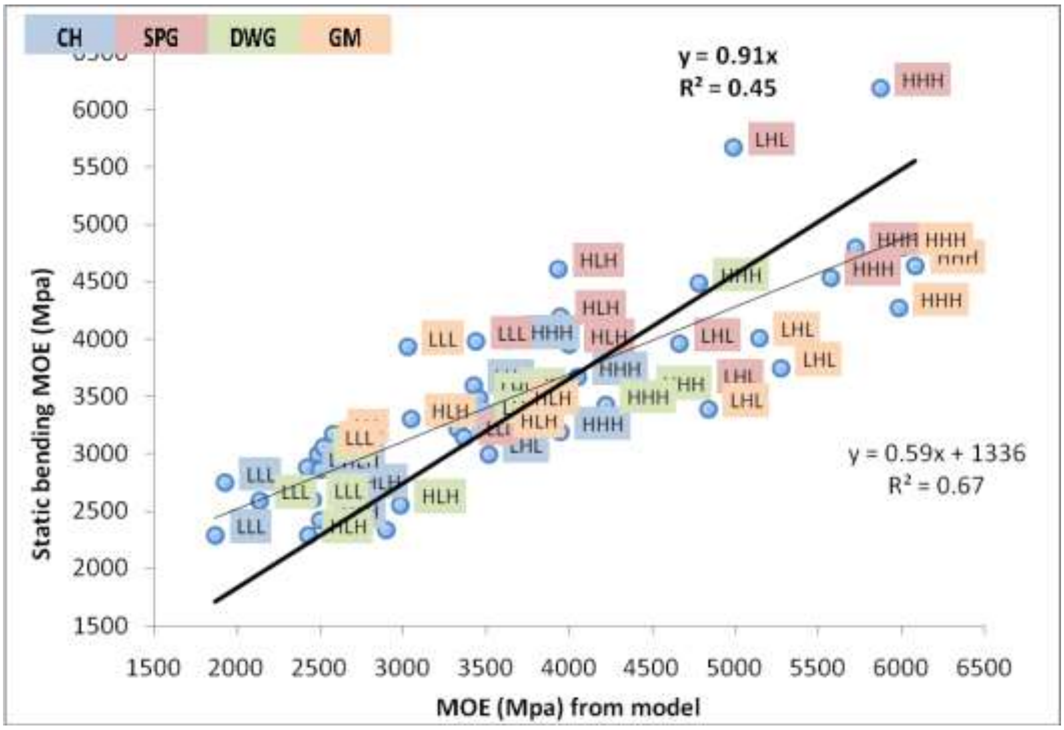


Figure 80. Plywood MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia). The grain of the face veneer is perpendicular to the main flexure axis of the specimen. Species (colour) and construction strategies (letters) are indicated. N= 47 for all four species.

4.7.2. Plywood: veneer longitudinal MOE directly measured

In this experiment, the longitudinal MOE (grain direction) was directly measured on each veneer by the acoustic method. The intent was to try to improve the correlation by a better assessment of the mechanical properties of each individual veneer. A total of 69 samples (300 mm x 1050 mm) were manufactured from red mahogany veneer.

Figure 81 displays the correlation between the model and the experimental data with the grain of the face veneer parallel to the main flexure axis of the specimen. The correlation was only slightly improved when compared to the previous experiment proving that the divergence between the predictive model and experimental data lies mainly in the experimental test design applied and the model hypotheses.

In addition, the veneer thickness was set at 2.4 mm for the model despite variation in actual veneer thickness in the panel which couldn't be accurately measured. To illustrate this variation, the thickness of the panels ranged from 13 mm to 17 mm. This thickness variation is a source of substantial deviation between model and experimental data. Indeed the veneer from the outer part of the log, which is also denser and stiffer, is systematically thinner than the veneer close to the centre of the log, which is the least dense and stiff. Typically this thickness variation ranges from 2.2 mm to 3.5 mm. In order to illustrate the consequence of the thickness variation on the model prediction, Table 49 displays two simulations with and without thickness variation on HLH type plywood. The magnitude of the panel MOE disparity due to the thickness variation between veneers, thus plies, is of the order of 20% in this case. As a consequence the model tends to over predict the HLH and HHH panels and under predict the LHL and LLL panels. This is clearly the tendency observed from the correlation between model and experimental data.

Table 49. Model simulations with and without thickness variation on HLH type 12 mm red mahogany plywood.

MOE (MPa)	Variable thickness (mm)	Fixed thickness (mm)
20 000 (face veneer)	2.0	2.4
1 000 (cross band veneer)	2.6	2.4
10 000 (core veneer)	2.8	2.4
1 000 (cross band veneer)	2.6	2.4
20 000 (face veneer)	2.0	2.4
Panel MOE (MPa) from model	14 500	16 000

Substantial improvement in model prediction can be expected from an accurate measurement of the thickness of each veneer or by using veneer with regular and unvarying thickness.

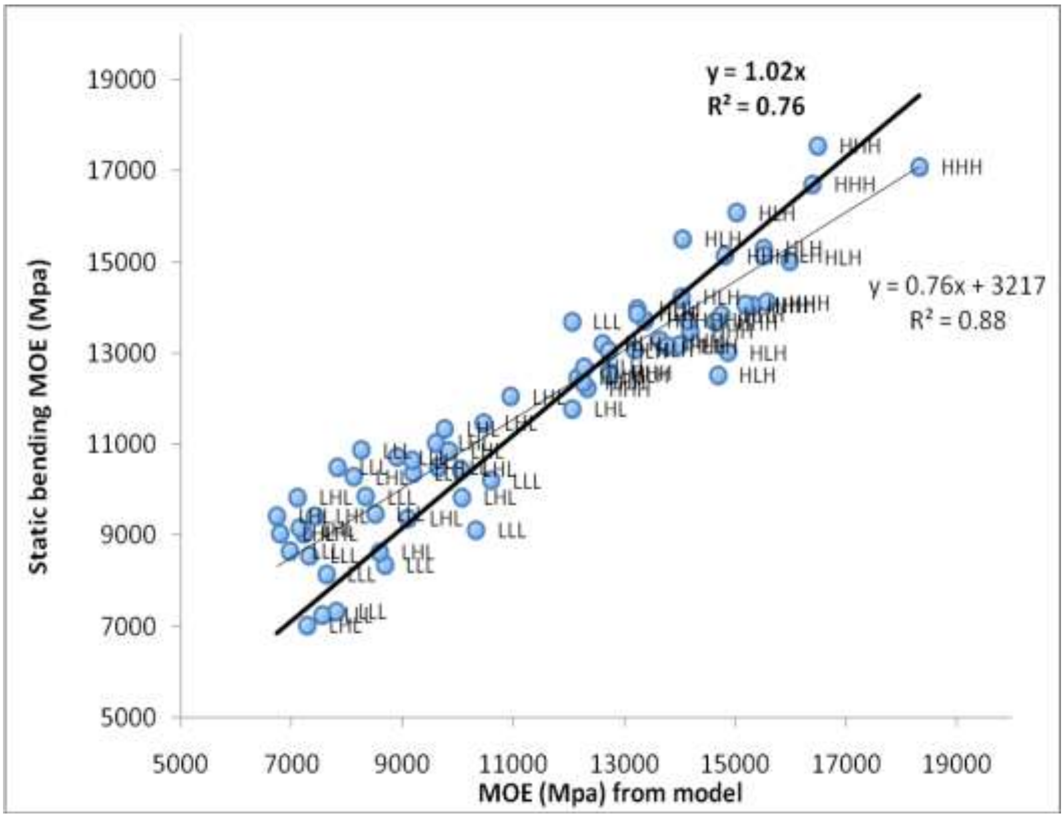


Figure 81. Plywood MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia). The grain of the face veneer is parallel to the main flexure axis of the specimen. Construction strategy (letters) is indicated. N= 69, red mahogany.

4.7.3. LVL: veneer longitudinal MOE deduced from adjacent veneers

Figure 82 displays the correlation between the model and the experimental data on LVL with the plies perpendicular to the plane of flexure (flat position) of the specimen. The correlation is high but significantly lower than those observed on plywood. Apart from the model hypothesis, it seems that the thickness variation of the veneers which wasn't taken into account in the model should explain the discrepancy between the model and the experimental data. Indeed, the variation observed on the sample height ranges from 37 mm to 45 mm due to veneer thickness variation. Since more plies are included in LVL, the impact due to veneer thickness variation on predicted MOE is higher than in plywood. This observation is consistent with the correlation observed. This issue should be resolved during processing by using a suitable control system of lathe cutting parameters.

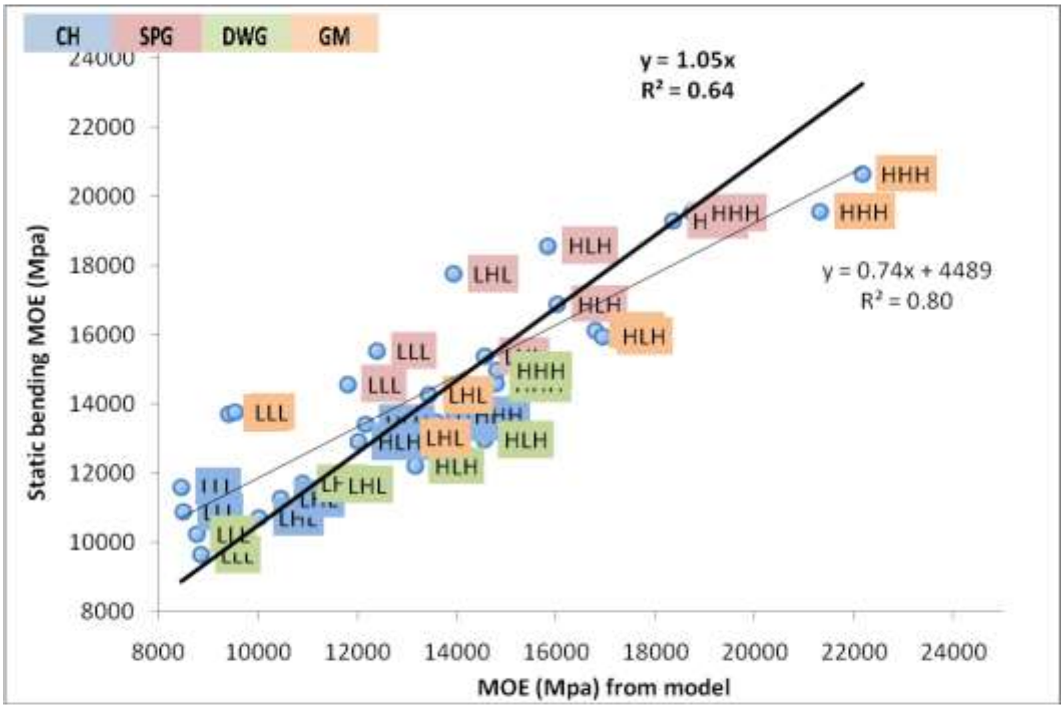


Figure 82. LVL MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia).The plies are perpendicular to the plane of flexure (flat position). Species (colour) and construction strategies (letters) are indicated. N= 32, each static bending MOE is the average measurement of four samples from the same panel for four species.

Figure 83 displays the correlation between the average MOE of the veneers which constitutes the sample and the experimental data on LVL with the plies parallel to the plane of flexure (edge position) of the specimen. The correlation level is satisfactory. We can note though that the average MOE of the veneer which constitute Dunn's white gum LVL samples tends to clearly over predict the static bending edge MOE relative to the other species. This tendency could be attributed to the high proportion of knots in this species whose occurrence on the stressed faces during bending, impact the MOE and the MOR.

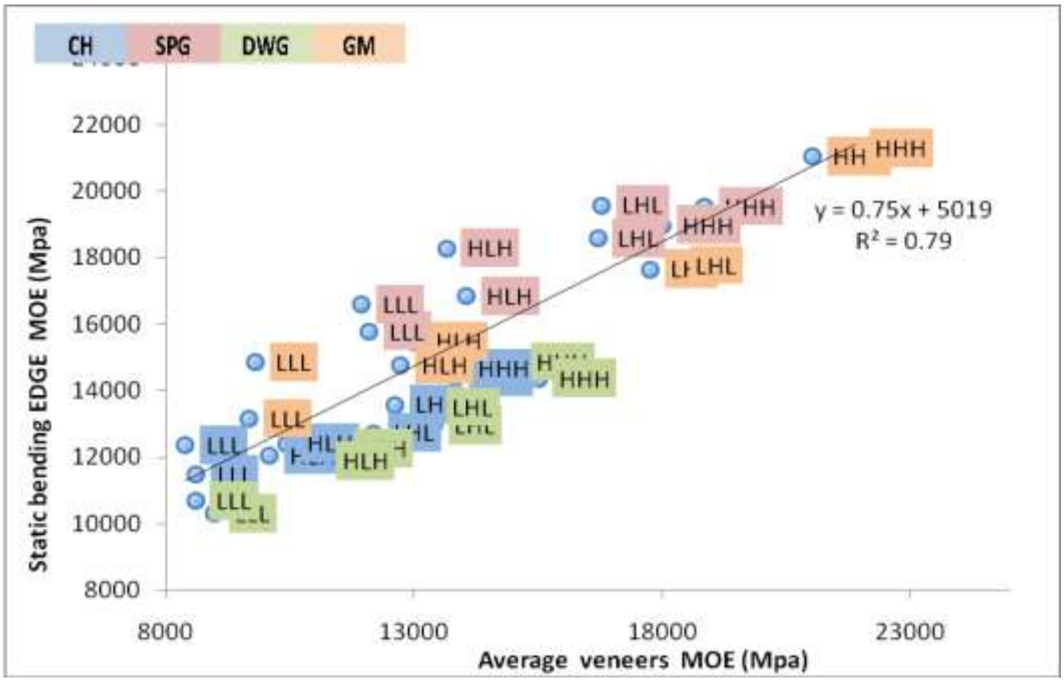


Figure 83. LVL MOE extracted from the laminated plate theory model versus the static bending MOE according to *AS/NZS 2269.1:2008* (MOE calculated from global inertia).The plies are parallel to the plane of flexure (edge position). Species (colour) and construction strategies (letters) are indicated. N= 32, each static bending MOE is the average measurement of four samples from the same panel for four species.

4.7.4. Hybrid plywood: properties enhancement by blending resources

The specific use of the excellent mechanical properties of young spotted gum and Gympie messmate from plantations can be a smart approach to improve current sub-optimal pine resources across Australia by mixing these two resources with an appropriate construction strategy. The LPT model can be an efficient tool to optimise resource and panel construction strategies.

In this experiment two plywood constructions with five plies were manufactured and tested:

- plywood with GMS face veneers and pine core veneers, and
- plywood made of pine veneers only.

All the pine face veneers were chosen with an MOE superior to 13 544 MPa and the core veneers with an average of 10 000 MPa. This pine plywood construction targets the upper end of the structural grade for pine panel products. Figure 84 displays the correlation between the model and the experimental data with the grain of the face veneer parallel to the main flexure axis of the specimen. The construction with Gympie messmate face veneers clearly improves the MOE of the plywood which is well predicted by the model. The improvement is around 4 000 MPa.

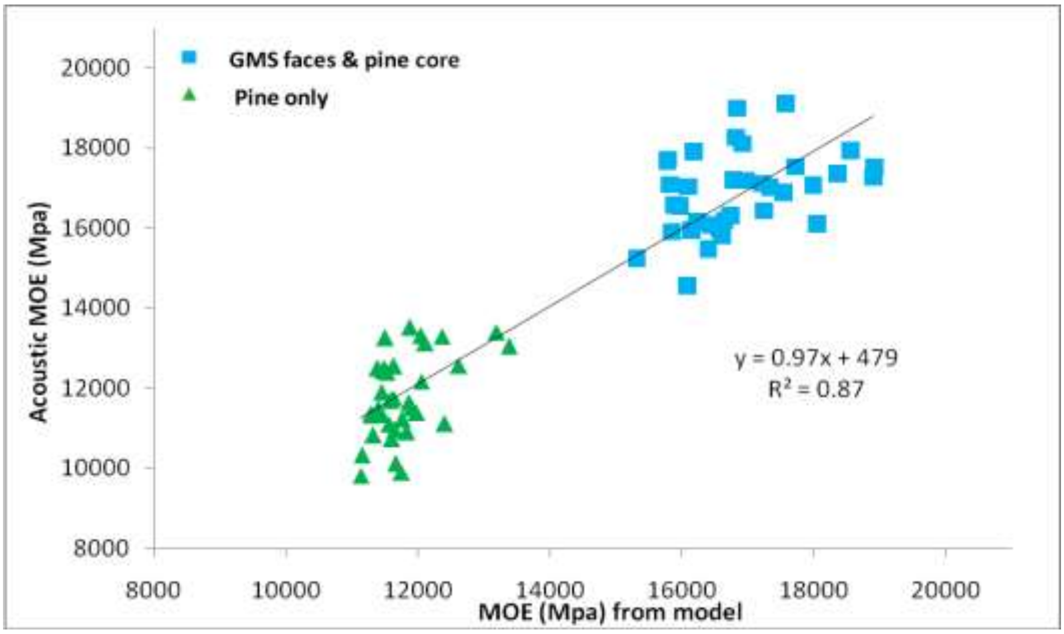


Figure 84. Plywood MOE extracted from the laminated plate theory model versus the acoustic MOE. The grain of the face veneer is parallel to the main flexure axis of the sample. Construction strategy of the plywood: blue squares are plywood with GMS face veneers and pine core veneers, green triangles are pine veneers only. GMS faces and pine core N= 35. Pine only N= 33.

5. Conclusions

Producing veneer from young plantation-grown hardwoods using spindleless veneer lathes has been demonstrated on a semi-industrial scale to be technically possible with green veneer recoveries ranging between 64% – 79%. These green recoveries are in the order of 50% higher than what would be expected from a standard sawmilling process. In addition to higher recoveries rates, the use of rotary peeling process also recovers more wood from the log periphery which is generally superior in wood and mechanical properties. Some challenges exist in further developing the technology to improve the variation in resulting veneer thickness to meet Australian manufacturing tolerances. Since the completion of the trials, modifications to the control system on the research lathe has commenced with preliminary results indicating that spindleless lathe can be operated to produce veneer within acceptable tolerances.

The pre-treatment of billets prior to peeling appears to result in improved veneer surface quality, at least for most of the species included in the study. Further studies are required to optimise the process however billet temperatures above 60 degrees are expected necessary to achieve any measurable benefit.

Veneer drying presented minimal challenges when using a standard commercial jet box drier with veneer able to be dried below 8% moisture content in less than 10 minutes. This extremely short drying time compared to sawn timber which can take weeks or months to season, is a real advantage of veneer processing.

The net recovery of veneer, which represents the volume of saleable veneer ranged between 45% – 53%. These recovery values are up to six times higher than what has been reported to be achieved from similar plantation resources when converted to sawn timber products. A very high proportion of the recovered veneer meets the requirements of D-grade in accordance with Australian and New Zealand standard AS2269.0:2008 with a small proportion meeting the requirements of higher grade qualities. These results lend the hardwood veneer to be used in mainly non-appearance structural plywood type products and/or core veneers. For products which require higher appearance qualities and high mechanical properties, the plantation hardwood veneer could be mixed with either other high quality resources (i.e. native hardwood forest face veneers) or other overlay systems (e.g. very thin softwood face veneers, overlay papers etc). Alternatively there may be application in LVL type products were structural properties are more emphasised than appearance qualities. Another option to improve the visual grade quality is through defect patching (removing a defect and replacing it with a patch of clear veneer) or veneer jointing (clipping out a defect and joining the veneer back together). While these practices have a long history of use within industry, they can add significant cost.

Resin pockets were the main reason for preventing veneers achieving a grade quality higher than D-grade. Opportunities potentially exist to review the grading standard as the grade limiting thresholds for resin pockets were probably developed for a softwood resource and potentially unnecessarily penalises the hardwood veneer. Veneer roughness, encased knots and splits also contributed but to a much lesser degree.

The method of visual grading data collection has provided a valuable opportunity to analyse the veneer under a range of grade quality scenarios. For example, the impact on pruning could be assessed in terms of grade distribution changes and ultimately change in product value. Alternatively, various scenarios could be analysed to guide a product manufacturer to identify the most profitable product or suite of products depending on individual product(s) veneer grade requirements. The simple grade quality scenario presented (section 4.3.4) does highlight the complexity that exists with veneers containing multiple grade limiting defects. It can not be assumed that by removing a defect (for example by changing grading standards, changing forest management practices etc) that the veneer grade limited by that defect, will automatically be moved to a higher grade quality.

All species included in the study have a history of challenging bonding behaviour, especially spotted gum. The development of a phenol formaldehyde (PF) adhesive system was targeted as this adhesive allows for weather exposed structural products to be pursued. Under laboratory conditions, several adhesive systems under controlled manufacturing conditions did demonstrate satisfactory bond quality across all species. Spotted gum and spotted gum hybrid proved to be the most challenging. Reliable, high quality bonds with melamine urea formaldehyde (MUF) proved challenging to achieve, despite many trials under very controlled conditions. The polyurethane adhesive trialled performed poorly. Additional studies are required to develop a complete understanding of the bonding behaviour of each of the species and the mechanisms preventing successful and reliable glue bonds. Further studies are also required to establish if the successful PF trials can be replicated in larger semi-industrial scale trials.

The hardwood veneer demonstrated stiffness properties (modulus of elasticity or MOE) that can meet or exceed that of mature plantation pine, despite being sourced from plantations at least half the age. Both spotted gum and Gympie messmate showed superior stiffness properties (average greater than16 000 MPa) followed by red mahogany, western white gum and Dunn’s white gum (average of 13 700 MPa, 13 300 and 12 300 MPa respectively). The spotted gum hybrid had an average MOE of 11 700 MPa. These excellent stiffness values were gained despite the majority of the veneers containing defects such as knots. While knots can have a devastating effect on mechanical properties, the presence of knots being generally small in size and scattered in nature, reduced the impact. This demonstrates a real advantage and unique quality that the hardwood resource has over the softwood resource which is predominately used around the world in veneer based composite products

The testing of manufactured products demonstrated the potential of all the species to produce structural products such as plywood and LVL. Unfortunately the low sample numbers for relevant construction strategies prevented the true potential from being recognised. The various construction strategies adopted do however clearly demonstrate the importance of effective veneer grading and sorting systems along with the importance of construction strategies to maximise the use and value of the available veneer.

The strategic mixing of softwood and hardwood veneers was well demonstrated with an increase of up to three stress grades being achieved by simply replacing the softwood face veneers with Gympie messmate veneers on a 5-ply 12 mm plywood product. The use of hardwood veneers in this manner could provide a real benefit to Australian softwood panel producers who may currently struggle to manufacture higher stress grade products (which may be more profitable) from a softwood only resource.

An analytical mechanical model based on Laminated Plate Theory (LPT) was demonstrated to have valuable application in the prediction of panel properties from veneer MOE data measured acoustically. This tool has the potential to be a valuable aid to industry in determining the most effective and economic way to utilise available resources in the most effective construction strategies, targeting the most profitable products.

A product manufactured in Australia that is considered to be profitable and in high demand is plywood used in the construction industry for forming concrete (known as formwood, formply etc.). This plywood product is usually covered with an overlay system which aids in concrete release and also ensure no wood pattern remains on the concrete surface. Demand potentially exists and a premium is potentially paid for higher stress grade plywood panels for this purpose and as such a number of overlay systems were trialled to establish whether there may be opportunities for the hardwood veneer to used as face veneers for this product.

Preliminary results indicate that even thin overlay systems bond satisfactorily and adequately cover the defects commonly occurring in the hardwood veneer. Additional testing is required to confirm market suitability.

While the project has demonstrated that high quality veneer can be processed from young, fast-grown plantation hardwood and a range of veneer-based composite products can be manufactured with attractive structural qualities, additional research is necessary to establish the economic parameters necessary to ensure commercial profitability. In addition, an intensive market analysis is also required to determine which products and markets are available and the most suitable for the quality and quantity of hardwood veneer that may be available.

6. References

Bailleres, H. Hopewell, G.P and McGavin, R.L., (2008) Evaluation of wood characteristics of tropical post-mid rotation plantation *Eucalyptus cloeziana* and *E. pellita*: Part (c) Wood quality and structural properties, Forest and Wood Products Australia (PN 07.3022) www.fwpa.com.au.

Berthlot, J-M. (1999) Composite Materials: Mechanical Behaviour and Structural Analysis. Springer - XXV, 676 p. 130 illus. ISBN 978-0-387-98426-1.

Bos, F. and Guitard, D. (1995) Validation expérimentale d'un outil de conception des contreplaqués. Annals of Forest Science.52, 423-431

Brancheriau, L. and Bailleres, H. (2002) Natural vibration analysis of clear wooden beams : a theoretical review. Wood-science-and-technology. 2002; 36(5): 367-383

Dorries, S. (2013) personal communication, General Manager, Engineered Wood Products Association of Australasia

Downes, G.M.; Hudson, I.L.; Raymond, C.A.; Dean, G.H.; Mitchell, A.J.;Schimleck, L.R.; Evans, R.; Muneri, A. 1997. Sampling Plantation Eucalypts for Wood and Fibre Properties". CSIRO Publishing, Collingwood, Victoria, Australia.132 p.

Guitard, D. and El Amri, F. (1987). Modèles prévisionnels du comportement élastique tridimensionnel pour les feuillis et résineux. Annals of Forest Science. 44(3): 335-358.

Hopewell, G., Atyeo, W. and McGavin, R.L. (2008), Evaluation of wood characteristics of tropical post-mid rotation plantation Eucalyptus cloeziana and E. pellita: Part (d) Veneer and plywood potential, Forest and Wood Products Australia www.fwpa.com.au.

Leggate, W., Palmer, G., McGavin, R. and Muneri, A. (2000), 'Productivity, sawn recovery and potential rates of return from eucalypt plantations in Queensland', paper submitted to the IUFRO Conference, The Future of Eucalypts for Wood Products, Launceston, March 2000

McGavin, R.L. and Bailleres, H. (2007), Wood properties, mechanical properties and commercial evaluation of eight year-old plantation grown Eucalyptus cloeziana, unpublished report, Horticulture and Forestry Science, Department of Primary Industries and Fisheries

McGavin, R.L., Davies, M.P., Macregor-Skinner, J., Bailleres, H., Armstrong, M., Atyeo, W.J. and Norton, J. (2006). Utilisation potential and market opportunities for plantation hardwood thinnings from Queensland and northern New South Wales. Forest and Wood Products Research and Development Corporation.

Websites

Engineered Wood Products Association of Australasia (2009), EWPAA: Plywood Manufacture, http://www.ewp.asn.au/library/downloads/ewpaa_plywood_manufacture.pdf, accessed 06.10.2010.

Engineered Wood Products Association of Australasia (no date), Library: Veneer Quality, http://www.ewp.asn.au/library/tut_ply/infoveneer.html, accessed 12.03.2012.

http://en.wikipedia.org/wiki/Sigmoid_function, accessed 02.05.2013.

Standards

Standards Australia (2007), *AS6669:2007 Plywood – Formwork,* SAI Global Limited. www.saiglobal.com

Standards Australia (2004), *AS/NZS2271:2004 Plywood and blockboard for exterior use,* SAI Global Limited. www.saiglobal.com

Standards Australia (2000), *AS/NZ 1080.3:2000 Timber – Method of test - Method 3: Density*, SAI Global Limited. www.saiglobal.com

Standards Australia (2012), *AS/NZS2098.2:2012 Methods of test for veneer and plywood – Method 2: Bond quality of plywood (chisel test),* SAI Global Limited. www.saiglobal.com

Standards Australia (2008), *AS/NZS 2269.0:2008: Plywood – Structural – Specifications*, SAI Global Limited. www.saiglobal.com

Standards Australia (2012), *AS/NZS 2269.0:2012: Plywood – Structural – Specifications*, SAI Global Limited. www.saiglobal.com

Standards Australia (2007), *AS/NZS 2269.2:2007 Plywood – Structural – Determination of structural properties – Evaluation methods*, SAI Global Limited. www.saiglobal.com

Standards Australia (2008), *AS/NZS 2754.1.2008 Adhesives for timber and timber products – Adhesives for the manufacture of plywood and laminated veneer lumber (LVL),* SAI Global Limited. www.saiglobal.com

Standards Australia (2010), *AS/NZS 4063.2:2010 Characterization of structural timber – Determination of characteristic values*, SAI Global Limited. www.saiglobal.com

Standards Australia (2005), *AS/NZS 4357.0:2005, Structural laminated veneer lumber – Specifications,* SAI Global Limited. www.saiglobal.com

International standard ISO/DIS 10033.1:2009 Laminated veneer lumber – Bonding quality – Part 1: Test methods

International Standard, ISO/DIS 10033.2:2009 Laminated veneer lumber – Bonding quality – Part 2: Requirements

International Standard ISO 12466.1:2007 Plywood – Bonding quality - Part 1 Test Methods

International Standard, ISO 12466.2:2007 Plywood – Bonding quality – Part 2: Requirements

7. Appendices

7.1. Appendix 1 Theory of laminated thin plates – Analytical model

Moduli calculations (from Guitard and El Amri, 1987)
Longitudinal modulus of elasticity at 12% moisture content

$$E_L = 14400\left(\frac{\rho}{0.65}\right)^{1.03}$$

Equation 1

The actual longitudinal MOE was measured by resonance method; the density ρ was then calculated with Equation 1.

$$MC_L = 1 - 0.03(H - 12)$$

Equation 2

Tangential modulus of elasticity at 12% moisture content

$$E_T = 1030\left(\frac{\rho}{0.65}\right)^{1.74}$$

Equation 3

$$MC_T = 1 - 0.01(H - 12)$$

Equation 4

Modulus of Torsion at 12% moisture content

$$G_{LT} = 971\left(\frac{\rho}{0.65}\right)^{1.26}$$

Equation 5

$$MC_{LT} = 1 - 0.02(H - 12)$$

Equation 6

$$\nu_{lt} = \frac{E_L}{31200\left(\frac{\rho}{0.65}\right)^{1.09}}$$

Equation 7

Calculations for a laminate layer
The model calculates each ply's longitudinal, transverse, and torsion moduli based on the density and moisture content. However, BING was used to attain the longitudinal modulus for all veneer strips and so equation **1** required rearranging so that the density could be calculated from the elastic longitudinal modulus instead.

$$\rho = \sqrt[1.03]{\left(\frac{E_L}{14400}\right)} \times 0.65$$

Equation 8

From this point, the resultant densities were subbed into equations **3 and 5** to attain the transverse and torsion elasticity.

To be able to calculate the stiffness matrix, the following variables were required:
Q_{11}, Q_{22}, Q_{66} and Q_{12}

These are found using equations:

$$Q_{ll} = \frac{E_L}{1 - \frac{\nu_{lt}^2 E_T}{E_L}}$$
Equation 9

$$Q_{tt} = \frac{E_T}{1 - \frac{\nu_{lt}^2 E_T}{E_L}}$$
Equation 10

$$Q_{lt} = Q_{ll} \times \nu_{lt}$$
Equation 11

$$Q_{ss} = G_{LT}$$
Equation 12

$$Q_{11} = Q_{ll}Cos\theta^4 + Q_{tt}Sin\theta^4 + 2Q_{lt}Cos\theta^2Sin\theta^2 + 4Q_{ss}Cos\theta^2Sin\theta^2$$
Equation 13

$$Q_{22} = Q_{ll}Sin\theta^4 + Q_{tt}Cos\theta^4 + 2Q_{lt}Sin\theta^2Cos\theta^2 + 4Q_{ss}Cos\theta^2Sin\theta^2$$
Equation 14

$$Q_{66} = (Q_{ll} + Q_{tt} - 2Q_{lt}) \times Cos\theta^2Sin\theta^2 + (Sin\theta^2 - Cos\theta^2)^2 \times Q_{ss}$$
Equation 15

$$Q_{12} = (Q_{ll} + Q_{tt}) \times Cos\theta^2Sin\theta^2 + (Cos\theta^4 + Sin\theta^4)Q_{lt} - 4Cos\theta^2Sin\theta^2 \times Q_{ss}$$
Equation 16

$$Q_{16} = Q_{ll}Cos\theta^3Sin\theta - Q_{ss}Cos\theta Sin\theta^3 - Cos\theta Sin\theta(Cos\theta^2 - Sin\theta^2) \times (Q_{lt} + 2Q_{ss})$$
Equation 17

$$Q_{26} = Q_{ll}Cos\theta Sin\theta^3 - Q_{tt}Cos\theta^3Sin\theta - Cos\theta Sin\theta(Cos\theta^2 - Sin\theta^2) \times (Q_{lt} + 2Q_{ss})$$
Equation 18

For any member with the grain angle equalling either 0 or 90:

At grain angle (θ) = 0; $\mathbf{Sin\theta = 0;}$ Therefore: $\mathbf{Cos\theta \times Sin\theta}$ = 0

At grain angle (θ) = 90; $\mathbf{Cos\theta = 0;}$ Therefore: $\mathbf{Cos\theta \times Sin\theta}$ = 0

Therefore, the simplified equations are as follows:

$Q_{11} = Q_{ll}Cos\theta^4 + Q_{tt}Sin\theta^4$ Equation 19
$Q_{22} = Q_{ll}Sin\theta^4 + Q_{tt}Cos\theta^4$ Equation 20
$Q_{66} = (Sin\theta^2 - Cos\theta^2)^2 \times Q_{ss}$ Equation 21
$Q_{12} = (Cos\theta^4 + Sin\theta^4)Q_{lt}$ Equation 22
$Q_{16} = 0$ Equation 23
$Q_{26} = 0$ Equation 24

Further simplified
when θ = 0; $Q_{11} = Q_{ll}$ *and* $Q_{22} = Q_{tt}$

when θ = 90; $Q_{11} = Q_{tt}$ *and* $Q_{22} = Q_{ll}$
when θ = 0 or 90; $Q_{66} = Q_{ss}$ *and* $Q_{12} = Q_{lt}$

From this the following table for calculations can be drawn

$$A^{\varphi}_{ij_p} = Q^{\varphi}_{ij_p} \times (e_p)$$ withi,j ϵ (1,2,6) Equation 25

$$B^{\varphi}_{ij_p} = Q^{\varphi}_{ij_p} \times (z_p e_p)$$ withi,j ϵ (1,2,6) Equation 26

$$D^{\varphi}_{ij_p} = Q^{\varphi}_{ij_p} \times \left(z_p^2 e_p + \frac{e_p^3}{12}\right)$$ withi,j ϵ (1,2,6) Equation 27

$$A_{ij} = \sum_{p=1}^{n} A^{\varphi}_{ij_p}$$ withi,j ϵ (1,2,6) Equation 28

$$B_{ij} = \sum_{p=1}^{n} B^{\varphi}_{ij_p}$$ withi,j ϵ (1,2,6) Equation 29

$$D_{ij} = \sum_{p=1}^{n} D^{\varphi}_{ij_p}$$ withi,j ϵ (1,2,6) Equation 30

Small p refers to the ply number/layer.

$$K^{\varphi}_{ij} = \sum_{p=1}^{n} D^{\varphi}_{ij_p} \left(z_p^2 e_p + \frac{e_p^3}{12}\right)$$

Stiffness matrix plate (Aij, Bij, Dij):

$$[K_{ij}] = \begin{array}{ccc|ccc}
\mathbf{A_{11}} & \mathbf{A_{12}} & \mathbf{A_{16}} & \mathbf{B_{11}} & \mathbf{B_{12}} & \mathbf{B_{16}} \\
\mathbf{A_{12}} & \mathbf{A_{22}} & \mathbf{A_{26}} & \mathbf{B_{12}} & \mathbf{B_{22}} & \mathbf{B_{26}} \\
\mathbf{A_{16}} & \mathbf{A_{26}} & \mathbf{A_{66}} & \mathbf{B_{16}} & \mathbf{B_{26}} & \mathbf{B_{66}} \\
\hline
\mathbf{B_{11}} & \mathbf{B_{12}} & \mathbf{B_{16}} & \mathbf{D_{11}} & \mathbf{D_{12}} & \mathbf{D_{16}} \\
\mathbf{B_{12}} & \mathbf{B_{22}} & \mathbf{B_{26}} & \mathbf{D_{12}} & \mathbf{D_{22}} & \mathbf{D_{26}} \\
\mathbf{B_{16}} & \mathbf{B_{26}} & \mathbf{B_{66}} & \mathbf{D_{16}} & \mathbf{D_{26}} & \mathbf{D_{66}}
\end{array}$$

Matrice of flexible plates *(aij, bij, dij):*
= Inverse of stiffness matrix of plates

$$[k_{ij}] = \begin{array}{ccc|ccc}
\mathbf{a_{11}} & \mathbf{a_{12}} & \mathbf{a_{16}} & \mathbf{b_{11}} & \mathbf{b_{12}} & \mathbf{b_{16}} \\
\mathbf{a_{12}} & \mathbf{a_{22}} & \mathbf{a_{26}} & \mathbf{b_{12}} & \mathbf{b_{22}} & \mathbf{b_{26}} \\
\mathbf{a_{16}} & \mathbf{a_{26}} & \mathbf{a_{66}} & \mathbf{b_{16}} & \mathbf{b_{26}} & \mathbf{b_{66}} \\
\hline
\mathbf{b_{11}} & \mathbf{b_{12}} & \mathbf{b_{16}} & \mathbf{d_{11}} & \mathbf{d_{12}} & \mathbf{d_{16}} \\
\mathbf{b_{12}} & \mathbf{b_{22}} & \mathbf{b_{26}} & \mathbf{d_{12}} & \mathbf{d_{22}} & \mathbf{d_{26}} \\
\mathbf{b_{16}} & \mathbf{b_{26}} & \mathbf{b_{66}} & \mathbf{d_{16}} & \mathbf{d_{26}} & \mathbf{d_{66}}
\end{array}$$

To calculate the Elastic modulus of each mode, the following equation is used:

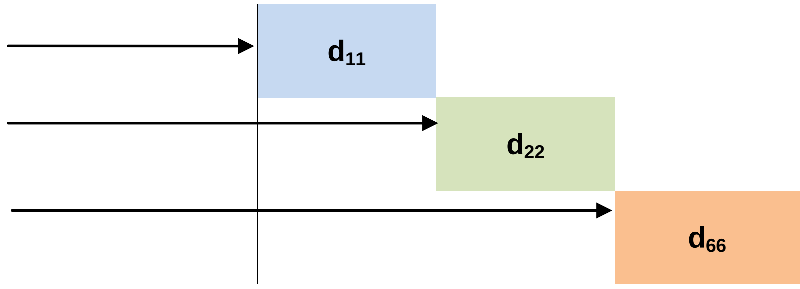
$$E_{ij} = \frac{12}{e^3 d_{ij}}$$ Equation 31

To calculate E_{11}, E_{22}, and E_{66}:

$$E_{11} = \frac{12}{e^3 d_{11}}$$

$$E_{22} = \frac{12}{e^3 d_{22}}$$

$$E_{66} = \frac{12}{e^3 d_{66}}$$



Sample calculations

Panel No. 1

Ply No.	E_L calc. with Bing GPa	Grain Angle, θ (°)	Density (using eq. 1) (g/cm^3)
1	13 588	0	0.614384974
2	19 284	90	0.863085409
3	15 765	0	0.709739968
4	15 431	90	0.695136719
5	12 953	0	0.586490263

Summary of the constants of all the plies (their reference)

Ply No.	E_L (MPa) (Using eq 1)	E_L (MPa) (Using eq3)	G_{LT} (MPa) (Using eq5)	ν_{LT} (Using eq 7)
1	13 588	934	904	0.46
2	19 284	1 687	1 388	0.45
3	15 765	1 200	1 085	0.46
4	15 431	1 158	1 057	0.46
5	12 953	861	853	0.46

Note that moisture content of the panel was 12%, therefore no moisture corrections were needed.

Calculation of the stiffness of the plies (the plies in references)

Ply No.	Q_{ll} (MPa) (Using Eq. 9 to 24))	Q_{tt} (MPa) (Using Eq. 9 to 24)	Q_{lt} (MPa) (Using Eq. 9 to 24)	Q_{SS} (MPa) (Using Eq. 9 to 24)
1	13 791	948	439	904
2	19 638	1 718	779	1 388
3	16 022	1 220	560	1 085
4	15 680	1 176	541	1 057
5	13 141	874	406	853

Ply No.	Q_{11} (MPa) (Using Eq. 9 to 24)	Q_{22} (MPa) (Using Eq. 9 to 24)	Q_{66} (MPa) (Using Eq. 9 to 24)	Q_{12} (MPa) (Using Eq. 9 to 24)
1	13 791	948	904	439
2	1 718	19 638	1 388	779
3	16 022	1 220	1 085	560
4	1 176	15 680	1 057	541
5	13 141	874	853	406

Ply No.	A_{11p} (MPa) (Using Eq. 25)	A_{22p} (MPa) (Using Eq. 25)	A_{66p} (MPa) (Using Eq. 25)	A_{12p} (MPa) (Using Eq. 25)
1	41 374	2 843	2 713	1 317
2	5 154	58 913	4 164	2 339
3	48 066.	3 660	3 254	1 680
4	3 529	47 039	3 170	1 622
5	39 424	2 621	2 559	1 217

Ply No.	B_{11p} (MPa) (Using Eq. 26)	B_{22p} (MPa) (Using Eq. 26)	B_{66p} (MPa) (Using Eq. 26)	B_{12p} (MPa) (Using Eq. 26)
1	-248 243	-17 060	-16 280	-7 901
2	-15 461	-176 739	-12 492	-7 016
3	0	0	0	0
4	10 587	141 116	9 510	4 866
5	236 546	15 729	15 354	7 304

Ply No.	D_{11p} (MPa) (Using Eq. 27)	D_{22p} (MPa) (Using Eq. 27)	D_{66p} (MPa) (Using Eq. 27)	D_{12p} (MPa) (Using Eq. 27)
1	1 520 487	104 491	99 715	48 390
2	50 248	574 402	40 598	22 800
3	36050	2 745	2 441	1 260
4	34 406	458 627	30 909	15 815
5	144 884.	96 337	94 044	44 738

Ply No.	$_{11}$ (MPa) (Using eq 7.7)	$_{22}$ (MPa) (Using eq 7.8)	$_{66}$ (MPa) (Using eq 7.10)	$_{12}$ (MPa) (Using eq 7.9)
ΣAij	137 547	115 076	15 861	8 174
ΣBij	-16 571	-36 954	-3 907	-2 745.
ΣDij	3 090 035	1 236 603	267 708	133 004

Stiffness matrix plate (Aij, Bij, Dij):

	1	2	6	1	2	6
1	137 547	8 175	0	-16 571	-2 745	0
2	8 175	115 076	0	-2 745	-36 955	0
6	0	0	15 861	0	0	-3 907
1	-16 571	-2 745	0	3 090 035	133 005	0
2	-2 745	-36 955	0	133 005	1 236 603	0
6	0	0	-3 907	0	0	267 708

Matrice of flexible plates (aij, bij, dij):
= Inverse of Stiffness Matrix of Plates

	1	2	6	1	2	6
1	7.31E-06	-5.19E-07	0.00E+00	3.89E-08	-3.48E-09	0.00E+00
2	-5.19E-07	8.81E-06	0.00E+00	-6.27E-09	2.63E-07	0.00E+00
6	0.00E+00	0.00E+00	6.33E-05	0.00E+00	0.00E+00	9.23E-07
1	3.89E-08	-6.27E-09	0.00E+00	3.25E-07	-3.51E-08	0.00E+00
2	-3.48E-09	2.63E-07	0.00E+00	-3.51E-08	8.20E-07	0.00E+00
6	0.00E+00	0.00E+00	9.23E-07	0.00E+00	0.00E+00	3.75E-06

$$E_{11} = \frac{12}{e^3 d_{ij}} = \frac{12}{15^3 \times 3.25\mathrm{E}-07} =$$ 10 940 MPa

$$E_{22} = \frac{12}{e^3 d_{ij}} = \frac{12}{15^3 \times 8.20\mathrm{E}-07} =$$ 4 336 MPa

$$E_{66} = \frac{12}{e^3 d_{ij}} = \frac{12}{15^3 \times 3.75\mathrm{E}-06} =$$ 948 MPa

This QR code links to: www.daff.qld.gov.au

QR codes can be obtained via the intranet under ‘Communications > Communication tools > QR codes’.