# Machinability Study of Australia's Dominate Plantation Timber Resources

**Nathan J. Kotlarewski [1],*** , **Mohammad Derikvand [1,2]** , **Michael Lee [3] and Ian Whiteroad [4]**

[1] Australian Research Council Centre for Forest Value, University of Tasmania, Launceston TAS 7250, Australia; Mohammad.Derikvand@utas.edu.au

[2] Department of Civil Engineering, Aalto University, 02150 Espoo, Finland

[3] Centre for Sustainable Architecture with Wood, University of Tasmania, Launceston 7250, Australia; M.W.Lee@utas.edu.au

[4] ARTEC Australia Pty Ltd., Launceston 7250, Australia; Ian.Whiteroad@artec.net.au

* Correspondence: Nathan.Kotlarewski@utas.edu.au; Tel.: +61-3-6324-4473

**Abstract:** This study tested the machinability of three major timber species grown in Tasmania, Australia, under different resource management schemes: plantation fiber-managed hardwood (*Eucalyptus globulus* Labill. and *Eucalyptus nitens* Maiden) and plantation sawlog-managed softwood (*Pinus radiata* D. Don). *P. radiata* was used as a control to identify significant differences in machining fibre-managed plantation timber against sawlog-managed plantation timber with numerically controlled computer technology and manually fed timber production techniques. The potential to fabricate architectural interior products such as moldings with plantation fiber-managed hardwood timber that is high in natural features was the focus of this study. Correlations between wood species, variation in moisture content, and density of individual machinability characteristics were analyzed to determine factors impacting the overall quality of plantation wood machinability. Correlations between species and within species groups from the resulting machinability tests are highlighted and discussed. The results indicate that the machinability of sawlog-managed softwood *P. radiata* is superior in some circumstances to fiber-managed hardwood *E. globulus* and *E. nitens* specimens, according to the American Society for Testing and Materials D1666-11.

**Keywords:** machinability; Eucalyptus; plantation timber; fiber-managed hardwoods

## 1. Introduction

Australia has close to one million hectares of plantation hardwood eucalypt species managed for pulplog production. The two major hardwood species grown under this management scheme are *Eucalyptus globulus* Labill., of which 52.7% is predominately grown in Western Australia and the Green Triangle region, followed by *Eucalyptus nitens* Maiden, of which 25.2% is predominately grown in Tasmania (a smaller proportion of the Tasmanian plantation estate for both species is also managed for sawlogs). In addition, there are over one million hectares of planation softwood species managed for sawlog production throughout Australia. *Pinus radiata* D. Don accounts for 74.5% of this estate, which is grown predominately in the Green Triangle region and the Murray Valley (Tasmania also has an established estate of this resource [1]).

In this study, different machinability characteristics of the three major plantation timber species in Australia (*E. globulus*, *E. nitens*, and *P. radiata*) have been evaluated and statistically compared to determine new applications for hardwood plantation resources in machine-manufactured products. With the current supply of planation hardwoods in Australia en masse, and a rise in demand for timber products in the built environment driven by state wood encouragement policies, there is

an opportunity to utilize hardwood pulplogs to produce value-added architectural products with advanced manufacturing technologies such as computer numerically controlled (CNC) machinery. The key driver for this research is refocusing hardwood plantation resources into higher-value sawn board applications for furniture and architectural products. To design and manufacture such products, the suitability of processing pulplog with CNC or manually operator-controlled technologies is needed to determine: (i) the machinability of timber derived from pulplogs according to the American Society for Testing and Materials (ASTM) D1666-11 (Standard Test Methods for Conducting Machining Tests on Wood and Wood-Based Materials, 2011) [2] and (ii) the timber properties that most affect the quality of finish for each species.

Utilizing low-quality and low-value plantation logs has been a global topic for a long time [3]. In recent times, *Eucalypts* have attracted much attention for improving the genetics for solidwood production [4] and utilization in value-added materials and product research [5], particularly mass-timber product development such as nail-laminated beams [6] and cross-laminated timber paneling [7]. Traditional wood products (board and veneer), engineered wood products (glulam) and wood-based panels (particleboard and medium-density fiberboard) have revolutionized the way wood is used in the built environment. Wood used in an appearance application relies on a high-quality surface finish to accommodate its final use [8], as well as the application of paints or lamella overlays. The literature consists of various machinability studies that investigate the quality of wood product surface finishes. Not surprisingly, a vast majority of the literature focus on homogeneous wood products such as medium density fiberboard and chipboards due to controllable conditions and less-variable moisture content (MC) and densities [9–11]. Considering these factors, it is of interest to determine the machinability properties of highly variable processed plantation solidwood. How wood specimens are assessed is also a widely presented topic in the literature [12]. Visual assessment has been the standardized procedure for some time now, and new technologies are increasingly being employed to validate quality and compare results [13]. Some researchers go beyond the parameters of ASTM D1666-11, adapting and capturing more data than specified such as the temperature of test specimen after sanding [14] to validate or conclude their findings. Other researchers focus entirely on specific machinability tests such as drilling [15] to advance knowledge. There has also been research conducted in the literature to determine the effects of wood modifications such as thermal treatments on wood machinability [16].

Key variables with any wood machining are cutting speed, feed direction, depth of cut, cutting tool (type and its sharpness) and quality of treatments applied to wood specimens (such as heat or chemical treatment). In addition, the literature states that anatomical characteristics such as species, MC, grain direction, sapwood/hardwood, and density affect the quality of surface machinability [17–19]. New manufacturing knowledge is needed to determine appropriate techniques and commercial processors for the incorporation and potential use of pulplog resources in high-value architectural products, as well as applications to encourage their use in current markets to fulfil demand.

## 2. Materials and Methods

### 2.1. Plantation Timber

The studied timber species included *E. nitens* and *E. globulus* obtained from unthinned and unpruned fiber-managed hardwood plantation resources (from Nook and Trowutta, Tasmania, respectively) for pulplog production in northern Tasmania. These two hardwood pulplog timber species were compared to softwood sawn-board timber obtained from a plantation *P. radiata* resource in Tasmania, Australia. A summary of the three species management schemes, ages and densities is given in Table 1.

**Table 1.** Species sample data.

| Specie | Management Scheme | Age (years) | Average Small End Diameter (mm) | Sample Density Range (kg/m$^3$) | Number of Specimens |
|---|---|---|---|---|---|
| *E. nitens* Maiden | Pulplog | 16 | 345 | 395–741 (523 *) | 54 |
| *E. globulus* Labill. | Pulplog | 26 | 403 | 409–763 (544 *) | 54 |
| *P. radiata* D. Don | Sawlog | 30 | N/A | 444–604 (521 *) | 53 |

* Average specimen density.

The variation in species heterogeneity such as density, presented in Table 1, highlights key characteristics of hardwood species managed under pulplog management schemes. Both hardwood species' density ranges were much wider than *P. radiata*. Specimens prepared for *E. nitens* and *E. globulus* were plainsawn for best recovery. A total of 54 specimens were prepared randomly from ungraded boards for both eucalypt species and varied in origin from each log, deriving from 140-, 120- and 90-mm dressed boards. A maximum of six specimens were machined from individual boards for all species (Figure 1).



**Figure 1.** Six samples machined from individual boards.

For the varying board widths in the hardwood specimens, three sets of six samples were machined from 140-, 120- and 90-mm dressed boards. A total of 53 specimens were prepared for *P. radiata*, all of which derived from utility grade 90-mm dressed boards. All boards designated for sample machining were randomly selected during final processing as run of the mill production to reflect market supply. Prior to testing, boards were stored in a joinery workshop environment at 10 °C (± 4 °C) and 40% (± 5%) relative humidity. This range of environmental conditions (in Tasmania, Australia) was set to test typical joinery workshop environments in which secondary manufacturing commonly takes place, thus allowing a true representation of timber MC in local manufacturing and in service.

*2.2. Machinability Tests*

The machining tests conducted in this study complied with ASTM D1666-11 (2011), with the exception of choice in tooling for CNC operations. All CNC tests were conducted at the Discipline of Architecture and Design, University of Tasmania. The tests conducted included boring, routing, shaping, mortising, and an additional test to determine biscuit boring (doweling) for a more contemporary reference in timber joinery. Each specimen was subjected to boring, routing, and shaping tests. Only a selected number of specimens for each species were subjected to mortising and biscuit boring, as initial results were consistent in machinability quality.

### 2.3. Tooling and Speed/Feed Rates

All boring and routing tests were conducted with a solid carbide, 9.5-mm, 3-flute roughing spiral cutter and finished with a solid carbide, 8-mm, 2-flute compression cutter. A spindle speed of 15,000 revolutions per minute (RPM) and feed rate of 6350 mm/min were used (the standard spindle speed for boring tests is 3600 RPM). The choice in tooling and spindle speeds represented a typical entry-level combination of available tooling in timber joinery workshops for CNC machining. Boring and routing profiles were cut in two passes: first, full depth conventional milling was performed with the roughing tool, leaving 1.6-mm clearance from the finish surface before climb milling with the compression cutter to remove the 1.6 mm overcut. New tools were used for each species. The intention of this change in the standard method was to determine the resilience in timber machinability quality in contemporary industry practice. This was further substantiated and compared with the use of sawlog-managed softwood as a control to determine significant discrepancies between fibre-managed hardwood test results. Mortising tooling complied with the standard (13-mm hollow chisel drill), as did the spindle speed (3600 RPM), which was hand fed by peck drilling on a pedestal drill. Specimen-shaping was conducted on a table router with a no-load spindle speed of 27,000 RPM. The shaping with the table router was done with a 2-flute face-molding carbide tip with a ball bearing guide for profiling. The specimens on the side grain were shaped via hand feeding in two passes due to the depth of the profile. The equipment used to machine biscuit dowels was a Festool DF 500 DOMINO, which cuts the timber stock in a pendulum motion and therefore no spindle speed was recorded. Chip thickness was not measured in any tests. The mortising, shaping, and biscuit-boring introduced a variable of unreliable human-controlled feed rates in comparison with CNC machining. To minimize this variable, one operator conducted each human feed test to maintain consistency in test conditions. This research acknowledges the differences between numerically controlled feed rates and human feed rates, although the intention of this research is still an investigation of the machinability of hardwood plantation resources in commercially mass-produced repetitive machining versus niche one-off productions.

### 2.4. Scoring and Results Analysis

All specimens were graded according to the visual examination classification in ASTM D1666-11 (2011) on the bases of six grades, namely, G0 (defect-free), G1 (excellent), G2 (good), G3 (fair), G4 (poor), and G5 (very poor). While this method of machinability grading is qualitative and context-specific, depending on the product's intended use, two industry-experienced wood machinists with years of sawing, machining, and grading Tasmanian hardwoods were used to visually grade the specimens for each species according to ASTM D1666-11 (2011) and Australian Standard (AS) 2796.3. Grading was conducted using a photo studio lighting kit (Figure 2).



**Figure 2.** Photo studio lighting kit used to grade specimens.

No mechanical or scanning techniques were employed to measure the precision of the visual grading evaluation. A combination of visual and tactile evaluations was employed to determine specimen surface quality as indicated by the existing literature [12,20]. Most of the machining quality was notable by eye and touch, as visual grading provides a rapid and complete analysis of surface quality [21]. The micro-level assessment of surface quality was deemed irrelevant, as products' appearances would normally be graded for Australian markets according to AS 2796. The grade given to each specimen was based on commercially acceptable appearance parameters for high-value architectural products. Commercially acceptable parameters were determined by referencing AS 2796.3 Appendix D, Table D1: "Limits of the machining imperfections and surface finish imperfection on exposed surfaces of hardwood timber for furniture components" [21]. Where specimen tests resulted in surface imperfections, a grade of G2 (good) to G5 (very poor) was given. Specimens with no imperfections were graded as G0 (defect-free) to G1 (excellent). These parameters were also determined by the consistency of surface finish and visually graded using the examples in ASTM D166 and the literature [22]. This process was used to justify allocated grades and to identify significant discrepancies between the resulting specimens within each species and against each species.

### 2.5. Statistical Analyses

The significance of differences between the machinability characteristics of the three wood species in this study were statistically analyzed via Chi-Square testing using IBM SPSS Statistics software (version 23, IBM Corporation, New York, USA). The Analysis of Variance (ANOVA) and Duncan's multiple range test were used for determining the differences between the three species with respect to density and MC. The correlations between machinability characteristics with the variations in density and MC were determined using Pearson's correlation test (interval by interval). All the statistical analyses were conducted at 0.05 significance level.

## 3. Results

### 3.1. Statistical Analyses of Density and MC between Species

The ANOVA results indicated no significant difference between the densities of the three species in this study ($p > 0.05$), which enabled a statistical comparison between the machinability characteristics. The difference between MC values in the three species, however, was significant ($p < 0.05$). The difference between the density and MC of *E. nitens* and *P. radiata* was less than 0.4% and 2.3%, respectively. The average density and MC of *E. globulus* samples were respectively 4.2% and 3.9% higher than that of *E. nitens*, and 4.6% and 1.5% higher than *P. radiata*. The variations in the density and MC values of the test samples within each species can be seen in Figures 3–5.
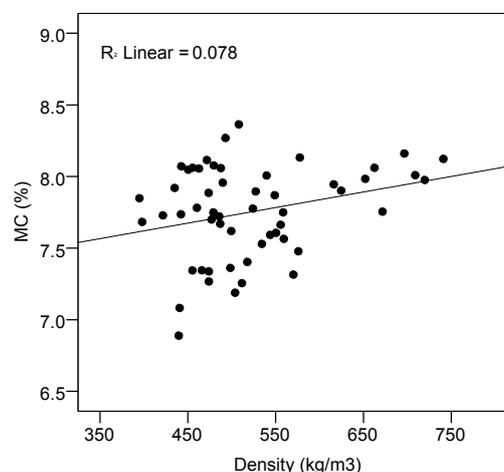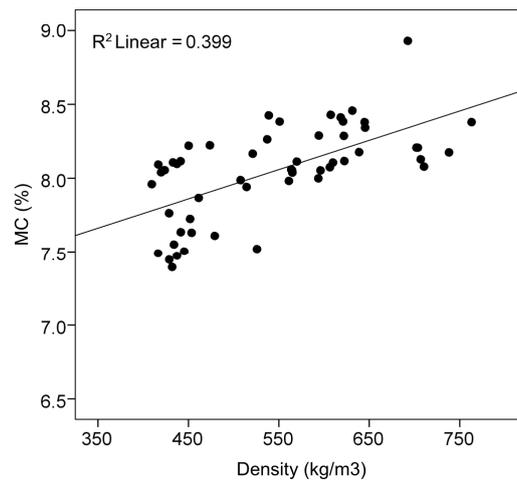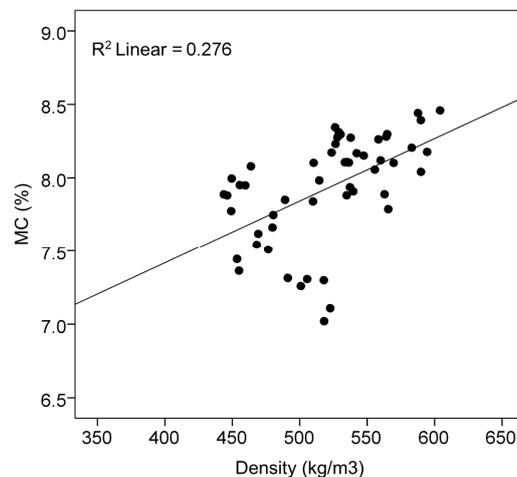


**Figure 3.** Variation in moisture content and density of *E. nitens* samples.

**Figure 4.** Variation in moisture content and density of *E. globulus* samples.



**Figure 5.** Variation in moisture content and density of *P. radiata* samples.

*3.2. Statistical Analyses of Machinability Results between Species*

The test results obtained with respect to routing end grain (fuzzy and raised) and boring (crushing, fuzzy, and smoothness) indicated that the test samples from the three species were all defect-free with consistent quality (having a grade of G0). These test results are therefore not presented in this study. The results of the statistical analyses for the remaining machinability characteristics are presented. No statistically significant difference was found between the three species with respect to raised routing side grain, chipped routing end grain, chipped shaping side grain, boring tear-out and biscuit bore (crushed and chipped) ($p > 0.05$). Statistically significant differences were found between the three species for routing side grain (fuzzy and chipped), shaping side grain (raised and fuzzy), mortising (crushing, tearing and smoothness) and fuzzy biscuit-bore grain ($p < 0.05$).

The grading results of the machinability characteristics for each species sample are shown in Tables 2–7. The values with the most important contributions to the statistical significance for each characteristic are highlighted in grey where applicable (indicating the differences within species and between species). All the *E. nitens* and *P. radiata* samples received a G0 grade (defect-free) for routing side grain (Table 2). The fuzzy routing side grain (Figure 6), was more variable within the *E. globulus* samples, with more than 37% of the samples having a grade between G1 to G4. There was no significant difference between the *E. nitens* and *P. radiata* samples with respect to the chipped routing side grain. The number of samples with a grade worse than G0 were significantly higher in *E. globulus* compared to *E. nitens* and *P. radiata*.

**Table 2.** Grading results according to routing side grain.

| Routing Side Grain Results | | Routing Side Grain (Raised) | | | Routing Side Grain (Fuzzy) | | | | | Routing Side Grain (Chipped) | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Grade 0 | Grade 1 | Grade 2 | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 4 | Grade 0 | Grade 1 | Grade 2 | Grade 3 | |
| Species | *E. nitens* — Count | 53 | 1 | 0 | 54 | 0 | 0 | 0 | 0 | 49 | 1 | 1 | 3 | 54 |
| | Standardised residual | 0.2 | −0.3 | −1 | 1 | −1.3 | −1.9 | −1 | −0.6 | 0 | 1.1 | −1.2 | 1 | |
| | *E. globulus* — Count | 49 | 2 | 3 | 34 | 5 | 11 | 3 | 1 | 44 | 0 | 8 | 2 | 54 |
| | Standardised residual | −0.4 | 0.6 | 2 | −1.9 | 2.6 | 3.8 | 2 | 1.1 | −0.7 | −0.6 | 2.9 | 0.2 | |
| | *P. radiata* — Count | 52 | 1 | 0 | 53 | 0 | 0 | 0 | 0 | 53 | 0 | 0 | 0 | 53 |
| | Standardised residual | 0.2 | −0.3 | −1 | 1 | −1.3 | −1.9 | −1 | −0.6 | 0.7 | −0.6 | −1.7 | −1.3 | |
| Total | Count | 154 | 4 | 3 | 141 | 5 | 11 | 3 | 1 | 146 | 1 | 9 | 5 | 161 |

**Table 3.** Grading results according to routing end grain.

| Routing End Grain Results | | Routing End Grain Chipped | | Total |
|---|---|---|---|---|
| | | Grade 0 | Grade 2 | |
| Species | *E. nitens* — Count | 53 | 1 | 54 |
| | Standardised residual | −0.1 | 1.1 | |
| | *E. globulus* — Count | 54 | 0 | 54 |
| | Standardised residual | 0 | −0.6 | |
| | *P. radiata* — Count | 53 | 0 | 53 |
| | Standardised residual | 0 | −0.6 | |
| Total | Count | 160 | 1 | 161 |

**Table 4.** Grading results according to shaping side grain.

| Shaping Side Grain Results | | Shaping Side Grain (Raised) | | | | Shaping Side Grain (Fuzzy) | | | | Shaping Side Grain (Chipped) | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 4 | Grade 5 | |
| Species | *E. nitens* — Count | 42 | 6 | 6 | 0 | 54 | 0 | 0 | 0 | 47 | 1 | 1 | 2 | 1 | 2 | 54 |
| | Standardised residual | −0.9 | 1.4 | 2.4 | −0.6 | 1.2 | −2.2 | −1.7 | −0.6 | −0.2 | 0.4 | 0 | 0.6 | −0.5 | 1 | |
| | *E. globulus* — Count | 48 | 4 | 1 | 1 | 47 | 0 | 6 | 1 | 44 | 1 | 2 | 2 | 4 | 1 | 54 |
| | Standardised residual | 0 | 0.4 | −0.9 | 1.1 | 0.2 | −2.2 | 1.7 | 1.1 | −0.6 | 0.4 | 1 | 0.6 | 1.8 | 0 | |
| | *P. radiata* — Count | 53 | 0 | 0 | 0 | 36 | 14 | 3 | 0 | 53 | 0 | 0 | 0 | 0 | 0 | 53 |
| | Standardised residual | 0.9 | −1.8 | −1.5 | −0.6 | −1.4 | 4.4 | 0 | −0.6 | 0.8 | −0.8 | −1 | −1.1 | −1.3 | −1 | |
| Total | Count | 143 | 10 | 7 | 1 | 137 | 14 | 9 | 1 | 144 | 2 | 3 | 4 | 5 | 3 | 161 |

**Table 5.** Grading results according to boring.

| Boring Results | | | Boring Tear-Out | | | Total |
|---|---|---|---|---|---|---|
| | | | Grade 0 | Grade 2 | Grade 3 | |
| Species | *E. nitens* | Count | 54 | 0 | 0 | 54 |
| | | Standardised residual | 0.1 | −0.6 | −0.6 | |
| | *E. globulus* | Count | 52 | 1 | 1 | 54 |
| | | Standardised residual | −0.2 | 1.1 | 1.1 | |
| | *P. radiata* | Count | 53 | 0 | 0 | 53 |
| | | Standardised residual | 0.1 | −0.6 | −0.6 | |
| Total | | Count | 159 | 1 | 1 | 161 |

**Table 6.** Grading results according to mortising.

| Mortising Results | | | Mortising (Crushing) | | | | Mortising (Tearing) | | | | Mortising (Smoothness) | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Grade 2 | Grade 3 | Grade 4 | Grade 5 | Grade 2 | Grade 3 | Grade 4 | Grade 5 | Grade 4 | Grade 5 | |
| Species | *E. nitens* | Count | 0 | 20 | 10 | 0 | 0 | 20 | 9 | 1 | 0 | 30 | 30 |
| | | Standardised residual | −1.4 | 1.2 | 1.5 | −2.5 | −1.4 | 0.8 | 0.2 | −1.2 | −1.4 | 0.4 | |
| | *E. globulus* | Count | 0 | 2 | 9 | 19 | 0 | 6 | 16 | 8 | 0 | 30 | 30 |
| | | Standardised residual | −1.4 | −3.4 | 1.1 | 5 | −1.4 | −2.6 | 2.7 | 2.9 | −1.4 | 0.4 | |
| | *P. radiata* | Count | 6 | 24 | 0 | 0 | 6 | 24 | 0 | 0 | 6 | 24 | 30 |
| | | Standardised residual | 2.8 | 2.2 | −2.5 | −2.5 | 2.8 | 1.8 | −2.9 | −1.7 | 2.8 | −0.8 | |
| Total | | Count | 6 | 46 | 19 | 19 | 6 | 50 | 25 | 9 | 6 | 84 | 90 |

**Table 7.** Grading results according to biscuit boring.

| Biscuit Bore Results | | | Biscuit Bore (Crushed) | | Biscuit Bore (Fuzzy) | | | | Biscuit Bore (Chipped) | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Grade 0 | Grade 3 | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 0 | Grade 4 | |
| Species | *E. nitens* | Count | 30 | 0 | 0 | 0 | 0 | 30 | 29 | 1 | 30 |
| | | Standardised residual | 0.1 | −0.6 | −1.5 | −0.8 | −2.5 | 2.1 | −0.1 | 0.4 | |
| | *E. globulus* | Count | 29 | 1 | 7 | 0 | 4 | 19 | 29 | 1 | 30 |
| | | Standardised residual | −0.1 | 1.2 | 3.1 | −0.8 | −0.9 | −0.4 | −0.1 | 0.4 | |
| | *P. radiata* | Count | 30 | 0 | 0 | 2 | 15 | 13 | 30 | 0 | 30 |
| | | Standardised residual | 0.1 | −0.6 | −0.5 | 1.6 | 3.4 | −1.7 | 0.1 | −0.8 | |
| Total | | Count | 89 | 1 | 7 | 2 | 19 | 62 | 88 | 2 | 90 |

(**a**)        (**b**)        (**c**)
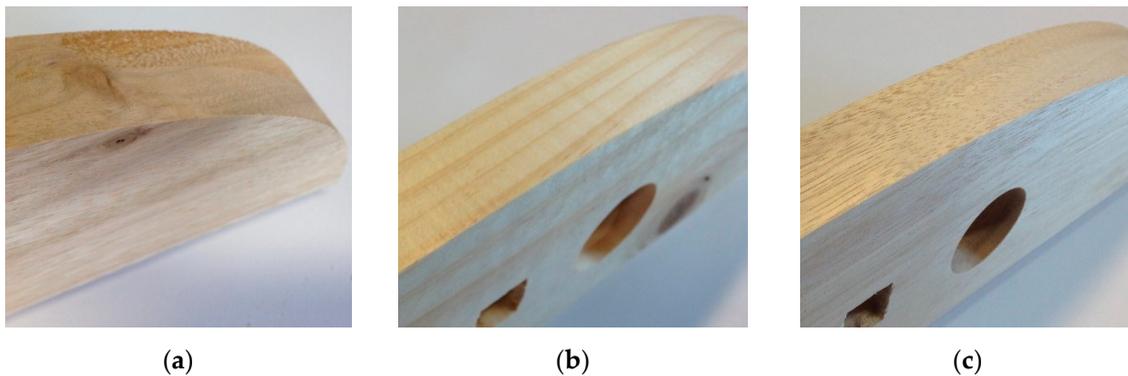
**Figure 6.** Examples of *E. globulus* (**a**) with a grade of G4 (poor) and *P. radiata* (**b**) and *E. nitens* (**c**) with a grade of G0 (excellent) for fuzzy routing side grain.

Routing end grain (Figure 7) divided the *E. nitens* samples into grades of G0 and G2; however, no statistically significant difference was found between the three species with respect to the chipped routing end grain (Table 3). This machinability characteristic was less sensitive among the species.



(**a**)             (**b**)
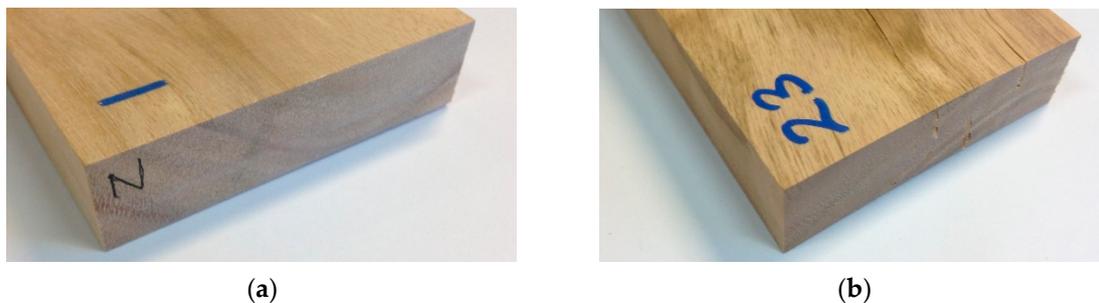
**Figure 7.** Examples of *E. nitens* with grades of G0 (excellent) (**a**) and G2 (good) (**b**) for routing end grain.

The grading results of the samples with respect to shaping side grain are shown in Table 4. For both shaping side grains (raised or chipped), *P. radiata* displayed a better finish quality than *E. nitens* and *E. globulus*, with 100% defect-free results. The *E. nitens* samples, however, had the highest fuzzy shaping side grain quality compared to *P. radiata* and *E. globulus,* with 100% of the samples being graded as G0. None of the test samples from the three species had any grade worse than G3 with respect to shaping side grain (raised or fuzzy) (Figure 8).



(**a**)             (**b**)

**Figure 8.** Examples of *E. globulus* with a grade of G2 (good) for fuzzy shaping side grain (**a**) and *E. nitens* with a grade of G5 (very poor) for chipped shaping side grain (**b**).

All the *E. nitens* and *P. radiata* samples were graded as G0 with respect to boring tear-out (Table 5). Only two samples from *E. globulus* had a grade worse than G0, a difference that was not statistically significant (Figure 9).



(**a**)                                                                              (**b**)

**Figure 9.** Examples of *E. nitens* with a grade of G0 (excellent) (**a**) and *E. globulus* with a grade of G2 (good) (**b**) for boring tear-out.

The results indicated that mortising quality is significantly correlated to the wood species (Table 6), with *P. radiata*, *E. nitens*, and *E. globulus* having the best to the worst overall mortising qualities, respectively (Figure 10). There was no statistically significant difference between *E. nitens* and *E. globulus* in respect to mortising smoothness, whereas *P. radiata* had significantly better mortising smoothness than both eucalypt species. All *E. nitens* and *E. globulus* samples had a G5 grade for mortising smoothness.



(**a**)                                                (**b**)                                                (**c**)
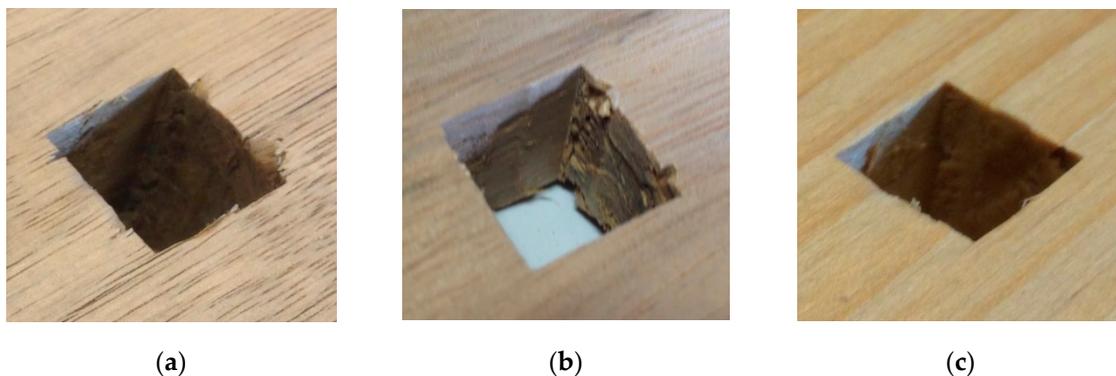
**Figure 10.** Examples of *E. nitens* (**a**) and *E. globulus* (**b**) with grades of G5 (very poor), and *P. radiata* (**c**) with a grade of G2 (good) for mortising (tearing).

The *E. nitens* samples had the worst quality when graded based on biscuit bore (Table 7), with 100% of the samples being graded as G3 (Figure 11). More than 30% of the *E. globulus* samples were defect-free (G0), which made a high contribution to the statistical significance between the three species. The three species had almost the same quality when the biscuit bore (crushed and chipped) was used as the grade-determining parameter. The *E. globulus* samples showed more variations in the fuzzy biscuit-bore grain compared to the other two species.

|            (**a**)            |            (**b**)            |            (**c**)            |
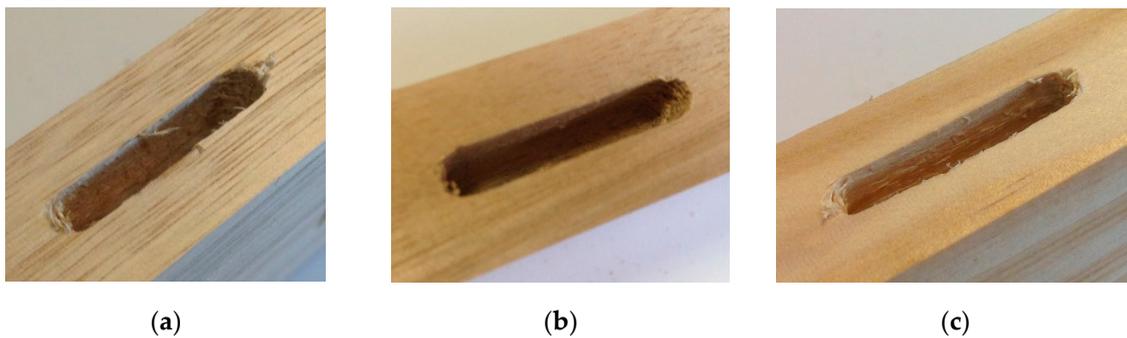
**Figure 11.** Examples of *E. nitens* (**a**) with a grade of G3 (fair) for fuzzy biscuit-bore grain and *E. globulus* (**b**) and *P. radiata* (**c**) with a grade of G2 (good).

## 4. Discussion

The findings in this research intend to demonstrate appropriate new applications for hardwood plantation resources in machine-manufactured products. The following sections validate opportunities where hardwood plantation resources could serve as appropriate materials of choice.

### 4.1. Statistical Analyses of Density and MC Within Species

The results indicate a higher variability in the machinability of the *E. nitens* and *E. globulus* specimens compared to that of *P. radiata*. Part of this is because of the variation in the density of the samples and its influence on the results obtained. A possible physical phenomenon that explains the variation in machinability results—due to the degree of changes in densities—could relate to the management of the resource that was initially intended for pulplog production. The variations in MC for *E. nitens* specimens showed no significant correlation with any of the studied machinability characteristics ($p > 0.05$). The variations in specimen densities, however, had significant correlations with chipped routing end grain, raised shaping side grain and mortising (crushing and tearing) ($p < 0.05$). For *E. globulus*, the variation in MC values had significant correlations with fuzzy routing side grain and fuzzy shaping side grain ($p < 0.05$). In addition, the variations in specimen densities also had significant correlations with fuzzy routing side grain, fuzzy shaping side grain and mortising (tearing) ($p < 0.05$). For *P. radiata*, the variations in MC values had significant correlations with mortising (crushing, tearing, and smoothness) ($p < 0.05$) and the variations in specimen densities showed no statistically significant correlation with the studied machinability characteristics.

### 4.2. Routing End Grain and Boring

Despite being managed for pulplog production, machinability tests of *E. nitens* and *E. globulus*—as well as sawlog *P. radiata*—for routing end grain (fuzzy and raised), boring (crushing, fuzzy, and smoothness), resulted in defect-free specimens. Both pulplog resources were out-graded in quality of finish by *P. radiata* due to chipping in the end grain (*E. nitens*) and tear-out from boring (*E. globulus*). Expectedly, chipping and tear-out were present in the fiber-managed plantation species given that the nature of the resource to break apart is a direct reason for its use in pulp production. The chipping observation could be due to the long fiber lengths when machined perpendicular to the grain, and the tear-out evident in boring (also perpendicular to the grain) may be caused by pulling fibers. Regardless, the results suggest that either species would be an acceptable choice for products such as cabinetry or acoustic panels that require end-grain routing or a degree of good and better surface boring for fixtures or perforations, particularly where high-quality surface finishes are essential. Extra care in machining could mitigate chipping or tear-out from the pulplog resources. As suggested in ASTM D1666-11 (2011), a roughing cut offset by 1.6 mm then finished in a final pass can ensure that any edge damaged in roughing is removed for a better surface finish. As previously highlighted in this study, two solid carbide tools—one for roughing and the other for finishing—were used to ensure that

the best surface quality could be achieved. In addition, the roughing cut was conventional milling and the finishing cut was climb milling. Generally, optimal surface qualities were achieved directly parallel and perpendicular to the wood grain, and most raised grain, fuzzing, and chipping were at tangent angles following a parabola specimen shape as set out in ASTM D-1666.

### 4.3. Routing Side Grain and Shaping

*E. nitens* and *P. radiata* samples showed better routing qualities on the side grain than *E. globulus*. Once again, *P. radiata* out-graded both pulplog resources, and *E. nitens* out-graded *E. globulus*. In line with routing end grain, chipping appears to have been dominant for both hardwood species, particularly towards the edge of a specimen. This could have been caused by the length of wood fiber in plantation *Eucalyptus*, which typically results in pulling out or tearing more stock material than intended by machining. Similarly, fuzzy routing side grain for *E. globulus* was the greatest reason for the downgrading of these specimens. The results of shaping on the side grain also suggest that *E. globulus* and *P. radiata* are less desirable for architectural applications such as moldings where high-quality surface finishes are necessary. In comparison, shaping on the side grain of *E. nitens* resulted in raised grain.

### 4.4. Mortising and Biscuit Boring

*P. radiata* out performed *E. nitens* and *E. globulus*, however the results for all species were far from perfect, with no tests resulting in a defect-free grade (G0). This may suggest that following the defined test method set out in ASTM D1666-11 (2011) for mortising is not an ideal form of joinery. The results also suggest that the surface hardness of the tested species could have been low, and therefore the observed crushing by compression and tearing could have been mitigated by a change in choice of tooling. Consideration should be made, however, of the fact that grading of the mortise refers to an internal surface that is not seen in final products such as assembled furniture. As an alternative to mortise and tenon joinery, boring via CNC fabrication would be an acceptable alternative, as substantiated in the boring tests. In keeping with the grading standards set out in ASTM D1666-11 (2011), this study considered the quality in surface finish from biscuit boring, a more contemporary approach to joinery with dowels. All species performed exceptionally well against crushing and chipping. In this test, it was fuzzy grain that was the dominate grade-reducing feature. This may have been due to the pendulum motion of the biscuit dowel cutter. Regardless, the extrusion generated in this test—like a mortise—is internal, and not seen in a product's finally assembly. Moreover, the fuzzy grain caused by the biscuit borer could advantageously improve the retention of the biscuit dowel and glue for furniture or table tops.

### 4.5. Other Considerations

Another reason for the higher variability in the machinability of the *E. nitens* and *E. globulus* specimens compared to that of *P. radiata* could be that the pulplog specimens were selected randomly from ungraded timber boards high in natural features. Considering this, there could be a high potential to improve the machinability of these plantation species by making use of an appropriate timber grading system that would allow proper resources to be selected for appropriate higher-value products. Although *E. nitens* and *E. globulus* specimens were derived from pulplog resources, the results suggest that in some applications these species are appropriate alternatives for products where hardwood species are desirable or in demand.

The physical phenomena observed in *E. globulus* and *E. nitens*, such as the tearing, fuzzing, and chipping throughout the test specimens, could be related to fiber length, elasticity, hardness, and ductility of the pulp resources [23]. *E. globulus* is known for its high density, high coarseness, and high fiber-length [23], which contribute to its use in pulp production; however, these properties also render the resource useful for raw forest products as well as other composite and engineering forest products [23]. Carefully considered machining processes to mitigate chipping and tearing

parallel and perpendicular to wood grains may improve and reduce the quantity of machining defects in these hardwood species. This could be as simple as including lead-ins and -outs, making helical cuts, and programming multiple steps to mitigate visible fibre damage to value-added timber products. Future research could investigate these multiple variables to identify processes or techniques to avoid when machining plantation *Eucalyptus* species.

All species demonstrated both a high-quality and less-than-favorable surface finished with both CNC and manual machining techniques. Where possible, any automated system that is replicable and controllable is ideal for consistency in quality. This research suggests that both forms of machining can produce acceptable finishes for architectural value-added products.

Further research on the machinability of *Eucalyptus* pulplogs could consider the origin of specimens from log and tree positions, as well as the orientations of cuts. The impact of surface and internal checking could also be investigated to determine if these characteristics impact chipping and tear-out from various machinability tests conducted on fiber-managed hardwood resources. Furthermore, the impact of live and dead knots on machinability properties could be investigated to determine the acceptable presence of different types of knots on the appearance of products that are routed, shaped, or bored.

## 5. Conclusions

The aim of this study was to determine the machinability of Tasmanian plantation fibre-managed hardwood *Eucalyptus globulus* and *Eucalyptus nitens* and to evaluate their potential use in architectural interior products such as moldings, as well as other timber products such as furniture. Plantation sawlog-managed softwood *Pinus radiata* was used as a control reference given its acceptable quality and use in a wide range of architectural and product applications.

- The results in this study suggest that fibre-managed plantation hardwood *E. nitens* and *E. globulus* have the same machinability qualities (with no statistically significant difference) as sawlog-managed *P. radiata* for routing end grain (fuzzy, raised, and chipped), boring (crushing, fuzzy, smoothness, and tear-out), raised routing side grain, chipped shaping side grain, and biscuit bore (crushed and chipped). In products and applications where secondary manufacturing involves routing (end grain and side grain), boring, shaping, and biscuit boring, producers can expect acceptable machinability qualities that would allow the use of fibre-managed plantation hardwoods as an alternative to sawlog-managed plantations softwoods.
- No statistically significant difference was observed between *E. nitens* and *E. globulus* except when routing side grain (fuzzy and chipped), shaping side grain (raised and fuzzy), mortising (crushing and tearing), and fuzzy biscuit-bore grain were used as the grade-determining parameters.
- The correlations between the variations in density and machinability characteristics of *E. nitens* and *E. globulus* were statistically significant, whereas no significant correlations existed between the variations in density and machinability of *P. radiata*.

### 5.1. E. nitens

- The machinability characteristics of *E. nitens* were statistically comparable to *P. radiata* in all cases except for shaping side grain (raised and fuzzy), mortising (crushing, tearing, and smoothness) and fuzzy biscuit-bore grain.
- The studied *E. nitens* samples received the worst grades among the studied timber species when graded against raised shaping side grain and fuzzy biscuit-bore grain as the grade-determining parameters.
- The machinability of the *E. nitens* samples was significantly better than both *E. globulus* and *P. radiata* in respect to fuzzy shaping side grain.
- The *E. nitens* had better quality than *E. globulus* in respect to routing side grain (fuzzy and chipped), fuzzy shaping side grain, mortising (crushing and tearing), and fuzzy biscuit-bore grain.

- Unlike *P. radiata* and *E. globulus*, the variations in the MC of the samples had no important correlation with the machinability characteristics of *E. nitens*.

*5.2. E. globulus*

- The machinability characteristics of *E. globulus* were statistically comparable to *P. radiata* in all cases except for routing side grain (fuzzy and chipped), fuzzy shaping side grain, mortising (crushing, tearing, and smoothness) and fuzzy biscuit-bore grain.
- The only cases in which the *E. globulus* samples showed significantly better qualities than *P. radiata* were fuzzy shaping side grain and fuzzy biscuit-bore grain.

## References

1. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). Australian Plantation Statistics 2017 Update, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, August 2017. CC BY 3.0. Available online: https://data.gov.au/dataset/ds-dga-a1fcbbec-807c-438e-b8fd-db1a9a93f887 (accessed on 4 October 2018).
2. American Society for Testing and Materials (ASTM). *Standard Test Methods for Conducting Machining Tests of Wood and Wood-Base Materials*; ASTM D1666-11; ASTM International: West Conshohocken, PA, USA, 2011; 23p.
3. Zobel, B. The changing quality of the world wood supply. *Wood Sci. Technol.* **1984**, *181*, 1–17. [CrossRef]
4. Hamilton, M.G. The Genetic Improvement of Eucalyptus Globulus and Eucalyptus Nitens for Solidwood Production. Ph.D. Dissertation, University of Tasmania, Newnham, Australia, 2007.
5. Dugmore, M.; Nocetti, M.; Brunetti, M.; Naghizadeh, Z.; Wessels, C.B. Bonding quality of cross-laminated timber: Evaluation of test methods on Eucalyptus grandis panels. *Constr. Build. Mater.* **2019**, *211*, 217–227. [CrossRef]
6. Derikvand, M.; Kotlarewski, N.; Lee, M.; Jiao, H.; Chan, A.; Nolan, G. Short-term and long-term bending properties of nail-laminated timber constructed of fast-grown plantation eucalypt. *Constr. Build. Mater.* **2019**, *211*, 952–964. [CrossRef]
7. Pangh, H.; Hosseinabadi, H.Z.; Kotlarewski, N.; Moradpour, P.; Lee, M.; Nolan, G. Flexural performance of cross-laminated timber constructed from fibre-managed plantation eucalyptus. *Constr. Build. Mater.* **2019**, *208*, 535–542. [CrossRef]
8. Aguilera, A.; Martin, P. Machining qualification of solid wood of *Fagus silvatica* L. and *Piceaexcelsa* L.: Cutting forces, power requirements and surface roughness. *Holz Als Roh-Und Werkst.* **2001**, *59*, 483–488. [CrossRef]
9. Aguilera, A.; Meausoone, P.J.; Martin, P. Wood material influence in routing operations: The MDF case. *Eur. J. Wood Wood Prod.* **2000**, *58*, 278–283. [CrossRef]
10. Lin, R.J.; van Houts, J.; Bhattacharyya, D. Machinability investigation of medium-density fibreboard. *Holzforschung* **2006**, *60*, 71–77. [CrossRef]
11. Szymanowski, K.; Gorski, J.; Czarniak, P.; Wilkowski, J.; Podziewski, P.; Cyrankowski, M.; Morek, R. Machinability index of certain types of chipboards. In *Forestry and Wood Technology; Annals of Warsaw*; Warsaw University of Life Sciences Press: Warsaw, Poland, 2015; p. 90.

12. Goli, G.; Sandak, J. Proposal of a new method for the rapid assessment of wood machinability and cutting tool performance in peripheral milling. *Eur. J. Wood Wood Prod.* **2016**, *74*, 867–874. [CrossRef]

13. Sütçü, A. Investigation of parameters affecting surface roughness in CNC routing operation on wooden EGP. *BioResources* **2012**, *8*, 795–805. [CrossRef]

14. Moya-Roque, R.; Tenorio-Monge, C.; Salas-Garita, C.; Berrocal-Jiménez, A. Evaluation of wood properties from six native species of forest plantations in Costa Rica. *Bosque* **2016**, *37*, 71–84. [CrossRef]

15. Podziewski, P.; Szymanowski, K.; Górski, J.; Czarniak, P. Relative Machinability of Wood-Based Boards in the Case of Drilling–Experimental Study. *BioResources* **2018**, *13*, 1761–1772. [CrossRef]

16. Ratnasingam, J.; Ioras, F. Effect of heat treatment on the machining and other properties of rubberwood. *Eur. J. Wood Wood Prod.* **2012**, *70*, 759–761. [CrossRef]

17. Laina, R.; Sanz-Lobera, A.; Villasante, A.; López-Espí, P.; Martínez-Rojas, J.A.; Alpuente, J.; Sánchez-Montero, R.; Vignote, S. Effect of the anatomical structure, wood properties and machining conditions on surface roughness of wood. Maderas. *Cienc. Y Tecnol.* **2017**, *19*, 203–212. [CrossRef]

18. Thoma, H.; Peri, L.; Lato, E. Evaluation of wood surface roughness depending on species characteristics. Maderas. *Cienc. Y Tecnol.* **2015**, *17*, 285–292. [CrossRef]

19. Aguilera, A.; Zamora, R. Surface roughness in sapwood and heartwood of Blackwood (*Acacia melanoxylon* R. Br.) machined in 90-0 direction. *Eur. J. Wood Wood Prod.* **2009**, *67*, 297–301. [CrossRef]

20. Ramanakoto, M.F.; Andrianantenaina, A.N.; Ramananantoandro, T.; Eyma, F. Visual and visuo-tactile preferences of Malagasy consumers for machined wood surfaces for furniture: Acceptability thresholds for surface parameters. *Eur. J. Wood Wood Prod.* **2017**, *75*, 825–837. [CrossRef]

21. Standards Australia. *Australian Standard 2796 Timber—Hardwood—Sawn and Milled Products Part 3: Timber for Furniture Components*; Standards Associations of Australia: Sydney, NSW, Australia, 1999; reconfirmed in 2016.

22. Goli, G.; Marchal, R.; Negri, M.; Costes, J.P. Surface quality: Comparison among visual grading and 3D roughness measurements. In Proceedings of the 15th International Wood Machining Seminar, Los Angeles, CA, USA, 30 July–1 August 2001.

23. Carrillo-Varela, I.; Valenzuela, P.; Gacitúa, W.; Mendonca, R.T. An Evaluation of Fiber Biometry and Nanomechanical Properties of Different Eucalyptus Species. *BioResources* **2019**, *14*, 6433–6446. [CrossRef]