ENGINEERED FLOORING FROM LOW-DENSITY PLANTATION HARDWOOD: EVALUATION OF LONG-TERM IN-SERVICE TRIALS

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Abstract. The use of short-rotation hardwood plantation species has been perceived to be unsuitable for flooring until recently, due to the lower densities. This study assesses the performance of a low-density plantation hardwood species, *Eucalyptus nitens* in engineered flooring applications. The selection of a suitable timber species for flooring has conventionally been based on its market acceptance or value and on its hardness to ensure minimal indentations or damages. While both of these reasons have determined flooring species selection, this is becoming more difficult as popular species is less available due to increasing flooring demand, and the diminishing supply of native timbers due to government regulations on harvesting and conservation. Typically, the species hardness is determined by static tests in the laboratory. Although these tests can compare species hardness, they might not reliably indicate an end product's performance, especially with engineered flooring. Despite the global interest in timber flooring manufacturing, investigations on the assessment of alternative testing methods to static hardness, methods to replicate in-service behavior, timber flooring quality determination, and characterization of timber properties for flooring applications are still scarce. In this study, in-service trials were conducted on solid and densified *E. nitens* boards and engineered flooring prototypes with *E. nitens* top layers, to better understand product behavior when exposed to moderate traffic with distinct temperature and RH variations. Dynamic impact hardness tests using the falling ball indentation method adapted from ASTM D 2394 were conducted to assess the surface hardness of the tested prototypes. *E. nitens* engineered prototype performance was comparable to the existing market products used as controls. This demonstrates the potential to use plantation-grown *E. nitens* in engineered flooring applications in domestic dwellings.

Keywords: *Eucalyptus nitens*, *Eucalyptus obliqua*, footprint diameter, dynamic hardness, falling ball indentation, short-rotation, performance evaluation.

INTRODUCTION

Hardwood timber flooring is considered one of the timeless and highly preferred floor covering options by consumers due to its versatility,

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durability (Uddin 2021), and aesthetics (ATFA 2009a). Although traditional solid timber flooring is still in demand, there is a gradual shift toward multilayer engineered timber flooring products (Sepliarsky et al 2022). While in Europe, 15% of timber floors are made from solid timber and 83% of total production corresponds to engineered parquet (European Parquet Federation 2023), the engineered timber flooring market share in North America, China (Blanchet et al 2002; Chen et al 2015) and Australia are gaining more significance. Engineered timber floor boards generally have multiple layers consisting of thinner top layers made from a hardwood species, placed on a substrate consisting of one or multiple support layers of a lower value species or composite product such as plywood or fiberboard (ATFA 2012; Acuña et al 2020). This facilitates greater product stability (Castro and Zanuttini 2004; Drerup et al 2013) and allows an increase in the square meters of engineered timber boards produced from the hardwood species utilized (Acuña et al 2020).

The selection of timber species for applications are generally governed by traditional convention over availability and technical or aesthetic considerations (Neyses and Sandberg 2015; Millaniyage et al 2023). In Europe, *Quercus robur* and *Quercus petrea* (European Oak) are the most commonly chosen species for parquet (82.1%) (Németh et al 2014; Grześkiewicz et al 2020; European Parquet Federation 2023) although they are moderately hard and dense. In the US, a few species including *Quercus* sp. (Red Oak and White Oak) make up almost 70% of the hardwood market (Uddin 2021; Khademibami et al 2022). Similar observations are made in Australia where the flooring choices are usually made based on a known performance in service for generations, appearance, and cost (ATFA 2009a, 2009b) rather than based on density. A survey conducted on Australian consumers and specifiers reported aesthetic preferences favored Australian hardwoods including *Corymbia* sp. (Spotted Gum), *Eucalyptus microcorys* (Tallowwood), and *Eucalyptus pilularis* (Blackbutt) (Knox 2016). A native forest species mix consisting of *Eucalyptus obliqua*, *Eucalyptus regnans*, and *Eucalyptus delegetensis* is marketed as Tasmanian Oak in Australia and has been widely used in flooring applications for decades (ATFA 2011; Wood Solutions 2020). The predictions on timber supply show that the access to these native species are rapidly decreasing (STT 2022) and native timber harvesting has recently been banned in two states of Australia. Similar observations are made in Europe for Oak.

Globally, commercial timber plantations are becoming an important source of raw material for the timber industry (FAO 2020). In the state of Tasmania (Australia) where the present study is conducted, *Eucalyptus nitens* is the major plantation species grown due to its ability to withstand frost (Onfray et al 2015). There are two types of *E. nitens* plantations present. The majority of the plantations are established to obtain fiber for pulpwood production (ABARES 2022), designed for short rotations of around 15 yr, and do not undergo silvicultural applications such as thinning and pruning (Harwood 2010; Derikvand et al 2019). As a result, the timber from this plantation resource contains many natural features such as knots and do not comply with Australian standards for appearance grading (AS 2796.2 1999, 2082 2007). In contrast, sawlog-managed plantations undergo thinning and pruning and harvested around 21-25 yr of age and are anticipated for future use as a sawlog resource (Washusen et al 2009; Harwood 2010). In this study, these resources are termed fiber *E. nitens* and sawlog *E. nitens* to reflect the silviculture management differences.

To introduce an alternative species for flooring applications that fits outside market conventions, the process is assisted by evaluating the species performance in expected end-use conditions (Németh et al 2014; Millaniyage et al 2023). The authors observed that the global standards commonly used in timber flooring have limitations in benchmarking eight species suitability for end-use applications. Moreover, the current Australian standards do not address the plantation resource base which has distinctive characteristics when compared with native, high-density species. The conventional technical criterion used in determining the suitability of a species for flooring is hardness (ATFA 2010; Vörös and Németh 2020). Traditional static hardness tests such as Janka hardness (ASTM D 143 2000) and Brinell hardness (EN 1534 2020) methods are commonly used to evaluate species performance. However, as reported by Millaniyage et al (2022) and Grześkiewicz et al (2020), these methods are impacted by the composite structure of engineered flooring and might not always generate reliable observations for engineered flooring products.

The study presented here took place in two stages. Stage one involved the evaluation of the performance of solid *E. nitens* timber boards, hereafter termed the solid flooring trial. Stage two included the development and evaluation of several engineered flooring prototypes with different *E. nitens* top layers. One of the developed engineered flooring prototypes consisted of densified solid *E. nitens* boards to increase the surface hardness of the timber. This in-service trial is hereafter referred to as the engineered flooring trial. To the author's best knowledge neither in-service trials with *E. nitens* has been reported nor has the testing of engineered flooring prototypes. After the in-service trials, each flooring was subjected to dynamic hardness tests using the falling ball indentation method.

In summary, the aim of the study described here was to: 1) evaluate the behavior of the short-rotation hardwood species *E. nitens*, which is not currently used in industrial-scale timber flooring manufacturing, through visual observations obtained from in-service trials and dynamic hardness tests; 2) compare the results with the controls; and 3) determine the suitability of plantation *E. nitens* for an engineered flooring product suitable for domestic/light commercial applications.

MATERIALS AND METHODS

The study used four different sources of *E. nitens* timber. The solid flooring trial included five timber flooring products. In the engineered flooring trial, eight types of timber flooring products including developed prototypes and existing market products were tested (six multilayer products, one solid overlay product, and one solid densified product) as specified in the following section.

Timber Flooring Specimens for the Solid Flooring Trial

The solid timber flooring trial was designed to understand how *E. nitens* would behave in a flooring application when exposed to in-service conditions in comparison with commonly used flooring timber species in Australia.

Two groups of solid timber flooring boards were developed using sawlog and fiber *E. nitens*, to evaluate their performance. *E. obliqua* (Tasmanian Oak species) termed as moderately hard (ATFA 2010), was selected as the main control species based on local industry interest and production. *E. pilularis* (Blackbutt) and *Eucalyptus sieberi* (Silvertop Ash) termed as very hard species (ATFA 2010) were also used for comparison. Based on the common industry practice in Tasmania, it was decided to use 19 mm thickness for solid timber boards used in the trial. From each timber species, ten samples were obtained to determine the MC and oven-dried density as per Australian/New Zealand Standards AS/NZS 1080.1 (2012) and AS/NZS 1080.3 (2000), respectively. The density, MC, and manufacturing details are shown in Table 1.

Timber Flooring Prototypes for the Engineered Flooring Trial

The development of engineered timber flooring prototypes with *E. nitens* top layers was conducted based on the feedback received from interviews conducted with a group of architects, flooring specifiers, and Tasmanian flooring manufacturers familiar with specifying or using Tasmanian Oak in their projects. Specifically for this research, six different prototypes were manufactured aligning with the in-state industry capabilities. Solid 12 mm thick *E. obliqua* overlay and a commercial Tasmanian Oak engineered flooring product processed overseas were used as controls.

Table 1. Solid timber flooring trial: species and properties.

Species	Oven-dried density (kg m^{-3})	MC (%)	Board surface cross section dimensions (mm)	No. of sample boards
Fiber *Eucalyptus nitens*	480 (9.48)	11.5 (8.60)	19 × 105	11
Sawlog *E. nitens*	510 (9.26)	11.1 (9.22)	19 × 105	11
Eucalyptus obliqua	600 (14.23)	10.8 (5.52)	19 × 105	11
Eucalyptus pilularis	815 (5.90)	11.9 (2.22)	19 × 130	10
Eucalyptus sieberi	785 (9.34)	11.4 (5.08)	19 × 130	09

The coefficient of variation percentage for density and MC are shown in the parenthesis.

The materials for the products were supplied from three sawmills in Northern Tasmania:

1. Sawmill A supplied the timber boards for sawlog *E. nitens*, *E. nitens* veneers, and commercially finished *E. obliqua* overlay floor boards;
2. Sawmill B supplied the boards for fiber-managed *E. nitens*;
3. Sawmill C locally manufactured the *E. nitens* plywood used as the substrate used in one of the engineered flooring prototypes;
4. The timber for densified samples was obtained from 26-yr-old sawlog *E. nitens* harvested from plantations located in Ridgely, Tasmania;
5. The marine plywood used as the substrate for other engineered flooring prototypes and Tasmanian Oak engineered flooring products were commercially acquired.

The densification process for sawlog *E. nitens* was conducted at the University of Melbourne. The densification involved three stages adapted from Tenorio and Moya (2019): stage 1 – preheating at 150°C for 10 min; stage 2 – compression perpendicular to the grain until reaching the target thickness of 12 mm (compression ratio of 25%) for 20 min, at the temperature maintained in stage 1; and stage 3 – cooling, the timber was kept compressed but without heat (platens temperature <60°C) for an additional 10 min (Belleville 2021). The compositions of the prototypes used in the trial are presented in Table 2.

The 1.2 mm thick top layers in prototypes $S_{1.2mp}$ and $S_{1.2np}$ were gained by laminating two 0.6 mm veneers together. The veneers were randomly selected from a commercial production line specialized to produce 0.6 mm thick veneers. The development of prototypes was conducted with existing production methods and the top layers of prototypes were laminated to the substrates using polyvinyl acetate using a hot press. All developed prototypes were tongue and groove profiled at the workshop.

Installation of the in-Service Trials

Both trials were installed consecutively at a high school in Launceston, Tasmania, enclosed in a glass-framed bridge linking two buildings. Each trial period was close to 1 yr and involved periodic visual assessments. The school was selected due to the continuity of traffic although moderate levels of traffic exposure and minimal use of stiletto heels were observed. The glass-framed corridor (Fig 1) facilitated dimensional stability and color change observations under extreme environmental conditions.

All timber boards were fixed to 16 mm structural plywood panels using elastomeric glue and secret nailed at the CSAW workshop before installation. This resulted in five panels in the solid flooring trial and eight panels in the engineered flooring trial. Each panel was then manually coated with a two-pack polyurethane waterborne coating system with a clear satin finish replicating industry practices, excluding the commercial Tasmanian Oak engineered flooring product (O_3) which had a prefinished UV-cured coating.

A solid flooring trial was installed on the existing reinforced concrete floor. It was monitored during the period of December 2020 to June 2022. The panels were laid and fixed to the concrete floor

Table 2. Composition of the tested prototypes in the engineered flooring trial.

Specimen codes	Flooring composition	Layer thickness (mm)	Cross section (mm)	Layer density (kg m^{-3})	Average composite density (kg m^{-3})	Layer description
S_{6a}	Sawlog *Eucalyptus nitens*	6.00	12.6 × 85	565 (7.48)	630 (13.59)	Top layer
	Marine plywood	6.00		495 (6.82)		Core layer
	E. nitens veneer	0.60		430 (3.99)		Backing layer
F_6	Fiber *E. nitens*	6.00	12.6 × 85	495 (7.59)	575 (6.96)	Top layer
	Marine plywood	6.00		495 (6.82)		Core layer
	E. nitens veneer	0.60		430 (3.99)		Backing layer
S_{6b}	Sawlog *E. nitens*	6.00	12.0 × 85	565 (7.48)	620 (9.69)	Top layer
	Marine plywood	6.00		495 (6.82)		Core layer
D_{12}	Densified *E. nitens*	12.00	12.0 × 85	670 (13.23)	670 (13.23)	One layer
$S_{1.2mp}$	*E. nitens* veneer	1.20	13.8 × 85	430 (3.99)	555 (3.86)	Top layer
	Marine plywood	12.00		495 (6.82)		Core layer
	E. nitens veneer	0.60		430 (3.99)		Backing layer
$S_{1.2np}$	*E. nitens* veneer	1.20	13.8 × 85	430 (3.99)	750 (6.88)	Top layer
	Local fiber *E. nitens* plywood	12.00		765 (6.65)		Core layer
	E. nitens veneer	0.60		430 (3.99)		Backing layer
O_{12}	Solid *Eucalyptus obliqua*	12.00	12.0 × 85	715 (7.38)	715 (7.38)	One layer
O_3	Prefinished Tasmanian Oak	3.20	14.2 × 165	625 (9.12)	605 (8.16)	Top layer
	Rubberwood (*Hevea*)	11.0		587 (6.02)		Segmented core

Specimen codes signify the top layer whether sawlog, fiber, or densified *E. nitens* followed by top layer thickness in millimeters. The coefficient of variation percentage for density is shown in the parenthesis.

using secret nailing and a clipping system. The trial was visually monitored fortnightly to check if significant shrinkages or indentations occurred. The temperature and RH of the environment was recorded as well as the amount of traffic over the floor. After the solid flooring trial was uninstalled, the engineered flooring panels were installed and monitored during July 2022 to April 2023, replicating the methods used in the solid trial.

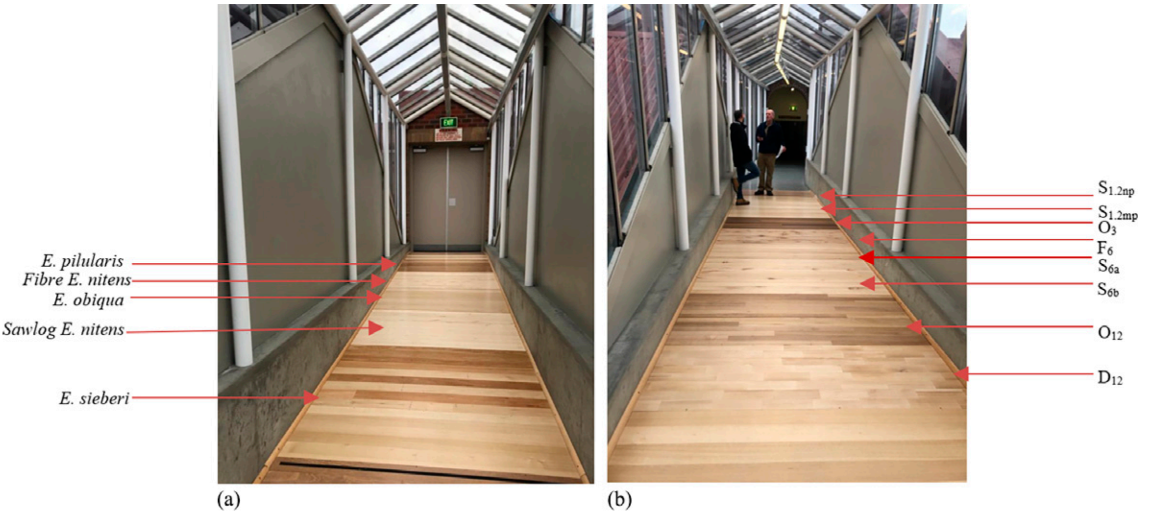


Figure 1. In-service trials (a) solid flooring trial and (b) engineered flooring trial.

Dynamic Hardness Test Using Falling Ball Indentation Method

Dynamic hardness was evaluated on solid and engineered timber flooring panels after they were uninstalled from the school premises. The test was conducted on the panels along with the 16 mm structural plywood backing used for installation in the school and were rested on a flat, reinforced concrete floor at the CSAW workshop to replicate in-service conditions. The test was developed as an adaptation from ASTM D 1037 (1999) and ASTM D 2394 (2017) following the methodology used by Acuña et al (2020) and Sepliarsky et al (2022). The timber hardness was defined by measuring the footprint diameter caused due to the impact from a 536 g and 50 mm diameter steel ball dropped from a determined height.

The steel ball was dropped from each reference height on the test panels using an auxiliary plastic pipe with holes at respective drop heights to guarantee precise height reference. A sheet of carbon paper was placed on the test panel surface to improve the accuracy of the impact reading. The surface deformation was measured using a digital caliper. Since an elliptical deformation was formed on the timber surface due to the differences in compressive strengths in the parallel direction as well as fibers in the perpendicular direction, the footprint diameter was calculated as an average between the highest and lowest observations (Acuña et al 2020; Sepliarsky et al 2022). This method allowed the comparison of both solid and engineered flooring based on the deformation produced by the steel ball. Ten hits per one drop height were conducted on each timber panel making sure that every timber board in the panel was reported once for each drop height. The hits were made at least 50 mm apart resulting in 120 hits per panel (Fig 2).

Statistical Analysis

The statistical analysis was conducted using R software for the data obtained from dynamic hardness tests. Altogether data from approximately 130 timber boards (from 13 panels: the five panels in the solid flooring trial and eight panels in the engineered flooring trial with 10 boards tested from each panel), were analyzed. The assumptions of normality, independence, and equal variances were verified for the data sets. The normality of the data was checked for each sample group at different drop heights using the Shapiro-Wilk test. The assumption of equal variances was contrasted by the Bartlett test on several occasions so that linear statistical methods using ANOVA could not be used. In this regard, Welch's heteroscedastic F test with trimmed means and winsorised variances was used in the analysis (Acuña et al 2020).

RESULTS AND DISCUSSION

In-Service Trials

During the monitored period of the solid flooring trial, no significant stability concerns were observed in the tested panels. The RH and temperature records (Fig 3) show that the environment showed high fluctuations due to the glass roof of the corridor which allowed the sunlight to fall on the timber during daytime. The pedestrian counter located at the entrance to the corridor showed that the solid flooring trial was exposed to 30,000 passes over the tested period (around 50 passes per day). The rationale of the trial was to assess the performance of plantation *E. nitens* in a domestic/light commercial application in comparison with *E. obliqua* (Tasmanian Oak sp.) which is a popular flooring species used for centuries in Australia. Tasmanian Oak is specified by the British Standard *BS EN 8201:2011: Code of practice for installation of flooring of wood and wood-based panels* as suitable for floors with light pedestrian traffic with traffic intensities less than 500 persons per day (BS 8201 2011). Therefore, visual assessments were conducted between plantation *E. nitens* and *E. obliqua* when subjected to similar traffic exposure for comparison. The traffic conditions at the installed site were less than expected due to the COVID-19 lockdowns but were still higher than a typical domestic dwelling.

However, the fiber-managed *E. nitens* panel started to show cracks during the first 3 mo of installation as shown in Fig 4. No such

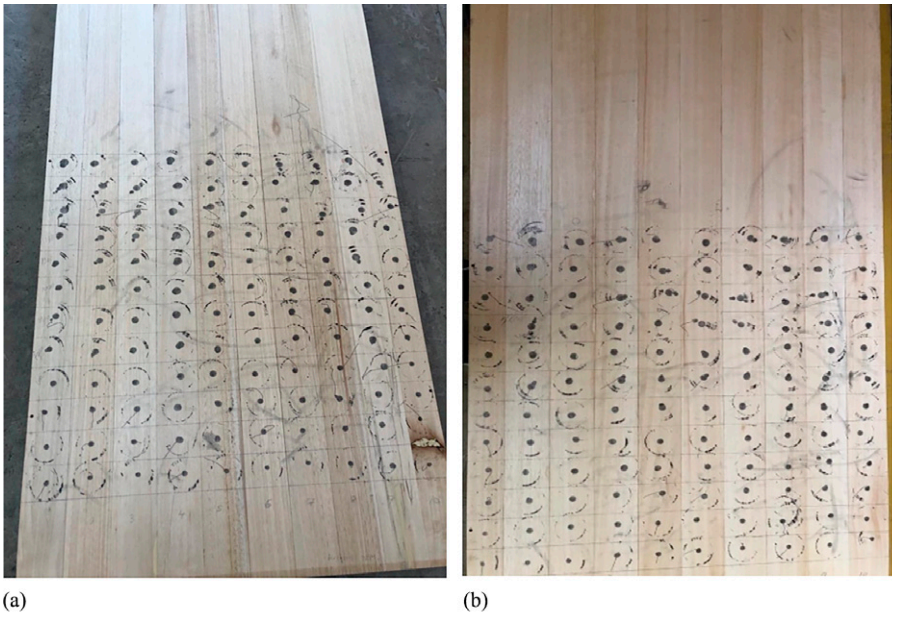


Figure 2. Footprint diameter caused by the steel ball on tested panels (a) 6 mm thick *Eucalyptus nitens* top layer and (b) 1.2 mm thick *E. nitens* top layer.

observations were found in sawlog-managed *E. nitens* boards (Fig 4). Visual assessment of all panels after the in-service period showed distinctive lightening of the timbers' original color due to the exposure of sunlight and *E. pilularis* showed the highest visual shrinkage while *E. obliqua* showed the lowest. Few indentation and scuff marks were seen in both *E. obliqua* and

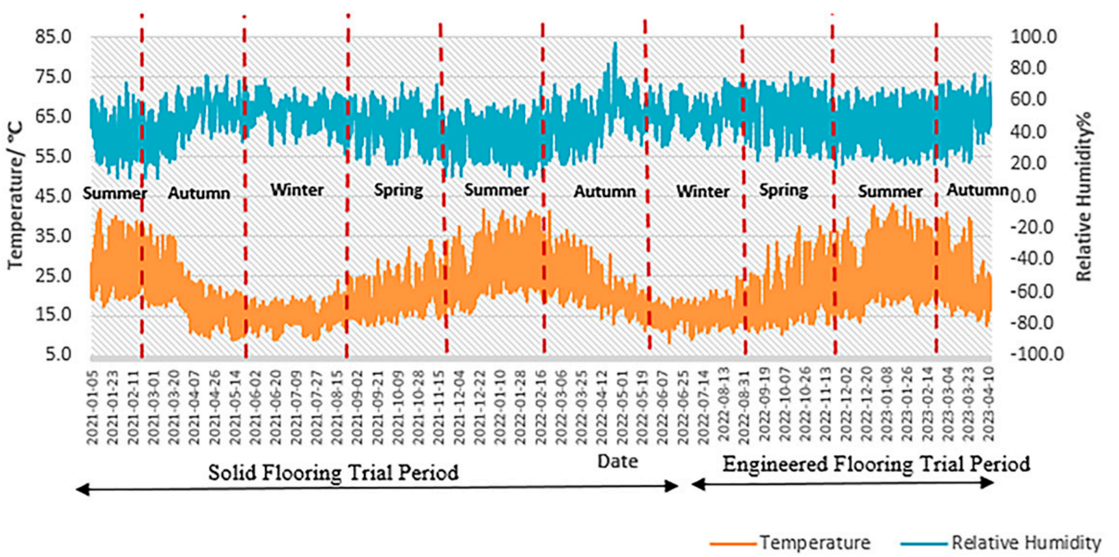


Figure 3. RH and temperature variation during the in-service trials.


(a) (b)

Figure 4. Visual observations of solid *Eucalyptus nitens* after in-service trial (a) fiber *E. nitens* boards showing cracks marked in red and (b) sawlog *E. nitens* panels.

E. nitens panels caused by footwear and cleaning equipment being dragged over the floor.

The consecutive engineered flooring trial was exposed to 11,200 passes of traffic (approximately 37 passes per day). Even the prototypes with 1.2 mm top layers showed no major indentation or scuff marks. The commercial engineered flooring control product (O_3) showed lesser surface color change in comparison with the rest of the panels (Fig 5).

As shown in F_6 of Fig 5, the fiber *E. nitens* panel had a high level of features including knots that impacted the aesthetic acceptance of the product among architects and specifiers. There is no commercial facility in Australia to conduct densification and the densified boards shown in D_{12} of Fig 5 were prepared in a laboratory setting. The densified boards were shorter in length in comparison with other tested prototypes, due to the dimensional restrictions of the laboratory-scale densifier.

Dynamic Hardness Assessment Using Falling Ball Indentation Test

After removing the panels from the installation site, they were subjected to a falling ball indentation test. The solid flooring panels were analyzed first. Residual footprint diameter values (mm) and their coefficient of variation for the tested species in the solid flooring trial are shown in Table 3. All the groups showed $p > 0.05$ in the Shapiro-Wilk normality test allowing the assumption of normality in the data sets.

The footprint diameter showed a clear tendency to increase when the drop height increased as shown in Fig 6 for solid timber flooring. The high-density species *E. pilularis* and *E. sieberi* showed lower footprint diameters in comparison with *E. obliqua* and *E. nitens*.

This was further confirmed by the statistical analysis conducted using Welch's ANOVA test which showed significance between the five tested timber groups in all drop heights. The Posthoc pairwise comparison between groups per each height showed a similar trend, as *E. pilularis* and *E. sieberi* were significantly different from fiber *E. nitens*, solid *E. nitens*, and *E. obliqua* in all drop heights. *E. pilularis* and *E. sieberi* were not statistically significant from each other in any of the tested drop heights (Table 4).

In the next stage, engineered timber flooring prototypes and controls used were subjected to the same test. The footprint diameter and coefficients of variations for the tested panels are shown in Table 5. Similar to the solid flooring data, the data sets in groups showed $p > 0.05$ proving the normality of the data sets but did not have equal variances according to the Bartlett test and showed an increase in footprint diameter with the increase of drop height in all the tested panels.

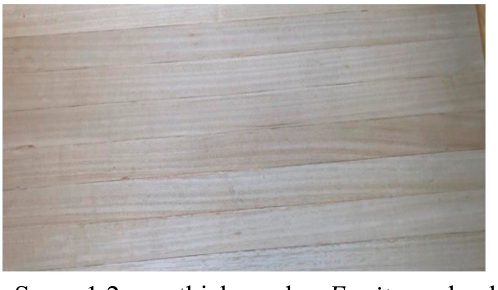
S_{6a}: 6 mm thick sawlog *E. nitens* glued to marine ply substrate and veneer backing

S_{6b}: 6 mm thick sawlog *E. nitens* glued to marine ply substrate

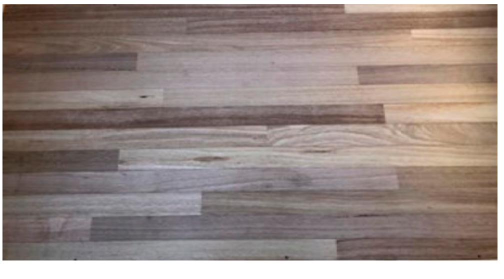
F_{6}: 6 mm thick fibre *E. nitens* glued to marine ply substrate and veneer backing

D_{12}: 12 mm thick solid, densified *E. nitens*

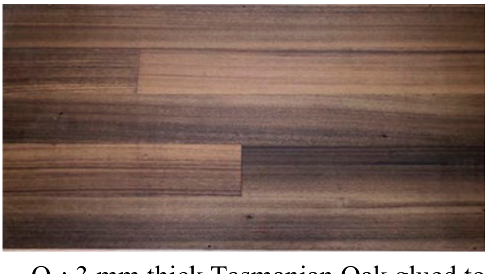
$S_{1.2mp}$: 1.2 mm thick sawlog *E. nitens* glued to marine ply substrate and veneer backing



$S_{1.2np}$: 1.2 mm thick sawlog *E. nitens* glued to *E. nitens* ply substrate and veneer backing



O_{12}: 12 mm thick *E. obliqua* overlay (commercial product used as control)



O_{3}: 3 mm thick Tasmanian Oak glued to Rubberwood substrate (prefinished, commercial product used as control)

Figure 5. Surface of the tested panels in the engineered flooring in-service trial.

Table 3. Footprint diameter of species in solid flooring trial. Main descriptive statistics.

Height (m)	Fiber *Eucalyptus nitens*	Sawlog *E. nitens*	*Eucalyptus obliqua*	*Eucalyptus sieberi*	*Eucalyptus pilularis*
0.15	**10.39** (6.65)	**9.82** (11.82)	**9.93** (7.18)	**6.96** (11.92)	**7.01** (5.63)
0.30	**12.24** (7.06)	**11.82** (13.10)	**10.94** (8.80)	**8.09** (9.64)	**8.45** (6.29)
0.45	**13.09** (7.23)	**12.86** (14.99)	**12.26** (7.74)	**9.08** (8.55)	**8.99** (8.06)
0.60	**13.64** (8.12)	**13.95** (12.00)	**13.61** (7.42)	**9.82** (8.25)	**9.74** (7.70)
0.75	**14.37** (8.28)	**14.48** (12.78)	**13.78** (8.52)	**10.26** (9.44)	**10.74** (10.31)
0.90	**14.83** (9.26)	**13.94** (13.89)	**14.65** (8.40)	**10.68** (7.38)	**11.47** (6.15)
1.05	**15.13** (10.37)	**15.05** (14.25)	**15.01** (8.00)	**10.91** (7.87)	**11.79** (7.98)
1.20	**15.50** (6.13)	**16.04** (12.26)	**15.03** (6.50)	**11.47** (8.76)	**11.88** (7.00)
1.35	**16.37** (5.02)	**15.74** (5.37)	**15.53** (8.13)	**11.54** (8.47)	**11.70** (7.70)
1.50	**16.24** (4.20)	**16.04** (5.71)	**15.55** (5.74)	**11.79** (10.92)	**11.93** (6.79)
1.65	**16.51** (6.20)	**16.44** (7.13)	**15.66** (8.08)	**11.79** (7.57)	**12.39** (8.61)
1.80	**16.69** (4.45)	**16.64** (7.73)	**16.17** (8.18)	**12.59** (10.15)	**12.30** (6.29)

Mean values in mm appear in bold. The coefficient of variation percentage is shown in the parentheses.

Since S_{6a} and S_{6b} prototypes both showed similar observations, only prototype S_{6a} with 0.6 mm backing layer was used in the statistical analysis as the rest of the designed engineered prototypes had the same design structure. Similar to the observations in the solid flooring trial, the footprint diameter showed a clear tendency to increase with increasing of drop height of the steel ball as shown in Fig 7. Figure 7 also shows the trends observed between the engineered prototypes in comparison with solid sawlog *E. nitens*, solid fiber *E. nitens*, and solid *E. pilularis* boards used in the solid flooring trial.

As shown in Fig 7, prototypes containing 6 mm top layers in sawlog *E. nitens* and fiber *E. nitens* and commercial Tasmanian Oak products with 3 mm thick top layers did not show much variation from the solid boards of the same species. Densified *E. nitens* showed the lowest footprint

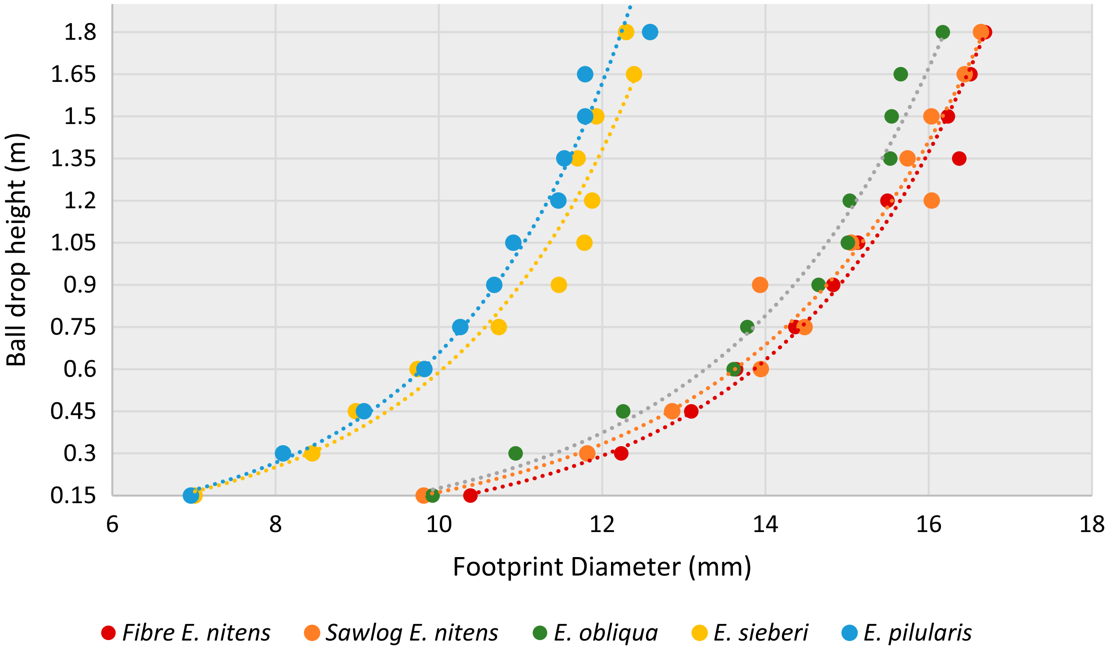


Figure 6. Footprint diameter with different drop heights.

Table 4. Pairwise comparison of solid timber flooring per species and drop height.

Drop height	*p* value from Welch ANOVA	Posthoc pairwise comparison*				
		Sawlog *Eucalyptus nitens*	Fiber *E. nitens*	*Eucalyptus obliqua*	*Eucalyptus pilularis*	*Eucalyptus sieberi*
All heights (0.15-1.8 m)	$p < 0.01$ for all drop heights	a, b	a, c	b, c	d	d

*The same lowercase letter indicates that the pairs are homogenous (ex: a: Sawlog and fibre E. nitens were not statistically significant).

diameter which means the highest impact resistance out of the developed prototypes, followed by 1.2 mm veneer product with *E. nitens* plywood substrate. In contrast, the lowest impact resistance was observed in 1.2 mm *E. nitens* veneer products with marine plywood substrate. It was also observed that the variation of footprint diameter data observed for each drop height was lower in the two veneer products in comparison with the higher-thickness top layers. Solid *E. pilularis* showed the lowest footprint diameter when compared with all products tested in both solid and engineered flooring trials.

Considering the possible deviations from the homoscedasticity of data, Welch's heteroscedastic F test with trimmed means and winsorised variances was used to perform comparisons between the different data groups. The results are presented in Table 6.

To identify the impact of design factors on the impact resistance of tested flooring prototypes, the analysis was conducted on four different categories using the data obtained from both solid and engineered trials. These included four groups evaluating the significance of: a) different top layer material, b) different thicknesses of the same top layer, c) different substrates, and d) comparison with the controls O_{12} and O_3. It should be noted that this experiment is based on a specific experimental design with customized conditions with panels been fixed to structural plywood to replicate in-serve installation, and the results may vary depending on environmental factors, in-service conditions, and installation techniques. Table 6 proves that the pairs compared show statistically significant differences in similar test conditions with the same drop height. Most number of statistically significant differences were observed among the pairs at the 1.8 m drop height of the steel ball. Key observations are as follows:

Impact of different top layers (group a): Other than one pair, all others compared showed significant differences at least for one height. A 6 mm top layers of fiber *E. nitens* (F_6) and sawlog-managed *E. nitens* (S_{6a}) did not show

Table 5. Footprint diameter of prototypes used in engineered flooring trial. Main descriptive statistics (prototype designation as mentioned in Table 2).

Height (m)	D_{12}	S_{6a}	S_{6b}	F_6	$S_{1.2np}$	$S_{1.2mp}$	O_{12}	O_3
0.15	**8.62** (9.68)	**9.20** (11.27)	**9.84** (11.61)	**9.55** (9.57)	**9.80** (11.13)	**9.82** (8.54)	**9.21** (8.84)	**8.74** (10.62)
0.30	**9.86** (8.55)	**10.81** (11.66)	**11.21** (8.18)	**11.27** (17.17)	**11.43** (8.90)	**11.33** (6.73)	**10.67** (8.12)	**11.34** (7.97)
0.45	**11.25** (6.42)	**12.08** (11.94)	**12.14** (8.65)	**12.61** (13.32)	**12.42** (8.59)	**12.88** (6.36)	**11.91** (7.29)	**11.95** (6.17)
0.60	**11.88** (7.72)	**12.72** (8.85)	**12.60** (16.94)	**12.97** (13.46)	**12.92** (8.09)	**13.91** (8.04)	**12.47** (6.13)	**12.83** (8.32)
0.75	**13.15** (6.07)	**13.41** (9.17)	**13.97** (7.99)	**13.99** (13.37)	**13.09** (4.90)	**14.38** (5.42)	**13.43** (11.29)	**13.56** (8.56)
0.90	**13.53** (9.38)	**14.48** (9.33)	**15.06** (10.07)	**15.28** (14.41)	**13.94** (6.10)	**15.07** (5.93)	**13.57** (10.77)	**13.50** (7.02)
1.05	**13.25** (10.00)	**14.21** (8.62)	**15.63** (8.00)	**14.94** (16.80)	**14.36** (6.69)	**15.55** (5.19)	**13.96** (10.39)	**14.55** (7.85)
1.20	**13.63** (8.24)	**15.05** (11.77)	**15.65** (6.54)	**14.52** (22.34)	**14.84** (3.98)	**16.36** (5.82)	**14.60** (8.94)	**14.87** (9.50)
1.35	**14.48** (8.68)	**15.84** (9.54)	**15.90** (7.36)	**15.95** (15.15)	**14.82** (4.09)	**16.83** (5.48)	**14.90** (8.35)	**15.00** (7.54)
1.50	**14.41** (6.83)	**15.79** (7.85)	**16.61** (7.53)	**15.96** (14.96)	**15.28** (4.34)	**17.09** (4.43)	**15.11** (8.41)	**15.33** (5.36)
1.65	**14.61** (7.88)	**16.24** (8.17)	**16.73** (7.54)	**16.88** (14.45)	**15.18** (7.32)	**17.01** (3.98)	**15.35** (7.69)	**15.42** (6.32)
1.80	**14.52** (7.88)	**17.05** (8.73)	**17.24** (10.84)	**17.47** (6.48)	**15.86** (5.30)	**17.57** (5.06)	**15.74** (10.64)	**15.85** (5.67)

Mean values in mm appear in bold. The coefficient of variation percentage is shown in the parentheses.

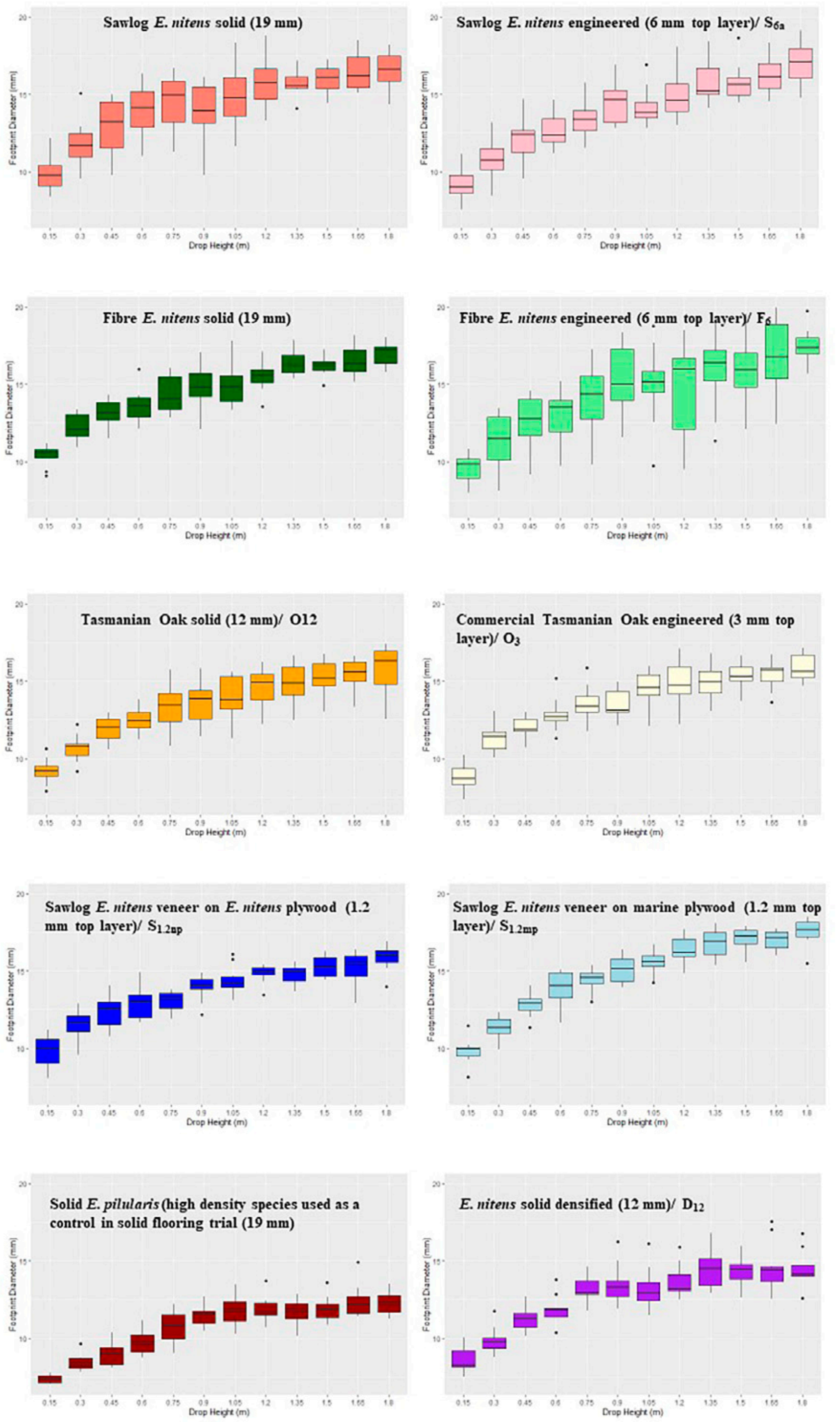


Figure 7. Boxplot graphics: footprint diameter trend against ball drop height for different flooring products.

Table 6. Pairwise comparison of footprint diameter of prototypes.

Pairs	Drop height (m)											
	0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20	1.35	1.50	1.65	1.80
Group a: different top layers												
F_6 (6mm Fiber *Eucalyptus nitens*) × S_{6a} (6mm Sawlog *E. nitens*)	=	=	=	=	=	=	=	=	=	=	=	=
F_6 (6mm Fiber *E. nitens*) × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on E. nitens Plywood)	=	=	=	=	=	=	=	=	=	=	=	×
D_{12} (12mm Densified *E. nitens*) × Solid 19 mm Sawlog *E. nitens*	×	×	×	×	=	=	×	×	×	×	×	×
D_{12} (12mm Densified *E. nitens*) × S_{6a} (6mm Sawlog *E. nitens*)	=	×	=	=	=	=	=	=	=	×	×	×
D_{12} (12mm Densified *E. nitens*) × F_6 (6mm Fiber *E. nitens*)	×	=	×	=	=	×	×	=	=	=	×	×
D_{12} (12mm Densified *E. nitens*) × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* Plywood)	×	×	×	×	×	=	×	=	=	=	=	×
D_{12} (12mm Densified *E. nitens*) × $S_{1.2mp}$ (1.2 mm Sawlog *E. nitens* on Marine Plywood)	×	×	×	×	×	×	×	×	×	×	×	×
Group b: different top layer thicknesses												
Solid 19 mm Sawlog *E. nitens* × S_{6a} (6 mm Sawlog *E. nitens*)	=	=	=	=	=	=	=	=	=	=	=	=
Solid 19 mm Sawlog *E. nitens* × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* ply)	=	=	=	=	=	=	=	=	×	=	=	=
Solid 19 mm Sawlog *E. nitens* × $S_{1.2mp}$ (1.2mm Sawlog *E. nitens* on Marine Plywood)	=	=	=	×	=	=	=	=	×	×	=	×
S_{6a} (6 mm Sawlog *E. nitens*) × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* Plywood)	=	=	=	=	=	=	=	=	×	=	=	=
S_{6a} (6 mm Sawlog *E. nitens*) × $S_{1.2mp}$ (1.2mm Sawlog *E. nitens* on Marine Plywood)	=	=	=	×	×	=	×	=	=	×	=	=
Solid 19 mm Fiber *E. nitens* × F_6 (6mm Fiber *E. nitens*)	×	=	=	=	=	=	=	=	=	=	=	=
O_{12} (12mm Solid *Eucalyptus obliqua*) × O_3 (3mm Tasmanian Oak on Rubberwood)	=	=	=	=	=	=	=	=	=	=	=	=
Group c: different substrates												
$S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* Plywood) × $S_{1.2mp}$ (1.2mm Sawlog *E. nitens* on Marine Plywood)	=	=	=	×	×	×	×	×	×	×	×	×
Group d: comparison with controls												
O_{12} (12mm Solid *E. obliqua*) × S_{6a} (6mm Sawlog *E. nitens*)	=	=	=	=	=	=	=	=	=	=	=	=
O_3 (3mm Tasmanian Oak on Rubberwood) × S_{6a} (6mm Sawlog *E. nitens*)	=	=	=	=	=	=	=	=	=	=	=	=
O_{12} (12mm Solid *E. obliqua*) × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* Plywood)	=	=	=	=	=	=	=	=	=	=	=	=
O_3 (3mm Tasmanian Oak on Rubberwood) × $S_{1.2np}$ (1.2mm Sawlog *E. nitens* on *E. nitens* Plywood)	=	=	=	=	=	=	=	=	=	=	=	=
O_{12} (12mm Solid *E. obliqua*) × $S_{1.2mp}$ (1.2mm Sawlog *E. nitens* on Marine Plywood)	=	=	×	×	×	×	×	×	×	×	×	×
O_3 (3mm Tasmanian Oak on Rubberwood) × $S_{1.2mp}$ (1.2mm Sawlog *E. nitens* on Marine Plywood)	×	=	×	×	=	×	=	×	×	×	×	×
O_{12} (12mm Solid *E. obliqua*) × F_6 (6mm Fiber *E. nitens*)	=	=	=	=	=	=	=	=	=	=	=	×
O_3 (3mm Tasmanian Oak on Rubberwood) × F_6 (6mm Fiber *E. nitens*)	=	=	=	=	=	×	=	=	=	=	=	×
O_{12} (12mm Solid *E. obliqua*) × D_{12} (12mm Densified *E. nitens*)	=	×	=	=	=	=	=	=	=	=	=	=
O_3 (3mm Tasmanian Oak on Rubberwood) × D_{12} (12mm Densified *E. nitens*)	=	×	×	×	=	=	×	×	=	×	=	×

×, difference is statistically significant ($p < 0.05$); =, difference is not statistically significant ($p > 0.05$).

statistical significance in all tested drop heights. F_6 showed significantly lower impact resistance with veneer product on *E. nitens* plywood substrate ($S_{1.2np}$) only at 1.8 m drop height. Densified *E. nitens* (D_{12}) showed statistically significant higher impact resistance in all tested pairs and was statistically different with 1.2 mm veneer product on marine plywood substrate ($S_{1.2mp}$) at all the considered drop heights.

Impact of different top layer thicknesses (group b): A 19 mm thick solid sawlog *E. nitens* did not show statistical difference with 6 mm top layer of the same species. Similar observations resulted with fiber *E. nitens* where statistical difference was only observed at the lowest drop height of 0.15 m. *E. obliqua* 12 mm thick solid overlay (O_{12}) and 3 mm thick Tasmanian Oak top layer in the commercial engineered product (O_3) also did not show statistical difference at any of the drop heights, suggesting that higher thicknesses in top layers (3-6 mm as observed in the present study) showed similar behavior with solid boards of the same species. However, the two veneer products with 1.2 mm top layers showed significant differences with higher thickness material. $S_{1.2np}$ showed significantly higher impact resistance at 1.35 m drop height with 19 and 6 mm thick sawlog *E. nitens* products. In contrast, $S_{1.2mp}$ showed significantly lower impact resistance with 19 mm sawlog *E. nitens* in four heights (0.6, 1.35, 1.5, and 1.8 m) and with 6 mm sawlog *E. nitens* in four drop heights as well (0.6, 0.75, 1.05, and 1.5 m). This proves that at thinner top-layer thicknesses, the impact resistance is governed by the substrate rather than the top-layer properties.

Impact of different substrates (group c): A comparison was conducted between the two veneer products which had similar structures and designs other than the core layer material. The results showed that $S_{1.2mp}$ with marine plywood (density: 495 kg m^{-3}) was significantly lower in impact resistance measured as footprint diameter in the majority of the tested drop heights (0.6-1.8 m) when compared with $S_{1.2np}$ with *E. nitens* plywood core layer (density: 765 kg m^{-3}) further confirming the observations of group b.

Comparison with controls (group d): All engineered prototypes developed were compared with 12 mm *E. obliqua* overlay (O_{12}) and the prefinished Tasmanian Oak commercial engineered product (O_3). O_{12} and O_3 both did not show significant differences with sawlog *E. nitens* engineered products (S_{6a} and $S_{1.2np}$) in all tested drop heights. O_{12} and O_3 both showed statistically higher impact resistance with F_6 in 1.8 m drop height. Both O_{12} and O_3 showed higher impact resistance in most of the tested drop heights in comparison with 1.2 mm sawlog *E. nitens* with marine ply substrate ($S_{1.2mp}$). O_{12} and densified *E. nitens* (D_{12}) were statistically different only at 0.3 m drop height while O_3 was statistically different with D_{12} in seven drop heights (0.3, 0.45, 0.6, 1.05, 1.2, 1.5, and 1.8 m).

At the start of this research, no published studies were available on how Tasmanian plantation-grown *E. nitens* would behave in a flooring application. An in-service trial conducted at the premises of the University of Tasmania during 2007-2009 indicated that only a few millimeters of resanding was required to remove the indentations caused by stiletto heels during the in-service trial. This was found to be comparable to native *E. obliqua* which was used as a control in the study. However, these findings were from personal communication with the research team, and due to unforeseen circumstances, it had not been reported. To understand how this novel timber resource would behave in flooring applications, it was decided to install a solid flooring trial before designing the engineered flooring prototypes. The observations proved that sawlog-managed *E. nitens* behaved comparable to native *E. obliqua* in stability considerations and had an aesthetic appeal due to its lighter color similar to Scandinavian timbers which is currently in trend in the flooring market. There are few studies reported in the literature on in-service trials, in comparison with studies based on analysis of individual timber properties. Harper (1961) is one of the early literatures mentioning the use of in-service trials for flooring materials. Harper (1961) suggests that it is an essential requirement in practical trials of materials that they should have usage of equivalent type and need to be as severe as possible to generate quick results. These two requirements have resulted in most researchers selecting places of high traffic exposure and large spaces for a series of finished products to be laid. The study further suggests that if the traffic remains constant or can be counted, several successive series can be compared for the purpose. Although moderate traffic conditions and exposure to sunlight were observed in the premises where the in-service trials were conducted in the present study, it facilitated quick results under extreme environmental conditions and provided higher traffic exposure than expected in an usual domestic application. Since the study is focusing on the potential of using plantation *E. nitens* in domestic or light commercial applications, the conditions herein provide comparable exposure situations.

It was observed that both types of engineered prototypes: consisting of 6 mm thick *E. nitens* top layers and 1.2 mm thick *E. nitens* top layers behaved comparatively as per visual observations. However, further analysis is recommended to understand how the 1.2 mm thick top layers might behave when exposed to the conditions over longer time periods and more traffic exposure. The feedback received on the developed prototypes from several architects and flooring manufacturers had different focuses on the significance of the thickness of top layers of engineered flooring products. The architects preferred 6 mm thick top layers as it gave them confidence in specifying the product with the knowledge of the possibility to resand the product and considered the product to be more sustainable as it ensured longer life spans for the product. However, some flooring manufacturers and experts expressed that most domestic household floors never get resanded and usually get replaced when the installed product gets out of fashion and that both 6 and 1.2 mm products provided the same surface appearance which is the major consideration by many domestic consumers when selecting a product.

Previous research suggests that dynamic hardness tests may more reliably simulate timber flooring performance in-service than static load tests (Oliveira et al 2019; Acuña et al 2020; Sepliarsky et al 2022). In addition, it can be conducted on an installed floor without the need for sophisticated equipment. As per ASTM D 2394 (2017), the falling ball indentation test requires to determine the indentation index by determining the intercept at 1.8 m drop height from the plotted graph between the drop heights and indentation depth. The present study conducted a modified approach to the method as followed by Acuña et al (2020) and Sepliarsky et al (2022), and used indentation diameter instead of the indentation depth as measuring the footprint diameter is more precise than measuring the indentation depth (Sepliarsky et al 2022).

Based on the observations of the falling ball indentation results in the present study, different top layer properties (densification), top layer thicknesses, and substrates had an impact on the residual footprint diameter caused by the steel ball. The observations showed that 6 and 3 mm thick top layers behaved similarly to a 19 mm thick solid timber board of the same species. This observation is different from the observations reported in Sepliarsky et al (2022) where the majority of significant differences were observed between solid timber boards of 25 mm thick *Q. robur* and *Hymenaea courbaril* and 16 mm thick *Eucalyptus globulus* and *Eucalyptus grandis* when compared with 3 mm thick top layer engineered products from each species when subjected to falling ball impact test of three diameter types of steel balls (50, 40, and 30 mm) at five drop heights (0.60, 0.75, 0.90, 1.05, and 1.20 m). The engineered products used in the study had a 9 mm thick high-density fiberboard substrate (density: 850 kg m^{-3}) and an additional 2 mm thick *Pinus radiata* layer (density: 500 kg m^{-3}) backing. *E. globulus* (density: 855 kg m^{-3}) and *E. grandis* (density: 490 kg m^{-3}) used in the study were fast-growing plantation timber from Spain. Figure 8 shows the results obtained in the present study for solid boards of sawlog- and fiber-managed *E. nitens* and *E. obliqua* in

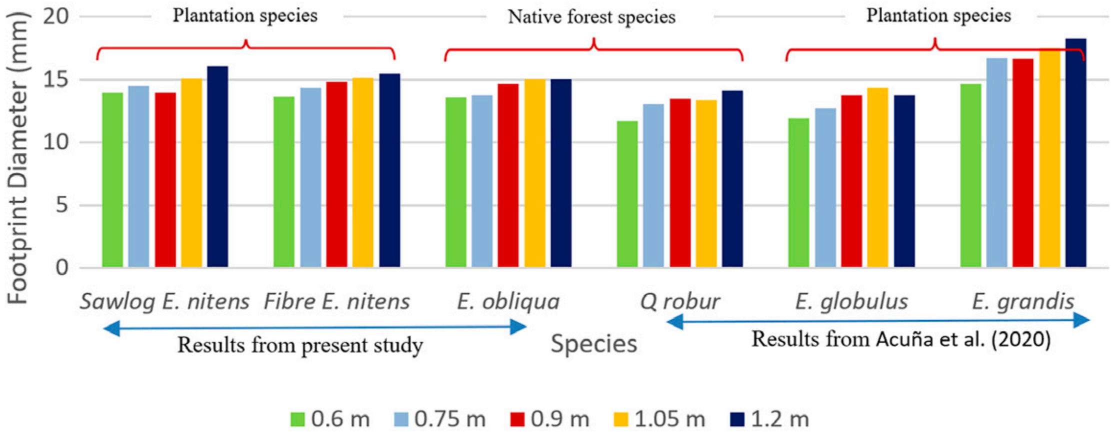


Figure 8. Comparison of the results from the present study with Acuña et al (2020).

comparison with values obtained in Acuña et al (2020) for solid *Q. robur*, *E. globulus*, and *E. grandis* boards subjected to the impact of a 50 mm diameter steel ball when dropped from five height intervals ranging from 0.60 to 1.20 m.

The results for footprint diameter of sawlog *E. nitens* (density: 510 kg m^{-3}), fiber *E. nitens* (density: 480 kg m^{-3}) and *E. obliqua* (density: 600 kg m^{-3}) in the present study were higher than those reported in Acuña et al (2020) for *Q. robur* (density: 685 kg m^{-3}) and *E. globulus* (density: 855 kg m^{-3}) but lower than those reported for plantation *E. grandis* (density: 490 kg m^{-3}). The differences in density of the tested species likely account for these observations. Furthermore, Sepliarsky et al (2022) reported an extension to the results from Acuña et al (2020), where comparisons were conducted between solid boards and 3 mm thick engineered flooring products from *Q. robur, H. courbaril, E. globulus*, and *E. grandis* with engineered products with 0.6 mm veneers from the same species. The top layer consisted of a sliced 0.6 mm veneer, a 9 mm thick HDF panel (density: 850 kg m^{-3}), and a 0. 5 mm thick *P. radiata* backing veneer (density: 500 kg m^{-3}). Similarly, the 1.2 mm *E. nitens* top layers used in the prototypes in the present study consisted of 0.6 mm sliced veneer which was glued together to obtain a 1.2 mm thickness. The results by Sepliarsky et al (2022) suggests lowest footprint diameter for each species was observed in the products with 0.6 mm veneer supporting the lower footprint diameters observed in the 1.2 mm thick top layer product with *E. nitens* plywood substrate in the present study. Similarly, the present study confirms that the design configuration of engineered timber flooring has an impact on its structural performance, especially when thinner top layers are of concern. In lower thinner layers, the substrate layer is responsible for absorbing the impact energy and actively forces the outer layer to recover from the deformation caused by external force on the surface.

CONCLUSIONS

Based on the observations of the in-service trials and results from falling ball indentation tests, the following key outcomes can be highlighted.

Sawlog *E. nitens* solid boards and engineered flooring products with sawlog *E. nitens* top layers showed similar behavior in comparison with *E. obliqua* in the solid flooring trial and dynamic hardness tests. Hence, sawlog *E. nitens*, a short-rotation, low-density species, may hold potential as an alternative species for the domestic and light commercial flooring market, especially in view of the limited access to native, high-density species in the upcoming years. Some boards in the fiber

E. nitens panel showed cracks after 3 mo of installation in the solid flooring in-service trial. Although this reduced the aesthetic acceptance of the product, further assessment with falling ball indentation tests was conducted on the panel to determine the dynamic hardness of the product. Falling ball indentation tests were conducted to generate new knowledge on the resource and as an alternative test for traditional hardness tests, better simulating the in-service conditions of an end product. Fiber *E. nitens* showed lower indentation resistance in comparison with sawlog *E. nitens* and *E. obliqua* but the values were not significantly different. It should be noted that the age, density of the plantation, site productivity, and location were not considered in the present study due to the material having been obtained from commercial facilities. These variables could impact the results but are beyond the scope of this study.

Among the developed engineered flooring prototypes, the highest indentation resistance was reported for densified *E. nitens* based on falling ball indentation tests. However, the densified timber boards showed increased brittleness during the processing stage. Further research on densification techniques for *E. nitens* has been identified as an important future research area. With respect to design aspects, the replacement of the solid timber with 12 mm thick plywood as a substrate showed a significant variation in the resistance to indentation with top layers of 1.2 mm thickness. The footprint diameter caused on the 1.2 mm top layer product with *E. nitens* backing demonstrated performance comparable to (or better than) those of solid timber flooring and engineered flooring with a 6 mm thick top layer. Although both veneer products tested in the study showed similar behavior in-service, the falling ball indentation test showed that the high-density substrate resulted in a significantly lower footprint diameter due to impact energy caused by the dropping of the steel ball. Similar observations were reported in Sepliarsky et al (2022) and Sydor et al (2020, 2022), where high-density substrate improved the behavior of the flooring product in terms of hardness tests, regardless of the hardwood species used in thinner top layers. This implies that using a high-density substrate and thinner top layers (0.6-1.2 mm) of the solid wood may produce a high-quality, low-cost final product with better performance in terms of resistance to denting caused by dynamic impacts. For instance, many producers in Europe produce engineered flooring with veneer top layers with high-density fiberboard in the substrate claiming the resistance to impact is better than the conventional engineered flooring products with 3 mm thick top layers (Sepliarsky et al 2022). However, it is important to note that the technical lifespan of a product is reduced in such circumstances due to the limitations of recoating and resanding. Usually, veneer flooring with top layers less than 0.7 mm might only be subjected to recoating and not resanding (Sepliarsky et al 2022). Therefore, such products should be developed to suit an expected end-use application, so that the consumers understand the expected performance of the product.

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