Technical Report

Machinability of 28-year-old *Eucalyptus globoidea* wood

Author

Hamish Scown & Clemens Altaner

Date: 5th December 2022

Report: SWP-T155

TABLE OF CONTENTS

Disclaimer

supported by forestgrowers commodity levy

EXECUTIVE SUMMARY

This report relates to SWP work plan 131 ‘Wood products from NZDFI species’, milestone 5 ‘Machinability of *Eucalyptus globoidea*; outdoor demonstration product’. The overall objective was to assess the technical feasibility of manufacturing various products from durable eucalypts and produce demonstration products, which could be used for marketing purposes.

E. globoidea heartwood boards cut from 28-year-old trees grown on Banks Peninsula were available. These boards were live-sawn with a mobile horizontal bandsaw from logs salvaged from trees that were felled in course of the SWP-funded work to establish heartwood volume and taper functions for *E. globoidea* (Boczniewicz, Mason et al. 2022).

Demonstration products, which were produced, are to be displayed at the National Field Days 2022. An outdoor bench was installed prominently at the entrance to the School of Forestry.

Figure 1: Kubb game made from 28-year-old NZ grown Eucalyptus globoidea

Figure 2: CLT (Cross Laminated Timber) made from 28-year-old NZ grown Eucalyptus globoidea

Figure 3: Outdoor bench made from 28-year-old NZ grown Eucalyptus globoidea

The comparative machinability study has shown that *E. globoidea* machines equally well or even better than *Pinus radiata*, which is known for its good solid wood processing characteristics. Consequently, solid wood processors set up to work with radiata pine can obtain satisfactory results with *E. globoidea* without the need to invest in new machinery. This was the result of a BForSc(Hon) dissertation, which is added as appendix to this report.

The machinability samples are available to be used as gifts or demonstration samples.

ACKNOWLEDGEMENTS

Gert Hendriks (School of Forestry) milled the timber. Jürgen Esperschütz (resycl limited) made the Kubb game and the outdoor bench. Thomas Lim (School of Forestry) made the CLT. Further acknowledgments relating to the machinability study can be found in the appendix.

REFERENCES

Boczniewicz, D., E. G. Mason and J. A. Morgenroth (2022). "Developing fully compatible taper and volume equations for all stem components of *Eucalyptus globoidea* Blakely trees in New Zealand." New Zealand Journal of Forestry Science **52**.

APPENDIX

MACHINABILITY OF 28-YEAR-OLD *EUCALYPTUS GLOBOIDEA* WOOD

A Dissertation

HAMISH SCOWN

School of Forestry

University of Canterbury, Aotearoa/New Zealand

Email: hms88@uclive.ac.nz

Student Number: 97224411

supported by forestgrowers commodity levy

Abstract

The New Zealand timber market is supplied predominately by locally-grown *Pinus radiata*. As evidenced by timber import data, the market for ground-durable, coloured appearance and high stiffness is currently not supplied by locally-grown timbers. In particular, there are concerns about the toxicity of CCA-treated *P. radiata* as a solution for ground durability. Eucalypts have been identified by New Zealand Drylands Forest Initiative (NZDFI) as suitable for supplying these markets. Three eucalypt species have been selected for development trials, one of which is *Eucalyptus globoidea.* The first genetically improved *E. globoidea* became available for sale in 2021. While some research into the wood quality and processing of this species has been conducted, the machinability of *E. globoidea* was unknown and the subject of this work.

It was found that *E. globoidea* machined better than *P. radiata* in all tested machine tooling parameters except planing and edge shaping, in which performance was the same. While literature suggests easier machining of *P. radiata* than found in this study (Forest Research Institute, 1988; Young, 1988), the identical machining and grading allowed the comparison of *E. globoidea* and *P. radiata*. This means a wood processing business in which machines P. radiata does not need to change their tooling to machine *E. globoidea.* Within species, density was not a significant predictor of machining grades for any machine tooling, except the planing of *E. globoidea*, which was inversely proportional to air-dry density (r^2 = 0.111). This implies that a reduction in density will have a net-positive effect on the machinability of *E. globoidea*.

Machining scores (grades 1 and 2) were affected mainly by one aspect of the machined surface. Finding a solution for these can improve the machinability of *E. globoidea*. It was speculated that a careful operator in a home-based workshop should be able to avoid these defects, implying that *E. globoidea* is suited to appearance-grade carpentry and furniture-making and durable outdoor uses such as children's playgrounds or farm buildings.

Acknowledgements

I want to acknowledge the assistance provided by Clemens Altaner and Hyungsuk (Thomas) Lim for their academic supervision and guidance throughout. Also, to the technical assistance offered by Gert Hendriks in his infinite engineering wisdom and unwavering willingness to assist in providing materials and training on all the machines used within this dissertation report. Monika Sharma, for her technical support throughout regarding data collection and assistance with machining. The Department of Mechanical Engineering for their help with CNC machining.

I would also like to thank the School of Forestry for their support and resources during my dissertation project and my undergraduate degree.

I would also like to acknowledge the New Zealand Drylands Forest Initiative for providing the basis for the dissertation project and funding this research.

Contents

1. Background

New Zealand Forestry

Forestry is a significant component of the New Zealand economy, representing approximately $7.9billion in direct, indirect, or induced economic impact (Te Uru Rākau, 2020). Over 1.7m ha of land is currently planted in plantation forestry, of which approximately 90% is stocked in *Pinus radiata* (Monterrey/Radiata pine), followed by about 6% in *Pseudotsuga menziesii* (Douglas fir), 2% in various other softwoods, and 2% in hardwoods (mostly eucalypts) (Te Uru Rākau, 2020).

P. radiata grows quickly across most forestry-suitable sites in New Zealand, has good form due to decades of breeding, and is stiff enough to be used in the construction of residential housing and other household uses (Cown, 1999). *P. radiata* wood has high permeability and, therefore, can be dried cheaply and treated effectively against decay by fungi or insects (Cown, 1999; Walker, 2006). With the growing development of specific silvicultural programmes, further enhancement in breeding, and increasing supply chain tuning, New Zealand, over the years, has geared its forest industry towards *P. radiata*. While *P. radiata* is a versatile wood, it is unsuitable for all products. Some need to be manufactured from alternative species, providing timbers for ground contact, coloured timbers used for appearance products, and timber for high stiffness, high strength applications.

Domestically, the ground-durable timber market relies on CCA-treated (Copper-Chrome-Arsenic) *P. radiata* timber. There are concerns that the extensive use of CCA has adverse outcomes for health (Gress et al., 2015; Hall & Beder, 2005) as well as being an environmental hazard requiring disposal at a lined landfill after its usable life (Jambeck et al., 2008; Khan et al., 2005; Townsend et al., 2003). Few alternatives to CCA-treated *P. radiata* are available in ample supply at low cost in New Zealand for durable timber products. Acetylated timber is one option that is becoming commercially available. However, the complex supply chain restricts access to this as a viable solution to the market in the short term (Pers. Comm., D. Evison., 2022). It is approximately four times more expensive. Apart from chemically modified timber, the heartwood of some tree species also shows resistance to decay.

While NZ plantation-grown spices such as Macrocarpa (*Hesperocyparis macrocarpa*) and Coastal Redwood (*Sequoia sempervirens*) are all suitable for above-ground uses (e.g., decking) (Page & Singh, 2014), ground-durable timber species are rare and not grown in New Zealand at commercial scale.

The New Zealand market for coloured appearance grade timber used in carpentry etc., was previously met by indigenous timbers. Over the previous 800-1000 years, Māori and European settlement has led to the deforestation of nearly 15 million hectares of indigenous forest. Indigenous forestry was regulated under The Forests Act 1949. An amendment in 1993 banned logging indigenous timbers on public land and required owners of private indigenous forests to require sustainable management plans for harvest (Forests Amendment Act, 1993). This amendment aimed to prevent further loss of New Zealand's indigenous biodiversity and woodland habitats. However, this amendment also led to a sharp decrease in the availability and utilisation of indigenous timber tree species. A notable exception to this is *Fuscospora spp.* (Southern Beeches) which are commercial hardwood timber crops in New Zealand. Hall (2020) found speciality timber imports valued at $112.5million, indicating a market is not being met with domestically supplied timber to that value.

Stiffness is a measure of the rigidity of timber expressed as the ratio of stress (load) over strain (deformation) (Vikram et al., 2011; Wang et al., 2001). Stiffness in wood is determined by wood density, i.e. the amount of cell wall material in a given volume and the properties of the cell wall (Walker, 2006). The microfibril angle mainly influences the latter, i.e. the angle the cellulose fibrils form with respect to the wood grain. For old-growth trees, higher-density timbers generally have good stiffness properties (Bier, 1986), and for younger trees, angiosperms are typically superior over gymnosperms due to their lower microfibril angle (Walker, 2006). Sufficient stiffness is required in constructing timber buildings (Standards New Zealand, 2011).

Certain eucalypts grow well in the New Zealand environment and produce coloured, ground-durable timber of high stiffness and strength. *E. globoidea* is one of the species developed by the New Zealand Drylands Forest Initiative (NZDFI), meeting these requirements.

New Zealand Drylands Forest Initiative

The New Zealand Drylands Forest Initiative (NZDFI) was established in 2008 by an agreement between Vineyard Timbers Ltd, Proseed NZ Ltd, the Marlborough Research Centre, and the University of Canterbury's School of Forestry. The NZDFI aims to develop a domestic eucalypt resource that supplies ground durable timber to the agricultural sectors (Millen et al., 2018). The wood of the identified tree species is also coloured. It features excellent mechanical properties, opening markets as appearance grade (outdoor) joinery and high-performing engineered wood products such as LVL (Guo & Altaner, 2018). It is class 2 durable, making it suitable for ground-contact uses.

A breeding programme was established for the identified eucalypt species to improve heartwood quantity and quality, tree health, tree form and growth, and processability (collapse and growth stresses). The species undergoing genetic improvement trials are *E. bosistoana*, *E. globoidea*, and *E. quadrangulata*, with the secondary species *E. argophloia* and *E. tricarpa*. *E. cladocalyx* is also identified as suitable for New Zealand durable timber growers but is not involved in a breeding trial in New Zealand due to improvement from breeding programmes in Australia. Further research in silviculture, propagation and site x species interaction adds to the breeding effort.

In 2021, the first batch of >200,000 improved *E. globoidea* seedlings was released under the 'Xylogene' brand by NZDFI. These seedlings will form the first generation of stands of the fledgling durable eucalypt resource in New Zealand. The NZDFI has identified twelve key wood supply catchments for investment, including small to medium-sized wood processing facilities (Figure 4).

These catchment areas were identified due to suitable land available (LUC 5 – 7), suitable climate, existing infrastructure, and proximity to markets. The twelve 40 km catchments expected to form the first twelve industrial centres for the durable eucalypt industry are Kaikohe, Dargaville, Taumaranui, Kawerau, Makaraka, Wairoa, Stratford, Whanganui, Hastings, Woodville, Masterton, and Kaituna.

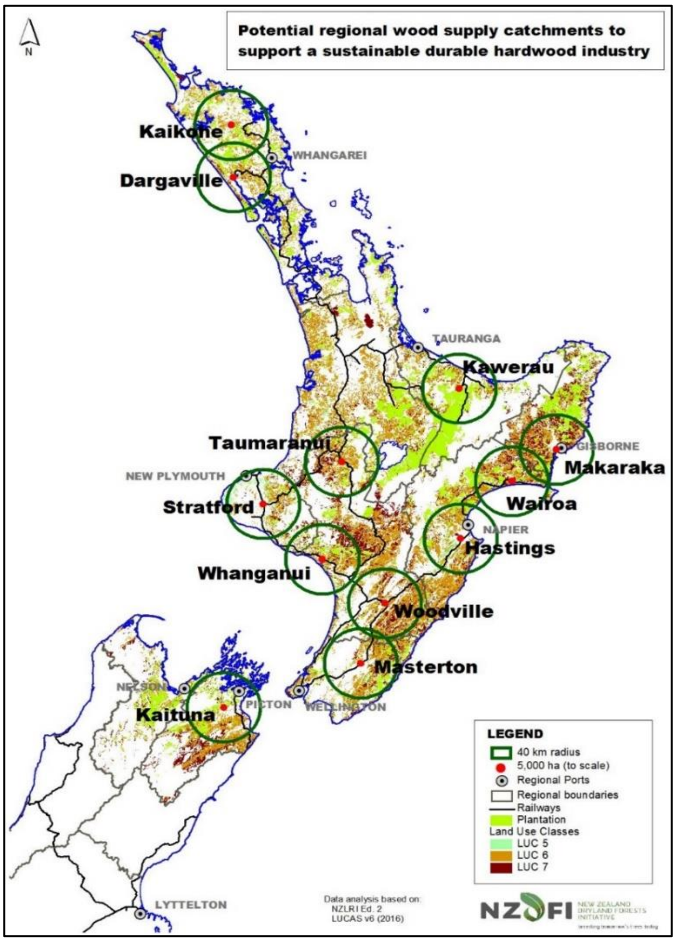

Figure 4: Map of Targeted Processing Hubs and Catchment Areas for Durable Eucalyptus Timber Processing. NZDFI. 2016.

The required target is for each catchment area to achieve planting of 170 ha per year for 30 years, totalling 5,000 ha. This equates to less than 5% of the suitable land available in each catchment.

Eucalyptus globoidea

E. globoidea, or White-Stringybark, is an angiosperm of the family Myrtaceae, endemic to Coastal South-Eastern Australia from Woolgoolga in the North to Melbourne in the South. In its native habitat, it can reach heights of 40 metres in optimal conditions (Boland et al., 2006). New Zealand-cultivated *E. globoidea* has been shown to have slightly lower density and strength properties than Australian-grown timber while remaining suitable for structural timber uses (Haslett, 1990).

Old-growth *E. globoidea* has a mean air-dry density of 880 kg/m^3 in Australia, and 805 kg/m^3 was reported for timber from age 25 stands in New Zealand (Nicholas & Millen, 2012). Modulus of Rupture (MoR) and compression strength parallel to the grain at 12% moisture content (MC) were similar for the *E. globoidea* timber grown in Australia and New Zealand. At the same time, the Modulus of Elasticity (MoE) and hardness were moderately lower for the New Zealand source (Table 1).

Machinability of Wood

Machinability as a characteristic of wood refers to the ability of a wood surface to be machined by a tool. Machinability is a crucial determinant of the viability of a wood species to be used in processing. Easily machinable wood species can consistently produce high-quality surface finishes after

Table 1: Wood Qualities Comparison Australia/New Zealand Grown Eucalyptus globoidea. NZDFI. Nicholas & Millen., 2012.

Origin/species	Modulus of Rupture (MPa)		Modulus of Elasticity (GPa)		Compression Parallel (MPa)		Hardness (kN)		Density (kg/m^3)		
	Green	12 %	Green	12%	Green	12%	Green	12%	Green	Air-Dry	Basic
Australia											
E. bosistoana	103	163	17	21	50	73	10	13	1180	1100	880
E. globoidea	92	133	14	17	43	68	6.8	8.8	1100	880	680
E. camaldulensis	64	101	8	11	33	55	5.3	7.5	1130	900	710
E. quadrangulata	**98**	**163**	**17**	**18**	**47**	**71**	**8.2**	**14**	**1230**	**1030**	**800**
New Zealand											
E. bosistoana	na	na	na	na	na	na	na	na	na	na	na
E. globoidea	81	132	7.7	15	38	67	4.5	6.9	na	805	635
E. camaldulensis	na	na	na	na	na	na	na	na	na	na	na
E. quadrangulata	**na**	**na**	**na**	**na**	**na**	**na**	**na**	**na**	**na**	**na**	**na**
Pinus radiata	40	89	6.2	8.5	16	38	2.4	5.0	960	500	420

machining. This means that easily machinable wood is suitable for various uses, especially carpentry and furniture-making, which requires various machining. The American Society for Testing and Materials (ASTM) has developed a standard to quantify the machinability of timber (D1666-64). This standard has been revised several times; the current version is ASTM D1666-17 (2017). This standard has an awareness of the unique properties of wood as a material, particularly the differences across species and the anisotropic nature of wood. The tests are designed to reflect the variability of the finishing quality of specific machining processes. The finishing quality is usually graded visually by a professional woodworker as specified by ASTM D1666-17 and focuses on defects and surface roughness.

Research Objective

This dissertation aims to describe the machinability characteristics of *E. globoidea* wood as specified by the standard (ASTM D1666-17). The standard specifies six machining processes to be evaluated as representative of a wood species' machinability. This research assessed four processes (Planing, Boring, Shaping, and Mortising), with two processes removed due to a lack of available equipment. The results were compared against a) a control of *P. radiata*, a timber with known good machinability and b) literature to put the results into context.

The results will ensure market access of *E. globoidea* timber into solid wood products such as outdoor furniture, flooring, and decking. Potential growers of *E. globoidea* plantations will have more confidence in their investments, drive the uptake of this species in New Zealand and contribute to establishing NZDFI regional catchment hubs.

Additionally, this research will provide the methods and conditions for future machinability testing within the School of Forestry for any additional species that are potential candidates for locally-grown speciality species. This research included testing an alternative method to visual grading that could speed up or automate the grading process for future research. Further, density was assessed within species as a predictor of machine grade to aid decision-making for silviculture trials and breeding.

Methods

This study was based on the ASTM D1666-17 standard “Machinability of Wood and Wood-Based Panels”. The standard required 50 boards of 1,220 mm length, 102 mm width and 19 mm thickness for each wood species tested. These boards were to be clear of knots/defects, flat sawn, untreated, and dried to uniform moisture content (MC) consistent with conditions typical of end users' requirements, i.e., 12% ± 3% for this study.

Material

Eucalyptus globoidea

Eucalyptus globoidea boards originated from trees planted in 1990 on a property on Reynolds Valley Road in the Okuti Valley, Banks Peninsula (43°47'32.0"S; 172°50'20.8"E), also known as the Ettrick site. The stand totalled 1 ha, and 31 trees were felled in 2018, aged 28 years old. The inventory reports a final stocking of 458 stems/ha with a mean diameter at breast height (DBH) of 45 cm and a mean top height (MTH) of 27.5 m. Table 2 shows the climate information for the site.

Table 2: Ettrick Site Information. Daniel Boczniewicz. 2018

Site name	Ettrick
Planting Year	1990
Age felled (years)	28.5
Location	Okuti Valley, South Island, Canterbury
Trees felled	31
Coordinates	43°47’32.0” S 172°50’20.8” E
Mean annual temperature (°C)	11
Mean minimum temperature of the coldest month (°C)	3.3
Mean annual solar radiation (MJ/ m^2/day)	13.8
Winter solar radiation (MJ/ m^2/day)	4.6
Annual water deficit (mm)	95
Monthly water balance ratio	28

The trees were felled during Daniel Boczniewicz's PhD thesis to gather data for the development of growth and taper functions. Discs (30 mm) were cut from labelled stems (A, B, C, etc.) at intervals representing a specific change in diameter over the length of the stem. The remaining logs were available for other purposes and given numeric labels (A1, A2, etc.). These logs were then live sawn into boards with a target thickness of 30 mm using a Woodland Mills HM130 mobile horizontal band saw. An upright bandsaw was used to rip 110 mm, wide heartwood boards without pith (i.e., removing sapwood and pith). The boards were labelled according to the log they came from (A1/1, A1/2, A1/3 etc.). The boards were stored at the School of Forestry Wood Technology Lab to air-dry for three years until 2021 (Figure 5).

As

Figure 5: Milled Eucalyptus globoidea boards stacked after drying in School of Forestry Wood Tech Lab, 2021.

the logs were live-sawn, most of the boards were a mixture of flat and quarter-sawn. Furthermore, due to the relatively young age of the trees, most boards were not defect-free. The most appropriate, i.e., least defective and approximately flat-sawn, boards were selected from the available material. Deviating from ASTM D1666-17, specimens with tiny live knots not larger than 50 mm in length and ten quarter-sawn boards were included. Seventeen samples were missing their labels and thus were labelled with the alphabet code “NA”. Overall, the study included boards from at least six trees.

The uneven *E. globoidea* boards were cut to lengths of 1600 mm (Makita LS1219L 305mm Compound Mitre Saw) and then passed through a jointer (Scheppach hms 2600ci) to create a flat face and a flat edge at a 90° angle. A thicknesser (Scheppach hms 2600ci) was used to obtain 20 mm thick boards. The 50 planed boards were cut to the length of 1,220 mm with the compound saw and then ripped to a width of 105 mm using an SCM ST4 table saw. These samples were then stored in an environment-controlled room at 65% relative humidity and 20°C, where they were conditioned to ~12% moisture content over two weeks. The conditioned samples were then planed to 19.5 mm thickness with a Makita 2012NB 304mm on one face and then 19 mm on the other. This thicknesser was running at 8500 RPM (revolutions per minute) and a feed speed of 8.5 m/min with two knives producing a finish of 2 cuts/mm.

Three boards were removed after a final quality control as their thickness was less than 19 mm, leaving 47 *E. globoidea* samples for the study.

Pinus radiata

Thirteen flat-sawn, kiln-dried, rough-sawn, clears grade *Pinus radiata* boards (5,200 mm x 150 mm x 25 mm) were purchased from a local timber supplier (Halswell Timber, Christchurch). The origin of the timber was unknown but likely from the South Island. The *P. radiata* samples were labelled P, followed by the number of the 13 boards. The origins of the boards were unknown, but at most, thirteen *P. radiata* trees were represented in this study.

Four lengths of 1,220 mm were cut from each 5,200 mm long boards (Figure 6). Each sample was labelled, including the board it came from, e.g., P1/1, P1/2, P1/3, P1/4. After conditioning at 65% relative humidity and 20°C temperature, these boards were further processed as described above for *E. globoidea*. Three of the 52 boards were removed after a final quality control as their thickness was less than 19 mm, leaving 49 *P. radiata* samples for the study.

Figure 6: 5,200 mm x 150 mm x 25 mm kiln-dried rough, flat-sawn, Pinus radiata *clears in stack at Halswell Timber. 2022.*

Machinability samples

The 47 remaining eucalyptus and 49 pine samples (1,220 mm x 105 mm x 19 mm) were then cut as specified by standard ASTM D1666-17, allowing six separate tests to be conducted (Figure 7). The 1,220 mm lengths were cut with the Makita LS1219L Compound Mitre Saw into 897 mm, 305 mm, and 13 mm lengths. All pieces were labelled with board code and the machining test.

The 897 mm x 105 mm boards were designated for planing and sanding tests (label 'PS'). The 13 mm x 105 mm (labelled 'SG') were used to determine moisture content and density. The 305 mm x 105 mm samples were further ripped to produce 77 mm wide pieces for boring, shaping, and mortising tests (label 'BSM') and 25 mm wide pieces for turning (label 'T'). All samples were stored in the environment-controlled room at 65% relative humidity and 20°C temperature, where they were conditioned to ~12% moisture content over two weeks.

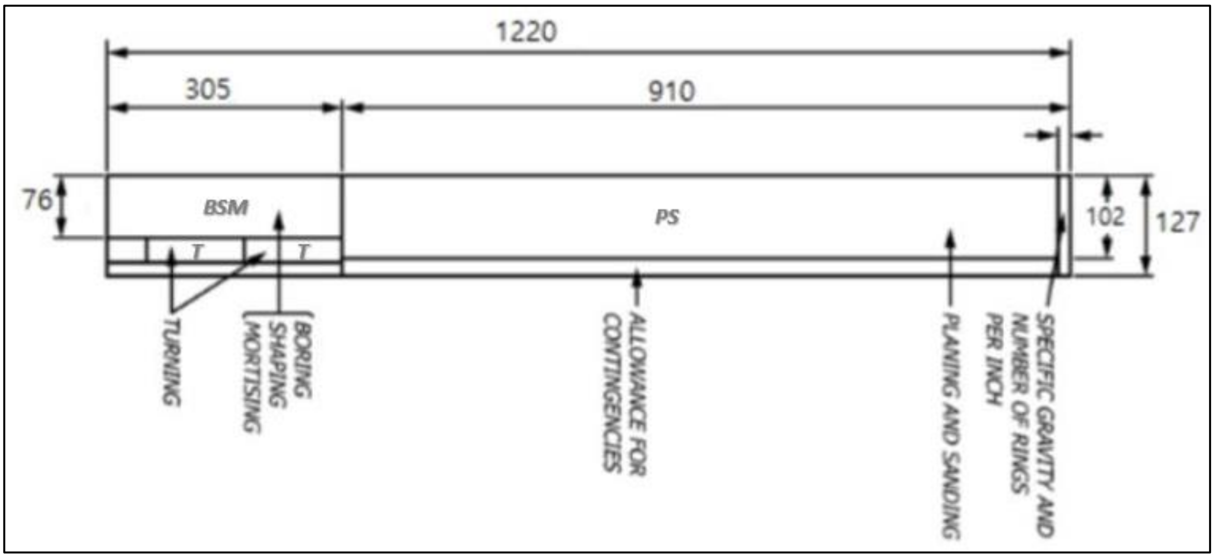

Figure 7: Cutting pattern to prepare samples according to ASTM D1666-17. 2017.

Density and Moisture Content

For each of the 13 mm x 105 mm x 19 mm samples, equilibrated to constant weight at 65% relative humidity and 20°C temperature, mass was measured with a balance and dimensions were measured with a Mitutoyo Vernier calliper. The geometric volume ($Volume_g$) was calculated according to:

$$Volume_g\ (mm^3) = \ Length\ (mm)\ x\ Width\ (mm)\ x\ Height(mm)$$

The displacement volume ($Volume_i$) was also determined by immersion weighing according to Archimedes' principle.

Air-density was calculated for both the geometric volume ($Volume_g$) and the Archimedean volume ($Volume_i$) for each sample according to:

$$Density_{air-dry}\left(\frac{kg}{m^3}\right) = \frac{Weight\ (kg)}{Volume\ (m^3)}$$

Samples were then dried in an oven at 103°C +/- 3°C until constant weight and reweighed. The following formula was used to calculate Moisture content (MC):

$$MC\ = \frac{Weight_{oven-dry} - Weight_{air-dry}}{Weight_{oven-dry}} \times\ 100$$

To assess the effect of density on machinability, within species densities were used as a predictor for machinability grades in linear regression modelling. This is useful for breeding and silviculture development if improved machinability is a goal.

Grading

The ASTM D1666-17 standard distinguishes five visually assigned grades for each machined surface. Visual grading is subjective to the grader. The effect of the grader was avoided in this study, as only one person did all assessments.

Table 3 depicts the specified quality for each grade from the standard ASTM D1666-17. Table 3 was interpreted as follows. Grade 1 was associated with defect-free pieces, where no fixing (sanding) would be required to finish the product to a high standard. Grade 2 was associated with areas where defects were visible but could be remediated by light sanding. Grade 3 refers to pieces where remediation would require significant sanding or chiselling, resulting in slightly rounded edges or reduced dimensions. Grade 4 is the same as Grade 3, except remediation will result in deep-rounded edges or visibly reduced dimensions. Grade 5 pieces have defects requiring the end user to create a new piece if a high-quality finish is needed. The lowest grade on each surface was used to represent the grade of the piece.

Machining defects associated with knots were excluded from the surface quality analysis after they were measured. Wood near knots is at higher risk of torn grain and fuzzy grain due to the transition from parallel grain in the clear wood to perpendicular grain in the knot wood, as well as an increase in density nearer the knot (Öhman et al., 2016). The defects measured around knots in this study were all torn grain. Torn grain that occurred within the region around the knots where the grain angle was affected by the knot as seen by the eye, was typically much deeper and longer in the machined direction. Therefore, the defective areas around knots were not assessed to bring the sample analysis back in line with the standard, though data was collected.

The overall machinability grade of each species for a tool was defined as the percentage of the combined Grade 1 and Grade 2 out of the total pieces per the standard.

Table 3: The definition of principles for visually grading machined surfaces. 2022

Grade	1	2	3	4	5
Quality	Perfect	High	Low	Very Low	Not Acceptable

Planing

Planing was carried out on an SCM S630 thicknesser operated at 4500 RPM. Four new high-speed steel (HSS) knives were installed at a cutting angle of 30° into the cutter head. To achieve the desired number of cuts per mm while maintaining balance, two opposing knives were redacted by 1 mm so that only two knives were cutting material.

In the first planing run, the feeding speed was set to 18 m/min resulting in 0.5 cuts/mm. The second run used a feeding speed of 11.25 m/min, resulting in 0.8 cuts/mm. Two unused sharp knives were installed before each run.

E. globoidea and *P. radiata* PS samples (102 mm x 910 mm x 19 mm) were fed through the planer in random order to avoid the effect of knife wear on the finish quality between the two species. The direction of feed was noted on the board to ensure that this factor was consistent between the runs. Each run consisted of two passes, with a first pass taking off 1 mm to remove artefacts of the previous machining and a second pass taking off a further 1.6 mm of the same face. The order of the second run was the reverse of the first to remove the effect of tool wear. After each run, the samples were stored in the environment-controlled room at 65% relative humidity and 20°C.

Planing - grading

Samples were visually graded after the second pass according to ASTM D1666-17, with the modification that only clear wood away from knots was assessed. ASTM D1666-17 specifies knot-free material; however, no knot-free *E. globoidea* material was available. An example of torn grain grades for Hard Maple (*Acer nigrum*) depicting the difference between grades 2, 3, and 4 is seen in Figure 8.

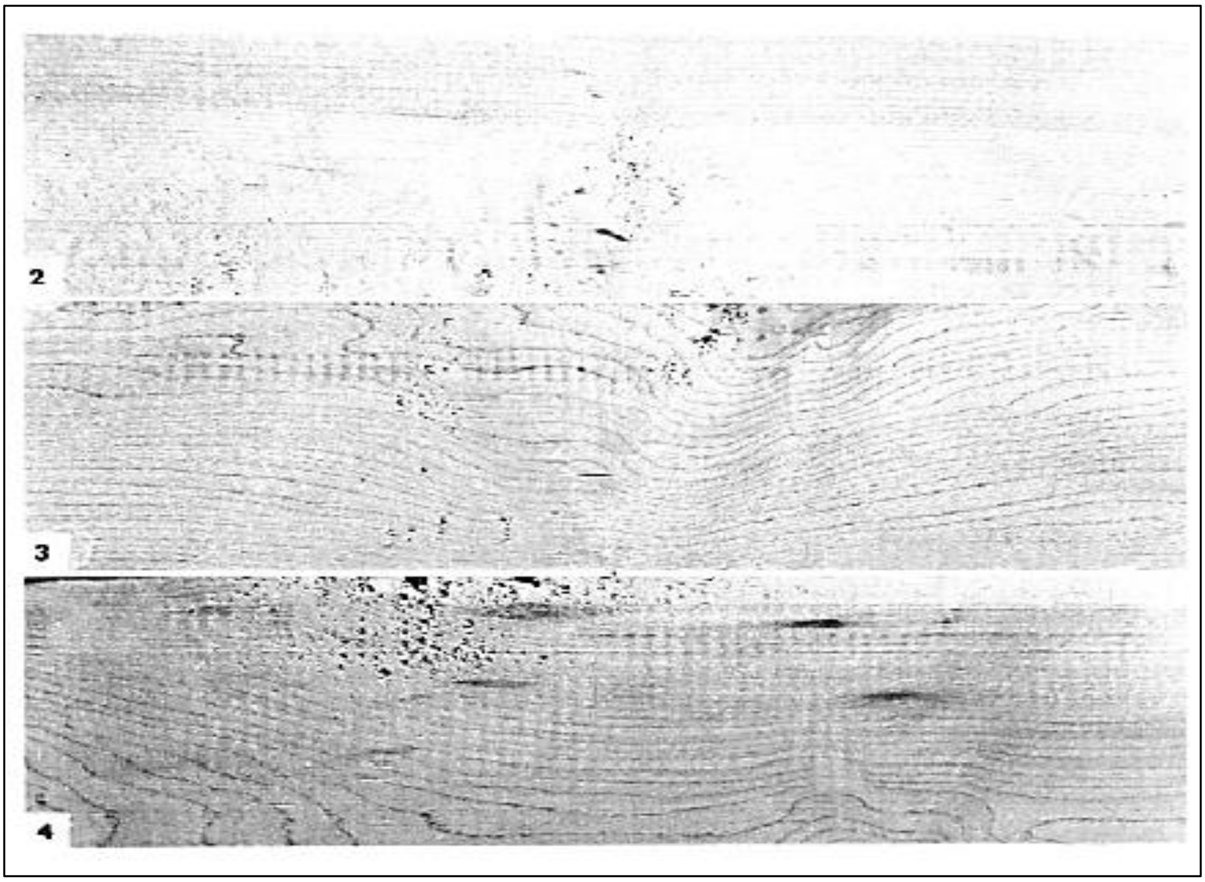

Figure 8: Depicting torn grain and example visual grade applied sourced from ASTM D1666-17.

The surface quality of the planed samples was also quantified with image analysis after the first and the second pass. This was to assess the possibility of photographic technology in the visual assessment process. It was initially thought that the photo scanner would show defects boldly as oblique shadows on the image. This was not the case, so the defects, according to Table 4, were drawn on all samples to assist in detection through imagery. Only torn grain was assessed as no fuzzy grain, raised grain, or loosened grain was detected in the machined surfaces. Torn grain (or chipped grain) is wood with fragments torn or chipped out below the line of cut in planing (USDA, 1965). Four types of torn grain, more or less than 0.2 mm in depth in clear wood or around knots, were defined and outlined on the boards with different coloured pencils (Table 4). The defect depth was measured with Vernier callipers' depth gauge. The 0.2 mm depth was chosen because remediation would be possible with light sanding. These grades will be referred to as the T-grades.

Table 4: Categories used for defects in the planing test (T-grades).

Defect	<0.2 mm Deep	>0.2 mm Deep
Clear	T1 - Yellow	T2 - Green
Around Knot	TK1 - Blue	TK2 - Red

Each sample with the marked defects was imaged in four 210 mm long segments with a Canon Lide400 A4 scanner with 11.58 pixels/mm resolution (Figure 9). A ruler was included in the image as a reference for scale.

The digital images were further analysed using ImageJ (Schneider et al., 2012). The coloured outlines (Figure 10) of the defects were captured using the multi-point area tool, and the area of each defect was noted as a percentage of the total board area using the formula;

$$Percentage\ Area_{Defect} = (Area_{Defect}(m^2)/\ Area_{Board}(m^2)\ x\ 100$$

Figure 9: Two Pinus radiata *samples being scanned on Canon Lide400 A4 Scanner.*

Figure 10: Example of coloured defects according to Table 4 on a Pinus radiata planed sample.

Boring

All 49 *P. radiata* and 47 *E. globoidea* BSM samples (76 mm x 305 mm x 19 mm) were tested for boring machinability in line with ASTM D1666-17. A Dyco 12 mm bench drill press (Figure 11, left) was used in conjunction with a 25 mm Bosch Forstner drill bit featuring a high-speed steel cutting edge (Figure 11, right). One machinist operated the manual bench press to reduce the effect of variation in feed speed. The targeted feed speed was 0.5 m/min (approximately 2.3 seconds per hole). The standard-specified 3600 RPM caused the burning of the samples and needed to be reduced to 1200 RPM. All samples were clamped into a custom-made jig to ensure precise hole placement and reduced movement while machining. All 96 samples were randomised to reduce to effect of tool wear, and two holes were bored into each sample.

The order was reversed in the second run to remove the effect of tool wear. After each run, the samples were stored in the environment-controlled room at 65% relative humidity and 20°C.

Figure 11: Dyco 12 mm Bench Drill Press and jig (left). Close-up of 25 mm Forstner Drill Bit (right).

Boring - grading

All boreholes were visually graded independently, representing 94 and 96 holes for *E. globoidea* and *P. radiata*, respectively (Figure 12).

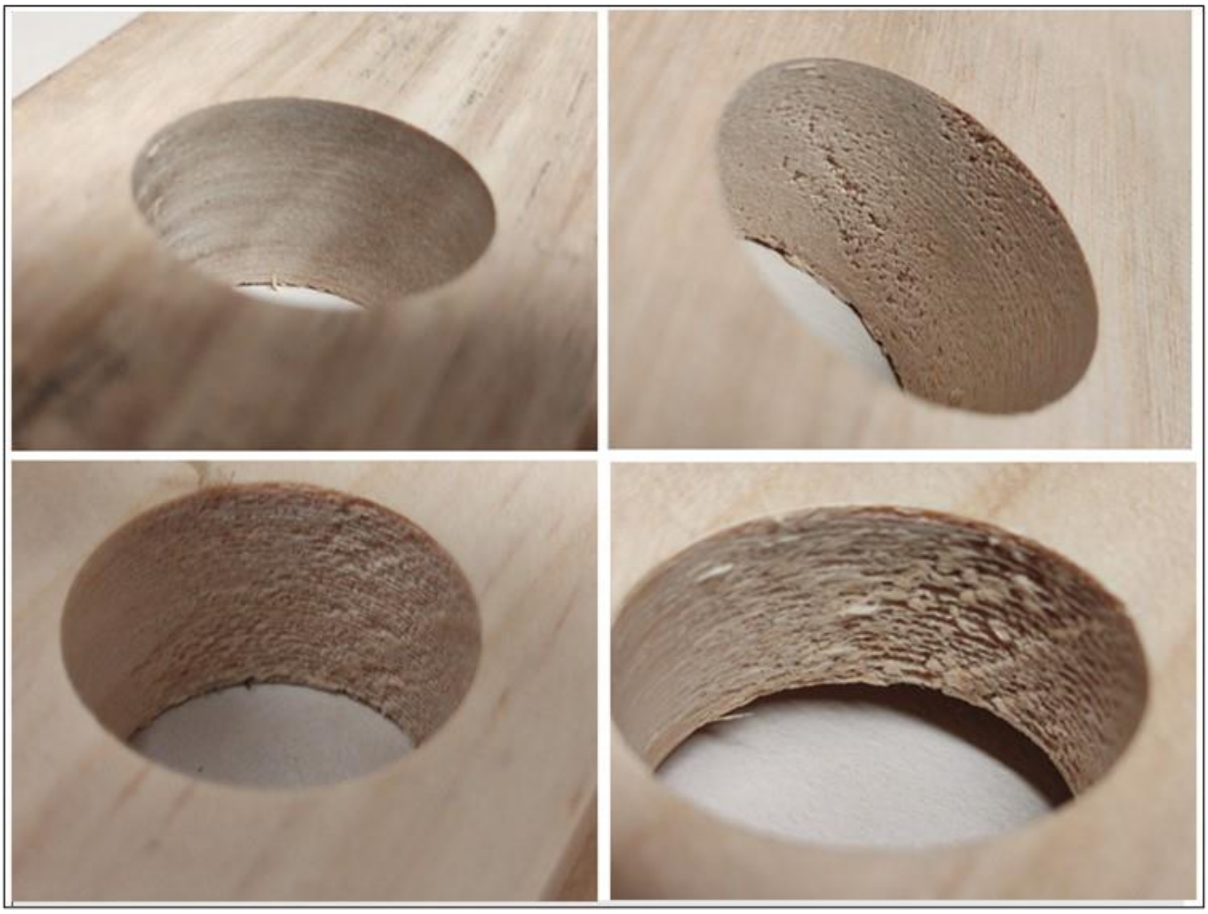

Figure 12: Grade 1 (top left). Grade 2 (top right). Grade 3 (bottom left). Grade 4 (bottom right).

Three data points were graded independently per borehole to identify if it is possible to improve machining quality by focussing on different aspects of the hole. These were:

- Entry: the edge around the top of the hole where the tool entered the wood.
- Hole: the inside plane around the whole inside of the borehole
- Exit: the edge around the bottom of the hole where the tool exited the wood.

The grade of the hole was assigned as the worst of the three grades of the individual data points. The machining order was found to have an effect, so the maximum grade of the sample (both holes) was assigned, thus removing the impact of the order.

Shaping

The BSM (76 mm x 305 mm x 19 mm) samples were used to test shaping machinability according to ASTM D1666-17. An Ascent Pro CNC machine (Figure 13) was used with three router bits featuring high-speed steel cutting edges: a 6.4 mm straight bit, a 10 mm rebating bit, and an 8 mm rounding bit.

Figure 13: Ascent Pro CNC machine used for shaping.

First, a J-shaped groove running parallel and perpendicular to the grain was cut with the 6.4 mm straight bit. The second run cut a rebate along the edge of the specimen, first parallel, then perpendicular, using the 10 mm rebating bit. Finally, the lower step of the rebate was rounded with the 8 mm rounding bit again, first the edge parallel and then the edge perpendicular to the grain (Figure 14).

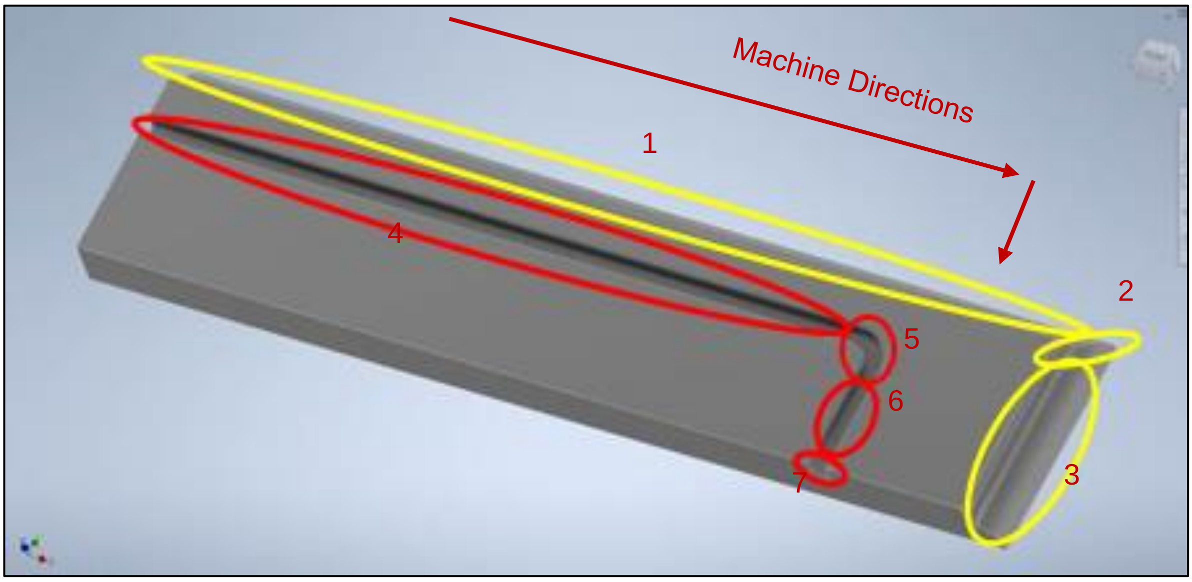

Figure 14: CAD design showing shaping profile and grading points for CNC machining by run. Yellow – Edge, Red – Groove.

The CNC machine was run with a feed speed of 4240 mm/min at 10,000 RPM. All samples were clamped into a custom jig to ensure precise placement and reduced movement while machining. The samples were machined in random order to reduce to effect of tool wear, and the order was recorded. After each run, the samples were stored in the environment-controlled room at 65% relative humidity and 20°C.

Shaping - grading

All 47 *E. globoidea* and 49 *P. radiata* had seven machined surfaces per sample that were independently visually graded. These were assigned into two runs: edge and groove. Edge was graded with three data points.

- Side grain (1)
- End grain (2)
- Corner (3)

Groove was graded with four data points.

- Side grain (4)
- Corner (5)
- End Grain (6)
- Exit (7)

The grades of the overall runs were assigned as the worst of the grades of the individual data points in each run.

Mortising

The BSM (76 mm x 305 mm x 19 mm) samples were used to test mortising machinability according to ASTM D1666-17. A Luxcut TM-3VSL turret mill (Figure 16) was used in conjunction with a 13 mm custom-made high-speed cutting steel mortising chisel (Figure 15) and a single spiral auger centre. One operator manually operated the machine. The targeted feed speed was 0.23 m/min (approximately 5 seconds per hole). Holes were mortised at 1200 RPM as the machine could not perform this task safely at the ASTM D1666-17 specified 3600 RPM. All samples were clamped into a jig to ensure precise hole placement and reduced movement while machining. The first hole was machined into the 96 samples randomly to minimise the effect of tool wear between species, and the order was recorded. The sample order was reversed for the second hole to minimise tool wear's effect further. After each run, the samples were stored in the environment-controlled room at 65% relative humidity and 20°C.

Figure 16: Luxcut TM-3VSL Turret Mill Used for Mortising.

Figure 15: Custom Mortise Attachment for Turret Mill.

Mortising - grading

All 47 *E. globoidea* and 49 *P. radiata* had two mortise holes per sample that were visually graded independently, representing 94 and 96 holes for *E. globoidea* and *P. radiata*, respectively. Each mortise hole had four data points that were graded independently.

- Entry (1)
- Exit (2)
- Side grain (3)
- End grain (4)

The hole grade was assigned as the worst of the four grades of the individual data points (Figure 17).

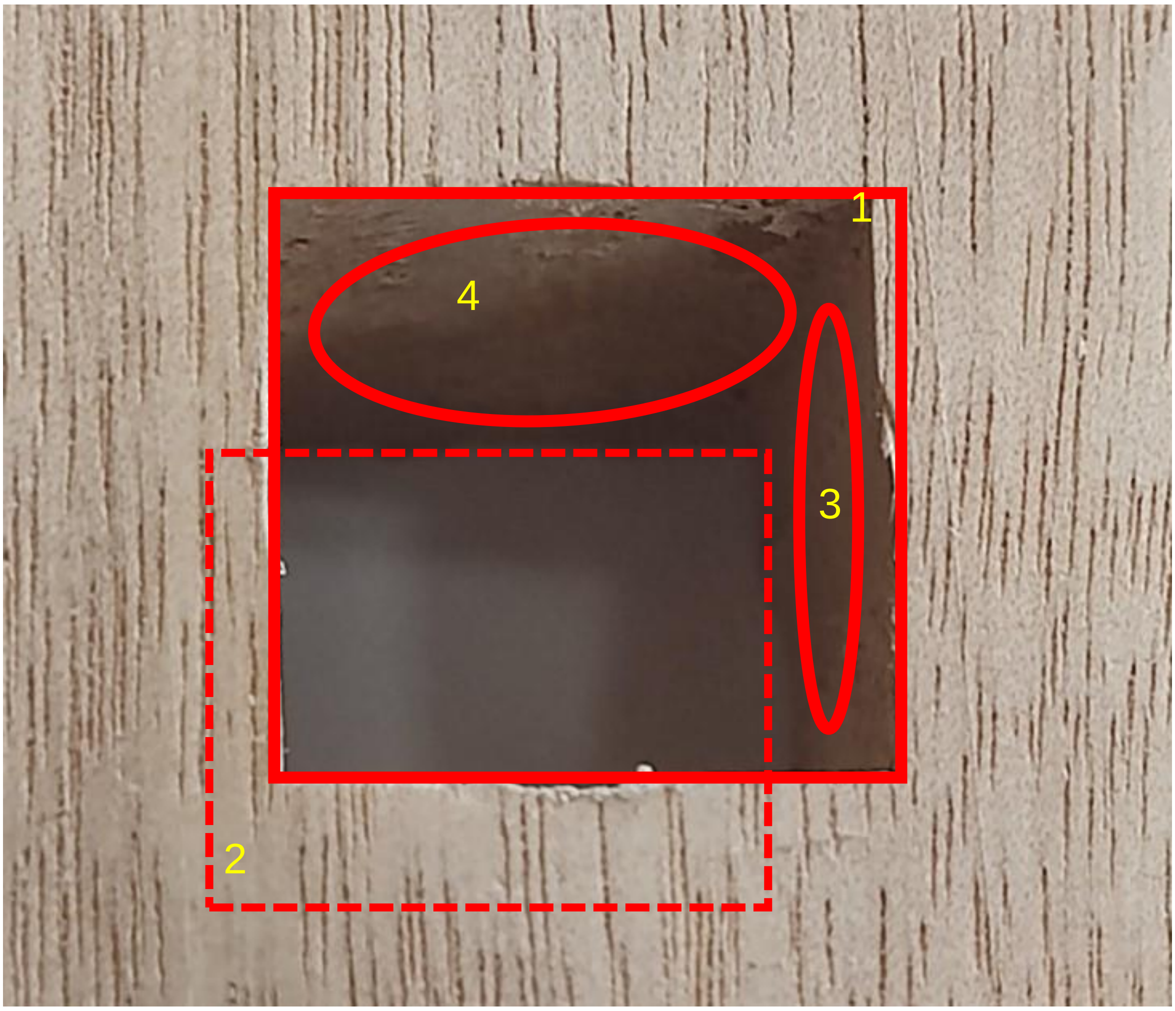

Figure 17: Example of a mortise hole in an E. globoidea sample with grading data points.

Analysis

All means were compared using t-tests: assuming unequal variance on Microsoft Excel (Microsoft Corporation, 2019) to assess the difference in means and conclude whether one species was objectively better in a machine parameter. Then the machinability score was calculated per the standard as a percentage of grades 1 and 2 per species per machine tool.

All regression modelling and graphical analysis were performed on R Studio (RStudio Team, 2021).

Results and Discussion

Preliminary data analysis showed that quarter-sawn boards showed significantly different machinability than flat-sawn boards. Thus, per ASTM 1666-17, ten *E. globoidea* quarter-sawn board samples were removed from the following analysis. The remaining sample count was 49 for *P. radiata* and 37 for *E. globoidea*.

Density and Moisture Content

Air-dry densities using the geometric and immersion volumes were highly correlated ($r^2 = 0.997$) (Figure 18). Air-dry density measurements based on immersion volume were chosen for further analysis. However, the strong relationship implied that it would not matter.

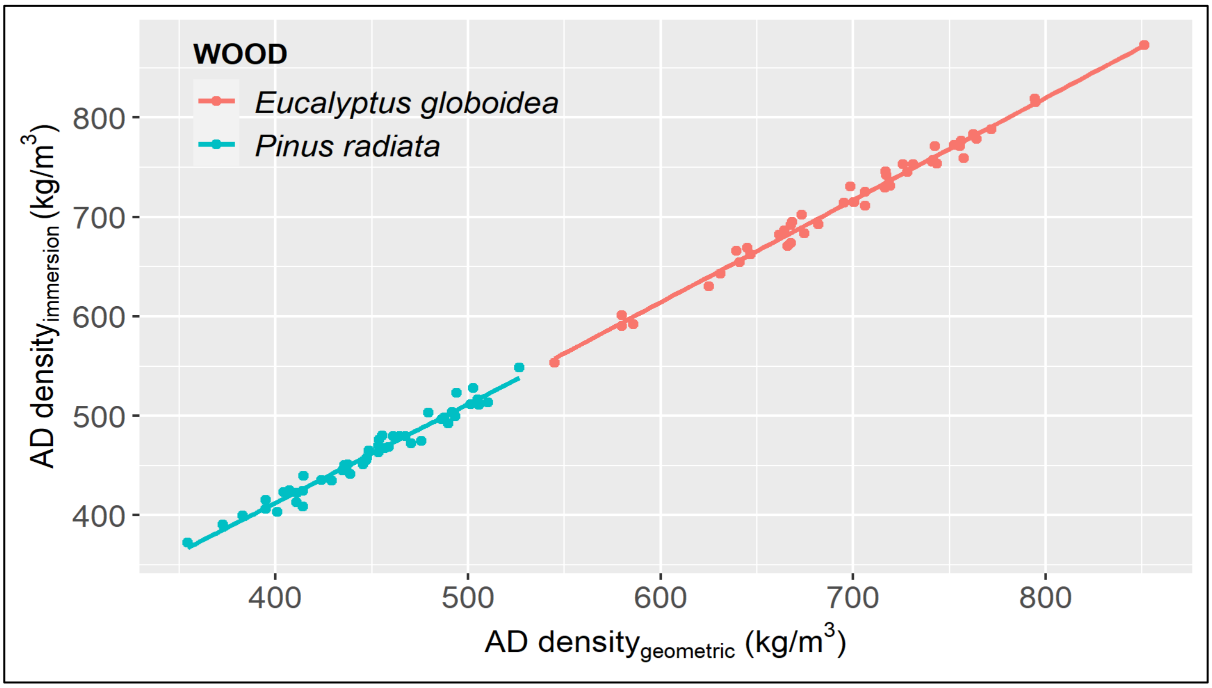

Figure 18: Relationship between Air-Dry (AD) density based on geometric and immersion volumes.

Air-dry densities were significantly higher in *E. globoidea* than in *P. radiata* (Figure 19) (Table 5).

The mean density for *E. globoidea* at age 28 was 723.3 kg/m^3 with a CV of 9% and a range from 553.7 kg/m^3 to 872.8 kg/m^3. The mean air-dry density was lower than found in Nicholas & Millen (2012) for New Zealand-grown *E. globoidea* (805 kg/m^3). This is likely due to the southern latitude in which the E. globoidea was grown (Table 2); Thomas et al. (2006) found increased growing temperature correlated to reduced lumen transverse area and increased wood density in *Eucalyptus grandis*. Mean annual temperature also affects density in P. radiata (Apiolaza, 2011; Cown et al., 1991). *Pinus radiata* was shown to have a mean density of 460.9 kg/m^3 ranging from 372.4 kg/m^3 to 548.3 kg/m^3, which is in line with the expectation for South Island grown *P. radiata* outerwood according to Cown et al. (1991). A CV of 9% is similar to those found in Apiolaza (2011) for *P. radiata*.

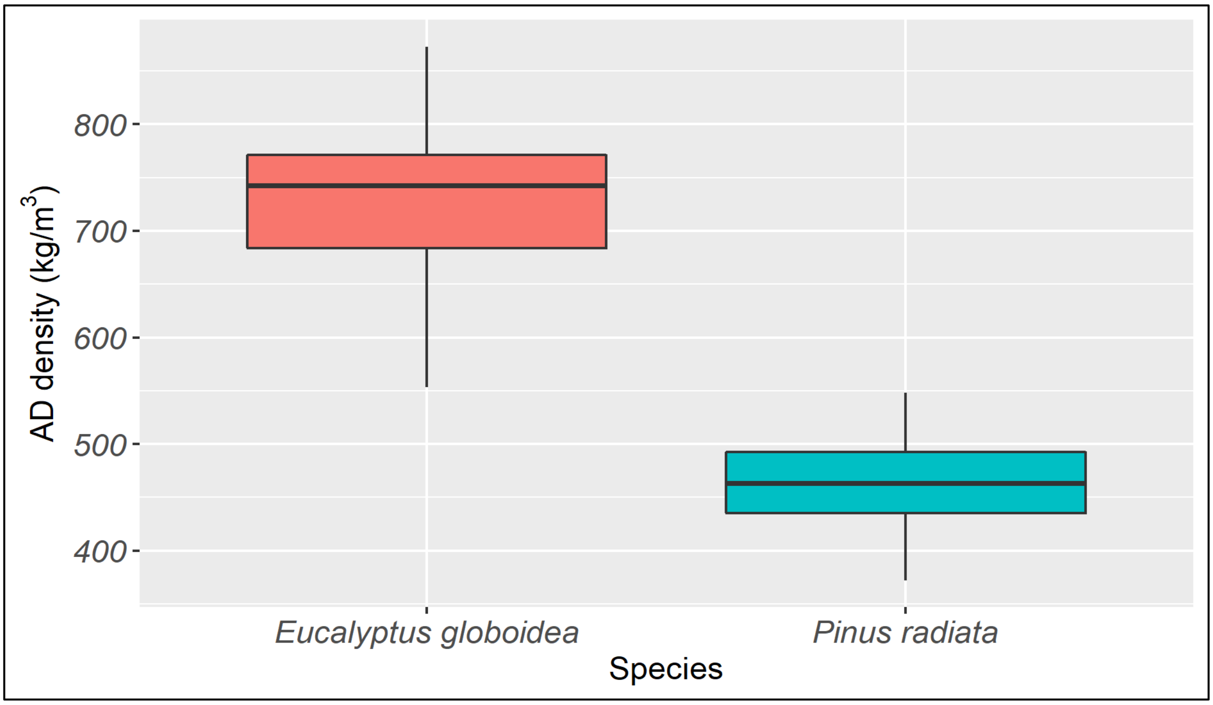

Figure 19: Boxplot of the distributions of densities by species.

The *E. globoidea* boards had a higher mean MC (13.8%) than the *P. radiata* boards (12%) (Figure 20) after conditioning at 65% relative humidity and 20°C. Equilibrium moisture contents in a given climate can differ between species (Walker, 2006). However, as the CV for MC of the *E. globoidea* boards (3%) was lower than that of the *P. radiata* boards (7%), the latter could have benefited from a longer conditioning time. The equilibration of the SG (13 mm x 105 mm) samples were tested with a subset of 6 pieces and may not have been representative of the MC conditioning of the entire sampling. While MC generally affects machinability, e.g., between saturated and air-dry conditions, the values appear to be in a reasonable range for a machinability study. The MC measurements were conducted several weeks before the machining, meaning true MC is likely less variable. Results also show that variability (CV) of visual grades was larger in *E. globoidea* than in *P. radiata* (Table 6), confirming that the observed variation in MC was irrelevant.

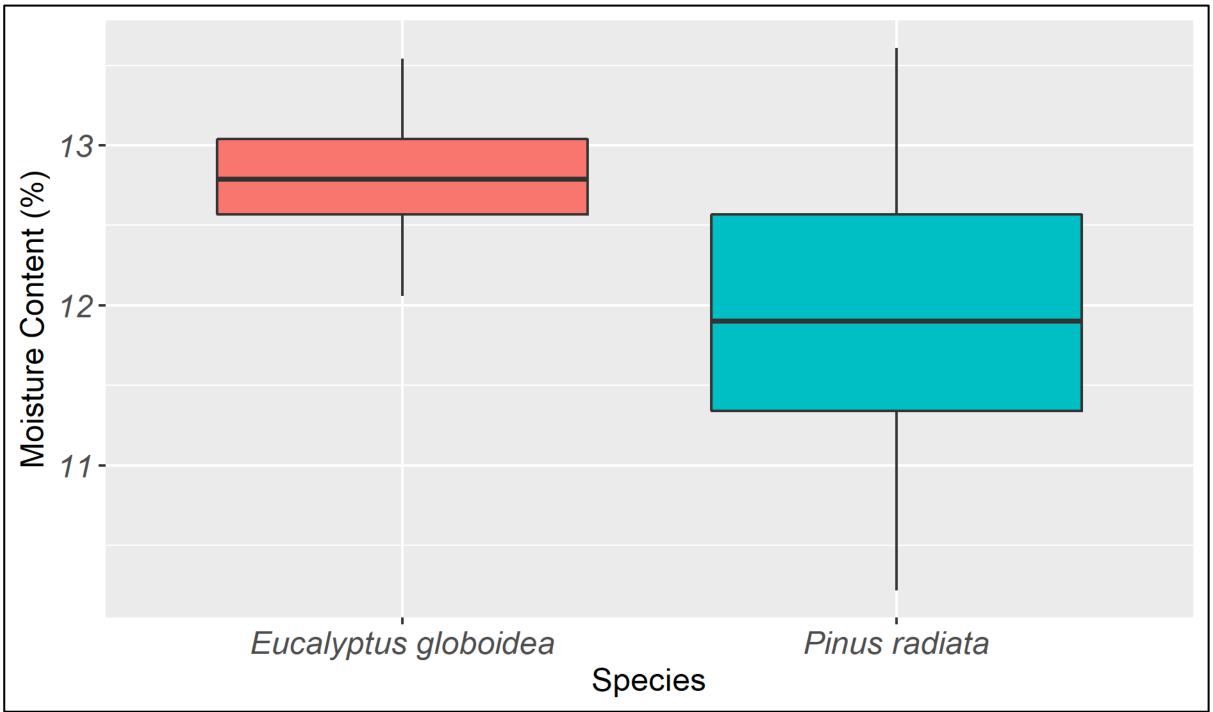

Figure 20: Boxplot of distributions of Moisture Contents by species. *Table 5* shows the summary statistics for air-dry density and MC measured within each species.

Table 5: Density and Moisture Content statistics measured in Pinus radiata and Eucalypts globoidea.

		Pinus radiata n = 49				***Eucalyptus globoidea n = 37***			
		Mean	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**
Samples	Density (kg/m3)	460.9	9%	372.4	548.3	723.3	9%	553.7	872.8
	MC (%)	12	7%	10.2	13.6	12.8	3%	12.1	13.5

Machinability

Table 6 summarised all grade assessments separated by tooling type. The means were tested to determine if there was any significant difference between the machinability of the two species. The machinability score was defined as the percentage of machined pieces deemed acceptable for high-quality uses (grades 1 and 2) and used for the overall conclusion into the machinability of the wood.

Table 6: Summary statistics for all grade assessments for each tool for E. globoidea and P. radiata as defined in the methods.

		Pinus radiata n = 49				***Eucalyptus globoidea n = 37***			
		Mean*	**CV**	**Min**	**Max**	**Mean***	**CV**	**Min**	**Max**
Planing 0.5 knife cuts/mm	T1 (%)	16.2	101%	0	80.5	7	156%	0	58.6
	T2 (%)	5	182%	0	44.6	5.2	119%	0	22.1
	TK1 (%)	0.1	290%	0	1	0.2	241%	0	3
	TK2 (%)	0.1	204%	0	1	1.7	102%	0	8.7
Planing 0.8 knife cuts/mm	T1 (%)	3.7	128%	0	25.5	1.5	151%	0	8.4
	T2 (%)	0.5	223%	0	5.2	0.8	188%	0	7
	TK1 (%)	0	206%	0	0.2	0.1	168%	0	0.6
	TK2 (%)	0.1	203%	0	0.6	1.1	92%	0	4.4
	VG	1.9	39%	1	4	1.9	46%	1	4
Boring	Entry (1)	1.3	36%	1	2	1	0%	1	1
	Hole (1)	2.9	21%	2	4	1.2	32%	1	2
	Exit (1)	4	15%	3	5	2.8	35%	2	5
	Entry (2)	1.4	40%	1	3	1	0%	1	1
	Hole (2)	2.8	22%	2	5	1.1	31%	1	2
	Exit (2)	3.7	17%	3	5	2.9	32%	2	5
	Entry (Avg)	1.4	32%	1	2.5	1	0%	1	1
	Hole (Avg)	2.9	18%	2	4	1.1	31%	1	2
	Exit (Avg)	3.9	12%	3	4.5	2.9	25%	2	4.5
	Max.	4.2	15%	3	5	3.3	32%	2	5
Groove Shaping	Side	2.6	20%	1	3	1.4	40%	1	3
	Corner	2.6	19%	2	3	1.5	35%	1	2
	End	3	18%	2	4	2	8%	2	3
	Exit	3	23%	2	5	2.9	24%	1	4
	Max	3.3	16%	3	5	3	21%	2	4
Edge Shaping	Side	2.1	25%	1	3	1.2	59%	1	5
	Corner	2.6	34%	1	5	2.9	42%	1	5
	End	2.9	8%	2	3	2.1	27%	2	5
	Max.	3.1	17%	2	5	3.1	38%	2	5
Mortising	Entry (1)	2.8	30%	1	5	1.9	22%	1	4
	Side (1)	2.7	19%	2	4	2.2	19%	2	4
	End (1)	3.5	21%	2	5	2.1	21%	1	4
	Exit (1)	3.6	26%	2	5	2.7	32%	2	3
	Entry (2)	3.3	30%	2	5	2.4	23%	1	5
	Side (2)	2.9	18%	2	4	2.5	23%	2	0

	End (2)	4.4	12%	3	5	2.4	18%	0	0
	Exit (2)	4.7	12%	3	5	3.4	0%	0	0
	Entry (Avg)	3	26%	2	5	2.2	26%	1	3.5
	Side (Avg)	2.8	15%	2	3.5	2.4	18%	2	3.5
	End (Avg)	4	13%	3	5	2.2	17%	1.5	3
	Exit (Avg)	4.1	13%	3	5	3.1	14%	2.5	4.5
	Max.	4.8	8%	4	5	3.6	16%	3	5

*1 – good to 5 – bad, except planing T-grades where grade = %area defective

Table 7 shows the summary statistics for the overall grades assigned to the samples by machine tool (maximum). Of note is that the CVs for all *E. globoidea* machine tool grades were higher than *P. radiata* CVs. This confirms that the variability in MC between species is irrelevant.

Table 7: Summary statistics for all maximum machinability grade measurements for E. globoidea and P. radiata.

		Eucalyptus globoidea				***Pinus radiata***					
		Mean Grade*	**CV**	**Min.**	**Max.**	**Mean Grade***	**CV**	**Min.**	**Max.**	**Significant Difference?**	**P-Value**
Planing	T2	0.8%	188%	0%	7%	0.5%	223%	0%	5.2%	No	0.2312
	VG	1.9	46%	1	4	1.9	39%	1	4	No	0.2295
Shaping	Groove Max.	3	21%	2	4	3.3	16%	3	5	Yes	0.0035
	Edge Max.	3.1	38%	2	5	3.1	17%	2	5	No	0.8169
Boring	Max.	3.3	32%	2	5	4.2	15%	3	5	Yes	6.1e-06
Mortising	Max.	3.6	16%	3	5	4.8	8%	4	5	Yes	<2e-16

*1 – good to 5 – bad, except planing T-grades where grade = %area defective

Planing

The CVs for the visual planing grade according to ASTM D1666-17 for *P. radiata* and *E. globoidea* were 39% and 46%, respectively (Table 6). Results from the experimental scanning method were more variable, with all CVs over 100%. Therefore, visual grading was more consistent.

Visual grading method

Both wood species had a mean visual grade of 1.9 (High quality, Table 3) with a range of grade 1 to grade 4 (Figure 21). A t-test assuming unequal variance showed no significant difference between the means of the visual grades assigned to *E. globoidea* and *P. radiata* (Table 7). Consequently, the machinability of *E. globoidea* when planing at 0.8 knife cuts/mm was the same as for *P. radiata*. As the good planing characteristics (1.9) were in line with the literature for *P. radiata* (Forest Research Institute, 1988; Young, 1988), it can be stated that *E. globoidea* produces high-quality planing finishes.

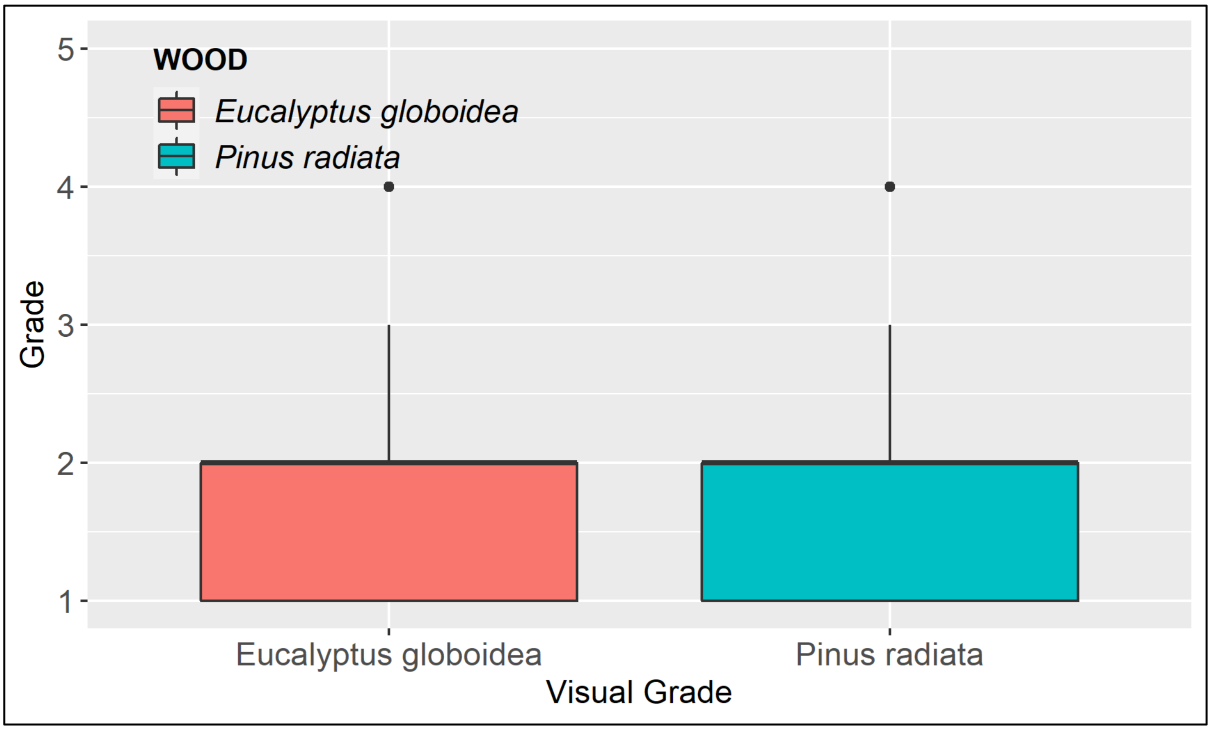

Figure 21: Boxplots of wood species' visual planing grades (1 – good to 5 – bad).

Scanning method

The T1 defects were restricted to 0.2 mm depth and can be assumed to be removed by sanding. Further, ASTM D1666-17 specifies clears grade wood, warranting the exclusion of defects around knots. Therefore, the most relevant scanning measure concerning ASTM D1666-17 was T2 assessing defects deeper than 0.2 mm in clear wood.

A t-test assuming unequal variance showed no significant difference between the T2 (%) means for either *E. globoidea* or *P. radiata*. Visual grading confirmed that the two species' planing characteristics at 0.8 knife cuts/mm were identical.

T2 (%) was correlated to the visual grade in the 0.8 knife cuts/mm planing run (Figure 22). The r^2 values for *P. radiata* and *E. globoidea* were 0.334 and 0.258, respectively. These were significant. A contributing factor for the weak correlation is that according to ASTM D1666-17, the visual grading requires the assessor to factor in severity and frequency, while T2% is independent of the severity. This means that higher (worse) visual grades were assigned to boards with frequent and severe T2 than to boards with frequent and less severe T2.

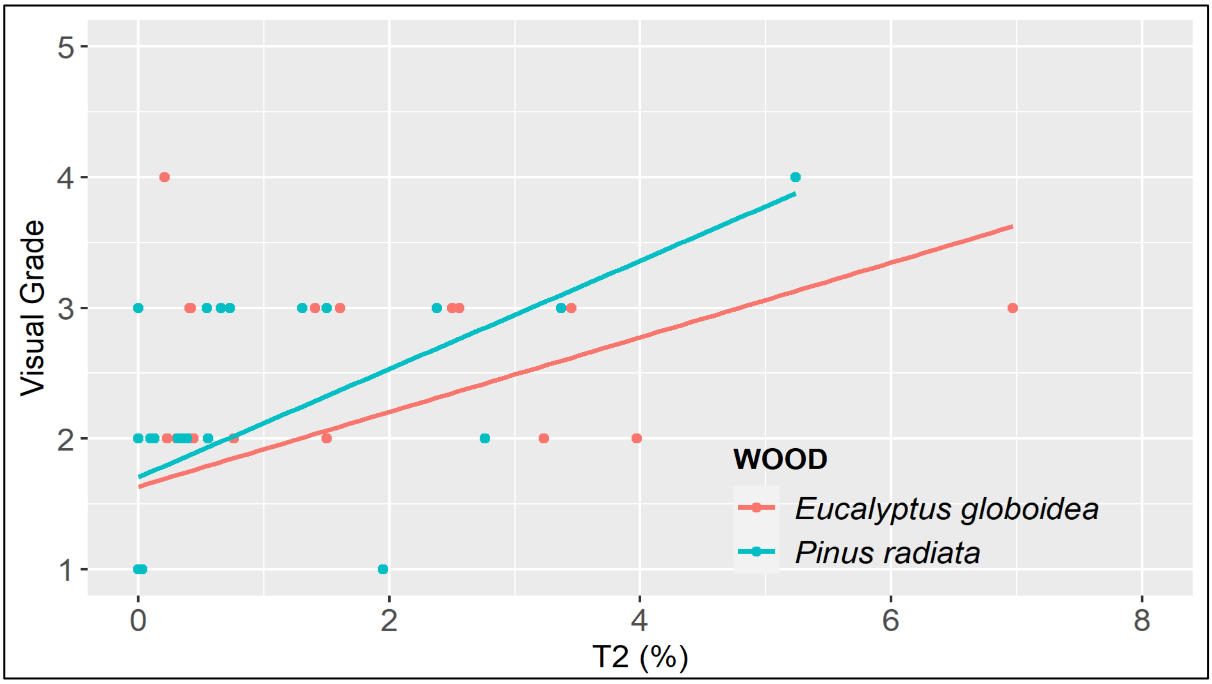

Figure 22: Linear regression between T2 visual grade (1 – good to 5 – bad) for planing at 0.8 knife cuts/mm for E. globoidea and P. radiata.

Boring

The bore holes' entry, hole, and exit were graded separately (Table 6). The observed means were lower (better) for all measures in *E. globoidea* than in *P. radiata*. Grades for the three measurement points were significantly different between both species (P<0.05). However, the overall grade for a board is that of the worst defect, termed the maximum boring grade.

A t-test assuming unequal variances showed a significant difference between the means for the maximum sample hole grades between *E. globoidea* and *P. radiata* (Table 7). As the mean grade was lower in *E. globoidea*, higher quality finishes were obtained when boring holes into *E. globoidea* than in *P. radiata* (Figure 23). A mean tool grade of 3.3 in *E. globoidea* can be considered low quality for boring (Table 3).

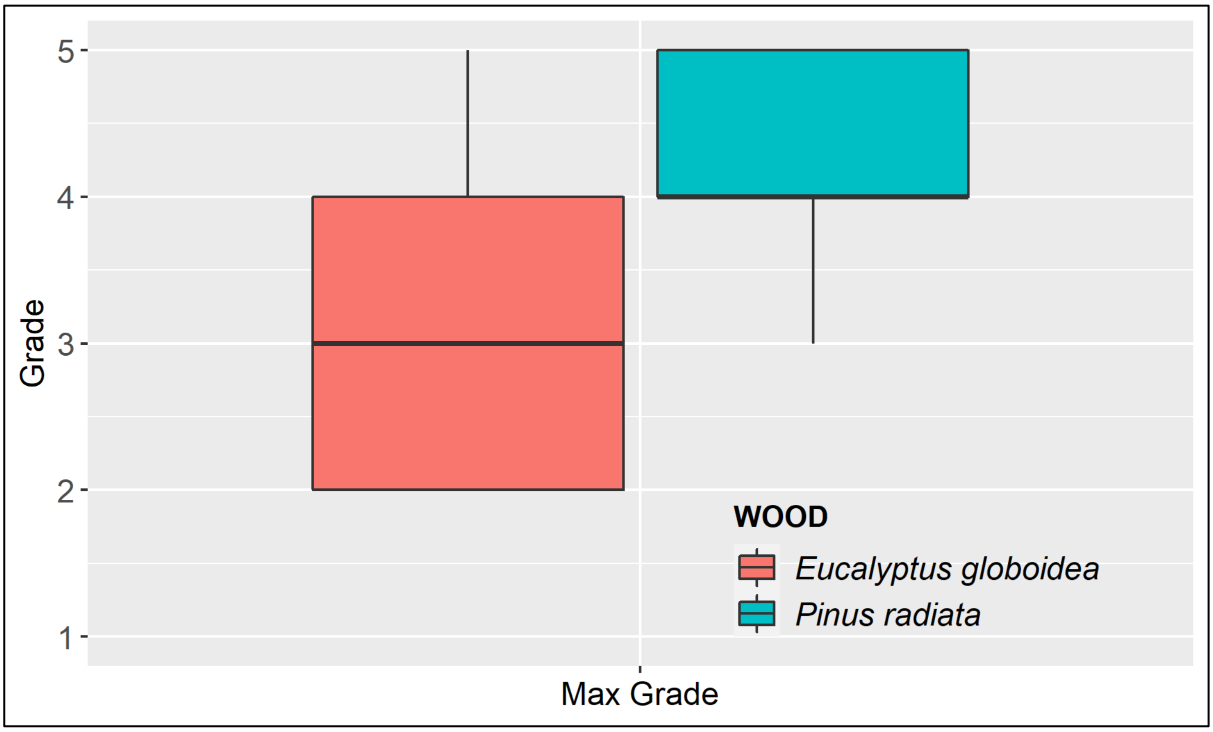

Figure 23: Boxplots of maximum boring grade (1 – good to 5 – bad) by sample for E. globoidea and P. radiata.

1.1.1. Shaping

Two types of shaping, edging and grooving, were tested. Each shaping type was assessed at different points (entry, side, corner, exit, end) (Table 6). Grades differed significantly between all assessed points except the edge corner and the groove exit (P<0.05). The observed mean grades of *E. globoidea* were lower (better) in all graded shaping data points except the edge corner and the groove exit than for *P. radiata*, which were found to be the same. Further, variation (CV) was larger for *E. globoidea* than for *P. radiata* (Table 6). The visual grade assigned to the board was the worst defect in any of the assessed points, i.e., the max grade for edge and groove, respectively.

A t-test assuming unequal variance showed a significant difference between the means of each species for groove shaping but no significant difference for edge shaping (Table 7). The observed mean for *E. globoidea* was lower in groove shaping. Therefore, groove shaping of *E. globoidea* produced better quality finishes than groove shaping *P. radiata* (Figure 24). However, the mean max grades of *E. globoidea and P. radiata* were 3 and 3.3, respectively. This indicated that the quality of groove shaping is low for both species (Table 3).

While the mean grade for edge shaping for both species was 3.1, it was more variable in *E. globoidea* (CV 38%) compared to *P. radiata* (CV 17%) (Table 6, Figure 25).

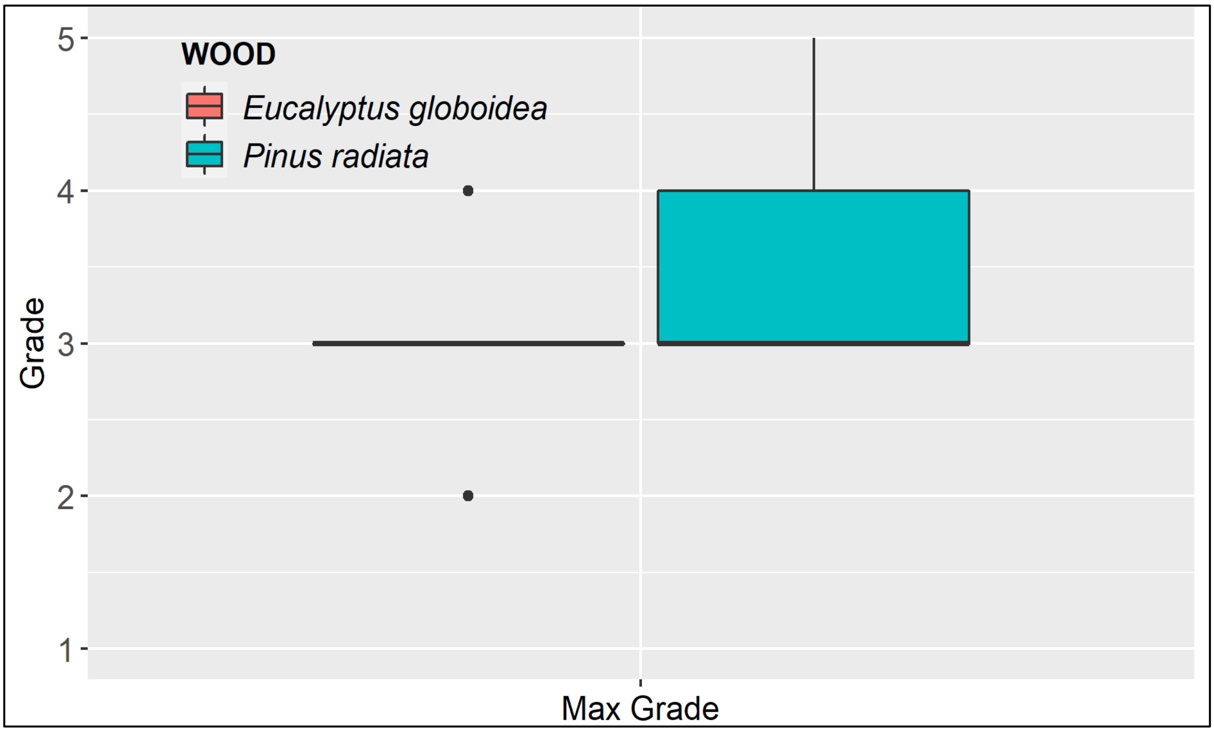

Figure 24: Boxplots of maximum groove shaping grade (1 – good to 5 – bad) for E. globoidea and P. radiata.

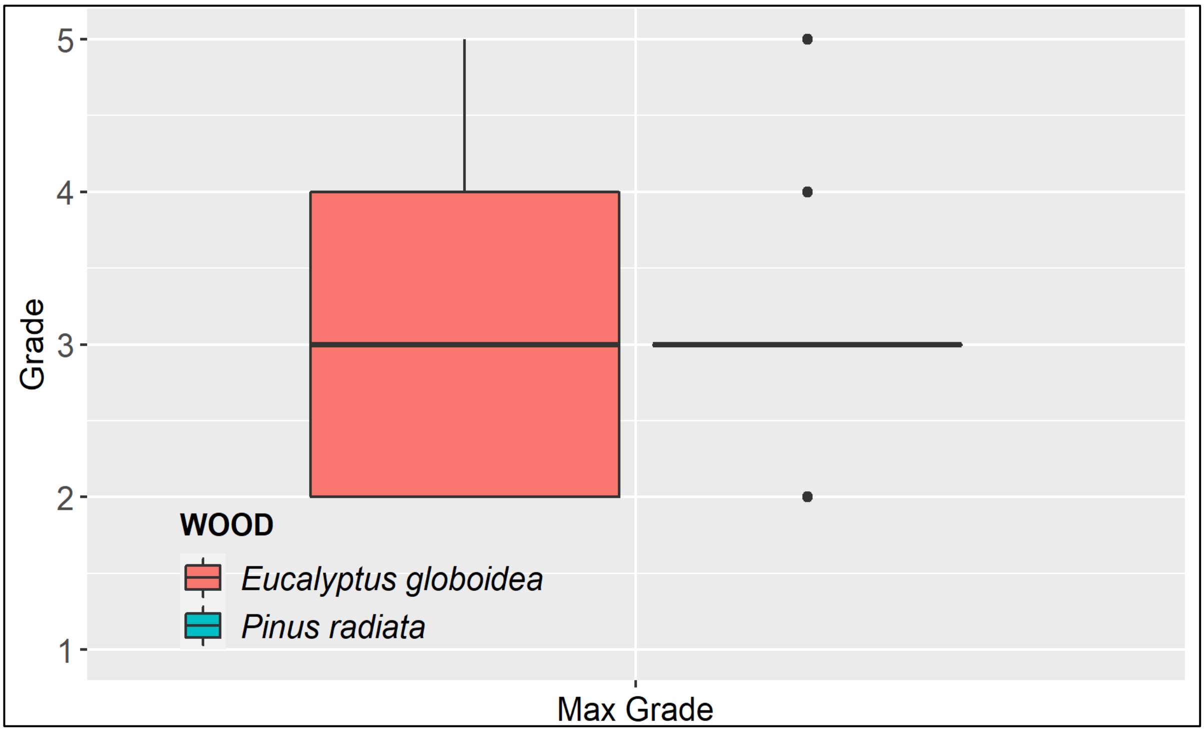

Figure 25: Boxplots of maximum edge shaping grade (1 – good to 5 – bad) for E. globoidea and P. radiata.

Mortising

Mortising defects were assessed for entry, side grain, end grain and exit. Observed means for all graded mortising data points were lower (better) for *E. globoidea* than for *P. radiata* with similar CVs (Table 6). Grades for the four measurement points differed significantly between both species ($P<0.05$). The worst defect determined the overall mortising grade for a board (max).

A t-test assuming unequal variance showed a significant difference between the two species' means for the mortising max grade (Table 7). The observed mean for *E. globoidea* was lower. Consequently, *E. globoidea* produces better quality finishes than *P. radiata* in mortising (Figure 26). However, a mean tool grade of 3.6 for *E. globoidea* can be considered low/very-low quality for mortising. A mean tool grade of 4.8 for *P. radiata* can be considered very low-not acceptable for mortising (Table 3).

Figure 26: Boxplot of maximum mortise grade (1 – good to 5 – bad) for E. globoidea and P. radiata

Machinability Scores

The machinability scores for *E. globoidea* and *P. radiata* for each tool are shown in Table 8 and Table 9. For both species, *E. globoidea* and *P. radiata*, planing resulted in the highest proportion of acceptable finishes. Belleville et al. (2016) found similar results with Eucalypts in planing conditions similar to those tested in this study. A t-test showed no significant difference between the planing machine grade means for the two species; the machinability scores can be assumed to be the same for planing between species. Machinability scores were better for *E. globoidea* than *P. radiata* with all other tools. This indicated that a woodworking business set up for radiata pine does not need new or modified planing, shaping, boring, or mortising equipment to get satisfactory or even better results when working with *E. globoidea*.

The machinability scores for *P. radiata* were low for shaping, boring, and mortising compared to the literature (Forest Research Institute, 1988; Young, 1988), where *P. radiata* is generally described as having good machinability characteristics. Therefore, the grading was likely too harsh. Turkish hardwoods have excellent planing properties, good shaping properties, and lower-quality boring and mortising qualities (Malkoçoğlu & Özdemir, 2006). As the grading was done consistently for both species, the conclusion that *E. globoidea* machined better than *P. radiata* is still valid.

Table 8: Machinability score for E. globoidea according to the standard ASTM D1666-17.

Eucalyptus globoidea					
Tool		**Grade 1**	**Grade 2**	**Grade 3 (Mortise)**	**Machine Score**
Planing	Visual Grade	15	13	NA	76%
Shaping	Groove Max.	0	8	NA	22%
	Edge Max.	0	16	NA	43%
Boring	Max.	0	10	NA	27%
Mortising	Max.	0	0	17	46%

Table 9: Machinability score for P. radiata according to the standard ASTM D1666-17.

Pinus radiata					
Tool		**Grade 1**	**Grade 2**	**Grade 3 (Mortise)**	**Machine Score**
Planing	Visual Grade	16	25	NA	84%
Shaping	Groove Max.	0	1	NA	2%
	Edge Max.	0	2	NA	4%
Boring	Max.	0	1	NA	2%
Mortising	Max.	0	1	0	2%

Critical Tooling Parameters

The detailed grading methodology, separating defects for different points on machined surfaces, allowed the identification of critical machining parameters. These control the machinability and guide further developments to improve machine design. Machinability scores for *E. globoidea* at each data point (Table 10) identified the problematic areas to be:

- Edge shaping – Corner (Figure 27)
- Groove shaping – Exit
- Boring – Exit
- Mortising – Exit

Table 10: Machinability scores per the standard ASTM D1666-17 for individual points for E. globoidea.

Eucalyptus globoidea		***Machine Score***
Edge Shaping	Side	97%
	Corner	46%
	End	95%

Groove Shaping	Side	97%
	Corner	100%
	End	97%
	Exit	22%
Boring	Entry	100%
	Hole	100%
	Exit	46%
Mortising	Entry	86%
	Side	99%
	End	100%
	Exit	76%

Figure 27: Example of typical defect on E. globoidea edge corner shaping.

Effect of Density

Within species, air-dry density variations showed no correlation to machine grades, except for planing in *E. globoidea* (Table 11). The significant but weak ($r^2 = 0.111$) was negative (Figure 28), suggesting that reducing density will improve the overall machinability of *E. globoidea* without compromising the results for other tested tools.

Table 11: Correlations between air-dry density and machining grade for E. globoidea and P. radiata.

		Eucalyptus globoidea	***Pinus radiata***
Planing	%T2	Not Significant	Not Significant
	Visual Grade	$r^2 = 0.111$	Not Significant
Shaping	Groove	Not Significant	Not Significant
	Edge	Not Significant	Not Significant
Boring	Max.	Not Significant	Not Significant
Mortising	Max.	Not Significant	Not Significant

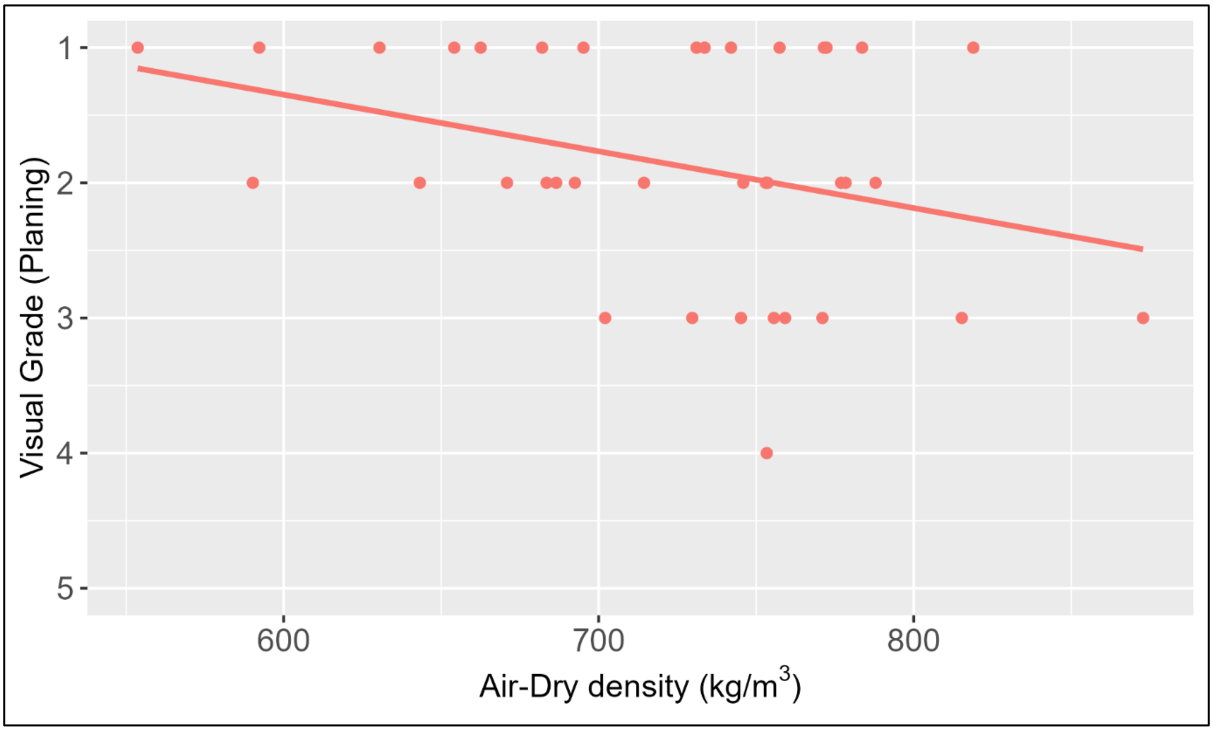

Figure 28: Relationship between air-dry density and planing visual grade for E. globoidea.

Conclusion

The air-dry density of the tested samples was at the lower end of the scale for *E. globoidea*. Machinability was not significantly correlated to density, except for planing, which was inversely proportional ($r^2 = 0.111$). This suggested that if machinability improvement was a goal for the NZDFI, selecting families and silvicultural regimes which produce lower-density wood might improve overall machinability for *E. globoidea*.

Machinability was constrained in each machine tool parameter by one data point. Improvements to the machinability score can be made by changes in the machining process or engineering tools to prevent these specific defects. It could be possible to remove the defining defects on the exit points for groove shaping, boring, and mortising by machining from two directions. This would effectively create two entry points, shown to have a better surface finish.

For edge shaping, chipping of the corner, as shown in Figure 27, is the limiting factor. This was a similar result found in Kotlarewski et al. (2019) for the *Eucalyptus globulus*, where they specified end-grain shaping as a problem area prone to chipping. Edge shaping was performed on the left-hand side of the samples with the cutting head spinning clockwise. It is possible that corner chipping could be mitigated by edge shaping from both directions or adapting the cutting direction to the spinning direction of the tool. Another means to control this defect would be to optimise the CNC spindle speed according to the shape of the corner. Tool engineers should focus their research on designing tools that prevent defects on the corners of edge-shaped *E. globoidea*.

Solving the critical machining points, the machinability scores would be improved from 22%-46% to 84%-100% (Table 12). For instance, this can be done by a careful operator in a home workshop, meaning *E. globoidea* is highly suited to appearance-grade uses such as carpentry and furniture making. These results were mirrored in the more detailed visual grades for the tools, as can be seen by comparing the adjusted (Appendix A) with observed visual grades (Table 7).

Table 12: Machinability score for E. globoidea for improved tools, i.e., adjusted by removing the critical defect point.

Tool		Grade 1	Grade 2	Grade 3 (Mortise)	Machine Score	Adjusted Machine Score
Planing	Visual Grade	15	13	NA	76%	76%
Shaping	Groove Cut	0	35	NA	22%	95%
	Edge Cut	0	35	NA	43%	95%
Boring	Max.	31	6	NA	27%	100%
Mortising	Max.	0	9	22	46%	84%

Due to class 2 durability and good machinability, *E. globoidea* is a suitable replacement for CCA-treated *P. radiata* where machining is also required. This could be in the use of children's playgrounds or playhouses or non-structural outdoor members. Also, due to high stiffness, structural indoor and outdoor members are suitable for E. globoidea, such as farm buildings.

The more laborious but quantitative scanning method did not improve the assessment of planing defects over quicker, semi-quantitative visual grading. The variation (CV) was significantly higher in the scanning technique. The correlation between the two assessments was low, with roughly 30% of the variation in visual grades explained by the presence of the defects assessed. This could have been remedied by an additional category for more severe torn grain that may have improved the correlation in the model, i.e., T3 etc.

References

Apiolaza, L. A. (2011, September). Basic density of radiata pine in New Zealand: Genetic and environmental factors. *Tree Genetics and Genomes, 8*, 87–96. https://doi.org/10.1007/s11295-011-0423-1

ASTM. (2017). *D1666-17: Standard Test Methods for Conducting Machining Tests of Wood and Wood-Base Panel Materials*. ASTM International.

Belleville, B., Ashley, P., & Ozarska, B. (2016). Wood planing properties of Australian plantation-grown Eucalypts. *Ciencia Y Tecnología*, *18*(3), 425–434. https://doi.org/10.4067/S0718-221X2016005000038

Bier, H. (1986). Log Quality and the Strength and Stiffness of Structural Timber. *NZ Journal of Forestry, 16*(2), 176–186. https://www.scionresearch.com/__data/assets/pdf_file/0015/30660/NZJFS1621986BIER176_186.pdf

Boland, D. J., Kleinig, D. A., Johnston, R. D., Hyland, B., Hall, N., Chippendale, G. M., Brooker, M., & Turner, J. D. (2006). *Forest Trees of Australia* (5th ed.). CSIRO Publishing.

Cown, D. J. (1999). *New Zealand Pine and Douglas-fir* (2nd ed.). New Zealand Forest Research Institute.

Cown, D. J., McConchie, D. L., & Young, G. D. (1991). *Radiata Pine Wood Properties Survey*. Ministry of Forestry. Retrieved 1 October 2022, from https://scion.contentdm.oclc.org/digital/collection/p20044coll6/id/100/

Forest Research Institute. (1988). New Zealand Radiata Pine: A technical appraisal of produce, processes, and uses. In *Scion*. Ministry of Forestry. Retrieved 4 October 2022, from https://scion.contentdm.oclc.org/digital/collection/p20044coll6/id/160/

Gress, J., de Oliveira, L., da Silva, E., Lessl, J., Wilson, P., Townsend, T., & Ma, L. (2015). Cleaning-induced arsenic mobilization and chromium oxidation from CCA-wood deck:

Potential risk to children. *Environment International*, *82*, 35–40. https://doi.org/10.1016/j.envint.2015.04.012

Guo, F., & Altaner, C. M. (2018, January 31). Properties of rotary peeled veneer and laminated veneer lumber (LVL) from New Zealand grown Eucalyptus globoidea. *New Zealand Journal of Forestry Science*, *48*(1). https://doi.org/10.1186/s40490-018-0109-7

Hall, N. L., & Beder, S. (2005, February). *Lansbury, N. and S. Beder (2005). Treated Timber, Toxic Time-bomb: The Need for a Precautionary Approach to the Use of Copper Chrome Arsenate (CCA) as a Timber Preservative*. University of Wollongong. Retrieved 1 October 2022, from https://ro.uow.edu.au/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1045&context=artspapers

Hall, P. (2020). *Assessment of afforestation and future wood processing opportunity with non-radiata species - Wairoa District*. Scion. Retrieved 1 October 2022, from https://www.mpi.govt.nz/dmsdocument/52972/direct

Haslett, A. N. (1990). *Properties and Utilisation of Exotic Speciality Timbers Grown in New Zealand. Part VI: Eastern Blue Gums and Stringy Barks. Eucalyptus botryoides Sm. Eucalyptus saligna Sm. Eucalyptus globoidea Blakey. Eucalyptus muellerana Howitt. Eucalyptus pilularis Sm.* FRI Bulletin. https://www.cabdirect.org/cabdirect/abstract/19910648357

Jambeck, J. R., Townsend, T. G., & Solo-Gabriele, H. M. (2008). Landfill Disposal of CCA-Treated Wood with Construction and Demolition (C&D) Debris: Arsenic, Chromium, and Copper Concentrations in Leachate. *Environmental Science &Amp; Technology*, *42*(15), 5740–5745. https://doi.org/10.1021/es800364n

Khan, B. I., Jambeck, J., Solo-Gabriele, H. M., Townsend, T. G., & Cai, Y. (2005). Release of Arsenic to the Environment from CCA-Treated Wood. 2. Leaching and Speciation during

Disposal. *Environmental Science &Amp; Technology*, *40*(3), 994–999. https://doi.org/10.1021/es051471u

Kotlarewski, N. J., Derikvand, M., Lee, M., & Whiteroad, I. (2019). Machinability Study of Australia's Dominate Plantation Timber Resources. *Forests*, *10*(9), 805. https://doi.org/10.3390/f10090805

Malkoçoğlu, A., & Özdemir, T. (2006). The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea Region of Turkey. *Journal of Materials Processing Technology*, *173*, 315–320. https://doi.org/10.1016/j.jmatprotec.2005.09.031

Microsoft Corporation. (2019). *Microsoft Excel* (16.0.10359.20023) [Software]. https://office.microsoft.com/excel

Millen, P., van Ballekom, S., Altaner, C., Apiolaza, L., Mason, E., McConnochie, R., Morgenroth, J., & Murray, T. (2018, May). Durable eucalypt forests – a multi-regional opportunity for investment in New Zealand drylands. *NZ Journal of Forestry*, *63*(1), 11–23. https://ir.canterbury.ac.nz/bitstream/handle/10092/15669/published_copy.pdf?sequence=3&isAllowed=y

Nicholas, I., & Millen, P. (2012). *Durable Eucalypt Leaflet Series: Eucalyptus globoidea*. NZDFI. https://nzdfi.org.nz/wp-content/uploads/2014/08/Leaflet3E.globoideaDec2012.pdf

NZDFI. (n.d.). *NZDFI Project History*. Retrieved 6 September 2022, from https://nzdfi.org.nz/about-nzdfi/project-history/

Öhman, M., Grubîi, V., Sandberg, D., & Ekevad, M. (2016). Moistening of the wood surface before planing for improved surface quality. *Wood Material Science &Amp; Engineering*, *11*(3), 156–163. https://doi.org/10.1080/17480272.2016.1166395

Page, D., & Singh, T. (2014). Durability of New Zealand Grown Timbers. *NZ Journal of Forestry*, *58*(4), 26–30. https://nzdfi.org.nz/wp-content/uploads/2016/12/Page-and-Singh-Feb-2014-Durability-of-NZ-timbers.pdf

RStudio Team. (2021). *RStudio: Integrated Development Environment for R* (1.4.1106) [Software]. RStudio, PBC. http://www.rstudio.com/

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Standards New Zealand. (2011). *NZS 3604*.

Te Uru Rākau. (2020). *Economic Impact of Forestry in New Zealand*. PWC. https://forest360.nz/wp-content/uploads/2021/04/Economic-Impact-of-Forestry-in-New-Zealand-report.pdf

Thomas, D. S., Montagu, K. D., & Conroy, J. P. (2006). Temperature effects on wood anatomy, wood density, photosynthesis and biomass partitioning of Eucalyptus grandis seedlings. *Tree Physiology*, *27*, 251–260. https://academic.oup.com/treephys/article/27/2/251/1664626

Townsend, T., Sologabrielle, H., Tolaymat, T., & Stook, K. (2003). Impact of chromated copper arsenate (CCA) in wood mulch. *The Science of the Total Environment*, *309*(1–3), 173–185. https://doi.org/10.1016/s0048-9697(03)00047-0

USDA. (1965). *Raised, Loosened, Torn, Chipped, and Fuzzy Grain in Lumber*. Forest Products Laboratory. https://agris.fao.org/agris-search/search.do?recordID=US201300012122

Vikram, V., Cherry, M. L., Briggs, D., Cress, D. W., Evans, R., & Howe, G. T. (2011, June). Stiffness of Douglas-fir lumber: effects of wood properties and genetics. *Canadian Journal of Forest Research*, *41*(6), 1160–1173. https://doi.org/10.1139/x11-039

Walker, J. C. F. (2006). *Primary Wood Processing: Principles and Practice* (2nd ed.). Springer.

Wang, X., Ross, R. J., Mattson, J. A., Erickson, J. R., Forsman, J. W., Geske, E. A., & Wehr, M. A. (2001, May). Several Non-Destructive Evaluation Techniques for Assessing Stiffness and MOE of Small-Diameter Logs. In *ResearchGate*. USDA-Forest Products laboratory. Retrieved 7 October 2022, from https://www.researchgate.net/profile/Xiping-Wang-6/publication/242128966_Several_Nondestructive_Evaluation_Techniques_for_Assessing_Stiffness_and_MOE_of_Small_Diameter_Logs/links/549aef960cf2b80371371692/Several-

Nondestructive-Evaluation-Techniques-for-Assessing-Stiffness-and-MOE-of-Small-Diameter-Logs.pdf

Young, G. D. (1988). Machining Properties: How Does Radiata Pine Shape Up? In *Tenon*. Holmes Printing. Retrieved 5 October 2022, from https://tenonclearwood.com/media/3483/comparative_properties_-_what_s_new.pdf

Appendix A

Summary statistics for all machinability tool grades point for E. globoidea and P. radiata adjusted by removing the critical defect.

		Eucalyptus globoidea				*Pinus radiata*					
		Mean Grade	**CV**	**Min.**	**Max.**	**Mean Grade**	**CV**	**Min.**	**Max.**	**Significant Difference?**	**P-Value**
Planing	%T2	0.8%	188%	0%	7%	0.5%	223%	0%	5.2%	No	0.2312
	VG	1.9	46%	1	4	1.9	39%	1	4	No	0.2295
Shaping	Groove Cut	2.1	11%	2	3	3.1	14%	2	4	Yes	<2e-16
	Edge Cut	2.1	27%	2	3	2.9	8%	2	3	Yes	4.4e-13
Boring	Max.	1.2	32%	1	2	3.1	23%	2	5	Yes	<2e-16
Mortising	Max.	2.9	22%	4	5	4.4	11%	4	5	Yes	<2e-16