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Author

Nguyen, Hoan H, Gilbert, Benoit P, McGavin, Robert L, Bailleres, Henri

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Names of Authors: Hoan H. Nguyen,[a] Benoit P. Gilbert,[a] Robert L. McGavin,[b] and Henri Bailleres[b]

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Affiliations and addresses of the authors:

a: School of Engineering and Built Environment, Griffith University, Australia;

b: Queensland Department of Agriculture and Fisheries, Horticulture and Forestry Science, Salisbury Research Facility, Australia;

Corresponding author: hoan.nguyenhai@griffithuni.edu.au, nguyenhaihoanvfu@gmail.com

Abstract

This paper presents a methodology to optimise the manufacturing strategy of structural cross-banded laminated veneer lumbers (LVL-C) manufactured by mixing species. The methodology is illustrated by blending native-forest spotted gum (*Corymbia citriodora*) with plantation southern pine (Caribbean pine (*Pinus caribaea var. hondurensis*) and slash pine (*Pinus elliottii var. elliottii*)) veneers. The aim is to minimise the cost of a family of products (i.e. several types of product manufactured from the same veneered stock) using a maximum allowable number of hardwood veneers, and in which each product has different targeted stiffness and embedment strength. Genetic algorithm, which is widely used in the optimisation of structural products, was selected as the optimisation algorithm. The orientation of the veneers and veneer grades are considered as design variables. Results show that the developed algorithm was able to consistently converge to similar solutions for all investigated cases, demonstrating its robustness. For all cases, the "high" modulus of elasticity graded spotted gum and southern pine veneers were found to be predominant in the final products. LVL-C are found in cases with high targeted embedment strength. Finally, the obtained optimum construction strategies are validated against experimental results.

Keywords: *Cross-banded laminated veneer lumber, genetic algorithm, embedment strength*

Introduction

Within Queensland's sustainably managed native forests, a supply of small diameter (*i.e*. less than 30 cm in diameter) spotted gum (*Corymbia citriodora* - SPG) logs is potentially available. Despite their high mechanical properties, these small diameter logs have limited opportunities for profitable conversion into value-added products. This is due to the incompatibility between the log size and traditional processing techniques. Processing small diameter logs through conventional sawing system leads to recovery rates well below 40% (McGavin et al. 2014). However, transforming these logs into rotary veneers, using low cost spindleless lathe technology, can produce recovery rates double that of sawing, thus providing a more attractive processing option (McGavin et al. 2014). While the quantity of the aforementioned SPG logs is yet to be determined, a large quantity of plantation softwood southern pine (Caribbean pine (*Pinus caribaea var. hondurensis*) and slash pine (*Pinus elliottii var. elliottii*) – SP) and Hoop Pine (*Araucaria cunninghamii* - HP) logs are available. These logs have lower mechanical properties than SPG logs and their likelihood of being used in the manufacture of high performing structural products is limited. However, manufacturing structural products, such as veneer-based products (VBP), by mixing these hardwood and softwood species may result in attractive products that maximise the advantages and overcome the disadvantages of the two resources, *i.e*. low available quantity for SPG and low mechanical properties for SP and HP.

The mechanical properties of structural VBP manufactured from blending species are affected by different factors, such as wood species (Erdil et al. 2009; H'ng et al. 2010) and adhesive types (Aydin et al. 2004; Kilic¸ et al. 2012). Various studies (Bal 2016; Dai and Wang 2005; De Souza et al. 2011; Kilic et al. 2010; Xue and Hu 2012) on laminated veneer lumbers (LVL) indicate that the layering pattern (or construction strategy) is a key factor in maximizing the products' mechanical properties and profitable utilisation of available resources. The effect of the layering pattern on the bending properties of mixed-species LVL, manufactured from oriental beech (*Fagus orientalis L.*) and Lombardy poplar (*Populus nigra L.*) veneers, was examined in Burdurlu et al. (2007). Results showed that two different construction strategies with similar ratios of poplar and beech veneers produced different bending properties. Mixed-species LVL products can increase value recovery, thus minimizing material cost (Burdurlu et al. 2007; Wang and Dai 2013). Another study conducted by Xue and Hu (2012), in which the modulus of elasticity (MOE) and modulus of rupture (MOR) of LVL manufactured from birch (*Betula platyphylla Suk.)* and poplar (*Populus ussuriensis Kom.)* veneers were investigated through the change of the ply pattern, noted that a suitable mix can result in products with high strength, thus profitable utilisation of available resources. Using softwood and hardwood veneers for manufacturing mixed-species plywood and LVL, McGavin et al. (2013) also concluded that correct mixing strategies could maximise the use and value of the available veneers. H'ng *et al.* (2010), for a series of LVL manufactured from combining high-density keruing (*Dipterocarpus sp.)* veneers (as outside veneers) with low-density wood veneers such as pulai (*Alstonia* sp.), sesendok *(Endsopermum* sp.) and kekabu hutan (*Bombax* sp.), also reported that an increased number of keruing veneers from 2 to 3 plies in 11-ply LVL led to an increase in the MOR and MOE of 5-30% and 10-15%, respectively. These results are consistent with the recent research conducted by Bal (2016) in which 7-ply LVL, fabricated from fast-growing poplar veneers, as inner layers, and eucalyptus veneers, as outer layers, were used to investigate the influence of mixing species on the LVL physical and mechanical properties. The author demonstrated that using two eucalyptus veneers on the faces significantly increased the edgewise bending MOE (30%) and MOR (12%) in comparison to single poplar LVL.

While studies on cross-banded laminated veneer lumbers (LVL-C) manufactured from single species (Ardalany et al. 2011; Kawazoe et al. 2006; Kobel et al. 2014; Norlin et al. 1999) are available in the literature, studies on LVL-C manufactured from mixing species are almost non-existent. A study on LVL-C from blending *Pinus* sp. and *Eucalyptus* sp. veneers was conducted by Iwakiri et al. (2015) and indicated that mixed-species LVL-C offer high bending properties when compared to LVL-C manufactured from *Pinus* sp. veneers alone. This result indicates a benefit in using mixed-species LVL-C as an alternative to single species LVL to increase MOE and possibly also to benefit embedment strength, and MOR properties.

While the aforementioned studies demonstrate a performance benefit of manufacturing structural VBP by mixing species, no effective tool exists to optimise the mix of available resources. This study aims to develop a tool to optimise the construction strategy of LVL-C and to demonstrate the effectiveness of blending SPG and either SP or HP veneers in the manufacturing process. Specifically, it investigates the more economical veneer arrangement to produce a family of three LVL-C structural products, each product with a targeted MOE and embedment strength (f_h), while limiting the use of SPG veneers. Representative distributions of the veneer MOE, as expected in a commercial veneer processing facility, are used as input values. Genetic Algorithm (GA) is used as the optimisation tool. This paper is divided into two main sections with the methodology behind the optimisation algorithm introduced, followed by the wood characteristics, the optimisation problem and the algorithm used. The results on optimised VBP from blending SPG and SP veneers are then presented and discussed. Furthermore, the accuracy of the algorithm was tested against manufactured "optimised" LVL and LVL-C from which the edge bending, and 5%-offset embedment strength were determined

Material and Methods

Wood species and characteristics

As part of a collaborative project between the Australian timber industry and the Queensland Department of Agriculture and Fisheries, aiming at developing solutions for the use of low-value native forest resources (harvested from the sustainable management of native forests), native forest SPG and plantation SP logs were harvested from four sites in South-west and South-east Queensland. In total, 163 SPG (2.6 m × 1.2 m) and 1091 SP (1.2 m × 1.2 m) veneer sheets were peeled from 21 and 60 logs, respectively, using spindleless lathes. The longitudinal dynamic MOE of each veneer sheet was determined through a non-destructive acoustic method (Brancheriau and Baillères 2002; CIRAD 2018). Due to the viscoelastic nature of wood, this measured dynamic MOE is higher than the corresponding static MOE (Banks et al. 2011; Bruel and Kjaer 1982), usually about 10% higher based on the authors' experience. As part of the veneer sheet MOE measurement, veneer density (at 12% moisture content) was also measured. This aimed at characterising the MOE distribution, which would be expected in a commercial processing facility for each resource. For each species, the grades are referred to as "Low", "Medium" and "High". They are termed "H_L", "H_M" and "H_H" for the SPG hardwood species and "S_L", "S_M" and "S_H" for the SP softwood species. For SPG, the cut-off values between the Low-Medium and Medium-High grades represent the 33th and 66th percentile values of the MOE cumulative distribution function (Fig. 1 and Table 1). For SP, veneers with MOE greater than 12 GPa would be usually used to manufacture currently commercialised structural VBP. This corresponds to about half of the veneers peeled, leaving the other half to be used with SPG veneers. The MOE cut-off values for SP between the Low-Medium and Medium-High grades therefore represent the 17th and 33th percentile values of the overall MOE cumulative distribution function (Fig. 1 and Table 1). Note that this grading approach represents a simple way for a manufacturer to classify veneers and may not be representative of actual practices. The average MOE value of each grade is used in the optimisation algorithm as an input value as detailed later.

In the algorithm, each grade is given a "weight" value (*g*) which represents its usage priority in the manufacturing process. The weightings are defined by the manufacturer based on its business strategy and associated costs. The greater the weight, the less the manufacturer wishes to use this grade. As the commercial value for graded SPG and SP veneers is difficult to access, for all investigated cases herein, the weight g for each grade per species is taken to be proportional to the average MOE value of the grade (See section "Optimisation problem"). It is therefore assumed in some ways that the price of a veneer is proportional to its MOE value. Additionally, while the availability of SPG logs is limited, a large quantity of plantation softwood SP logs is available. Hence, it is recognised in this work that the price of a SPG veneer is higher than the price of a SP veneer. Therefore, the weight of the highest SP grade is assumed to be less than the weight of the lowest SPG grade. Setting the lowest weight as 1.0, from above and discussions with industry, the 'weights' are set to 5.0, 4.0, 3.5, 2.5, 1.5 and 1.0 for the "H_H", "H_M", "H_L", "S_H", "S_M" and "S_L" grades, respectively, in this study.

Table 1 MOE cut-off value based on dynamic MOE for each wood species

Species	Grade	MOE threshold (MPa)	Average MOE (MPa)
Spotted gum	Low	MOE < 20,340	18,380
	Medium	20,340 ≤ MOE <23,750	22,165
	High	MOE ≥ 23,750	26,175
Southern pine	Low	MOE < 7,880	6,400
	Medium	7,880 ≤ MOE < 10,000	8,945
	High	10,000 ≤ MOE ≤11,860	10,980

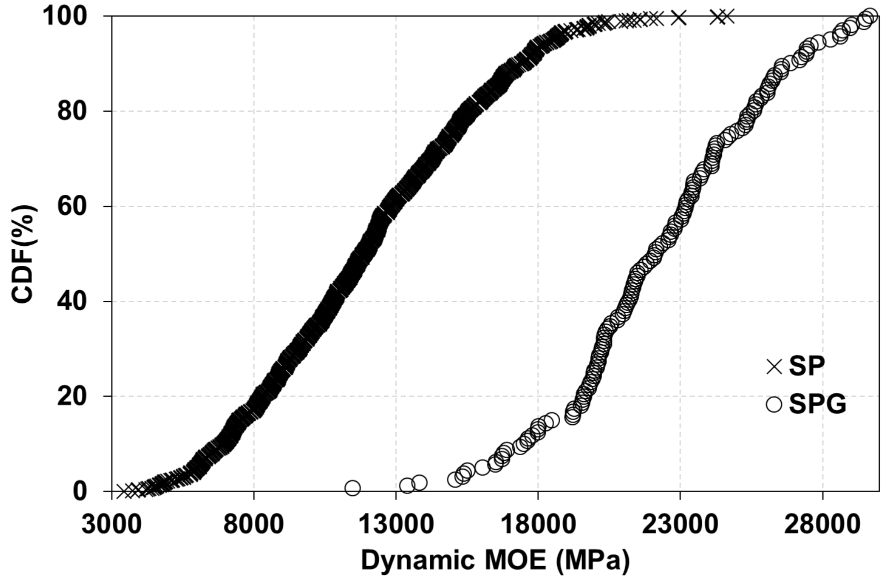

Fig. 1 Measured MOE Cumulative distribution function (CDF) for all investigated species

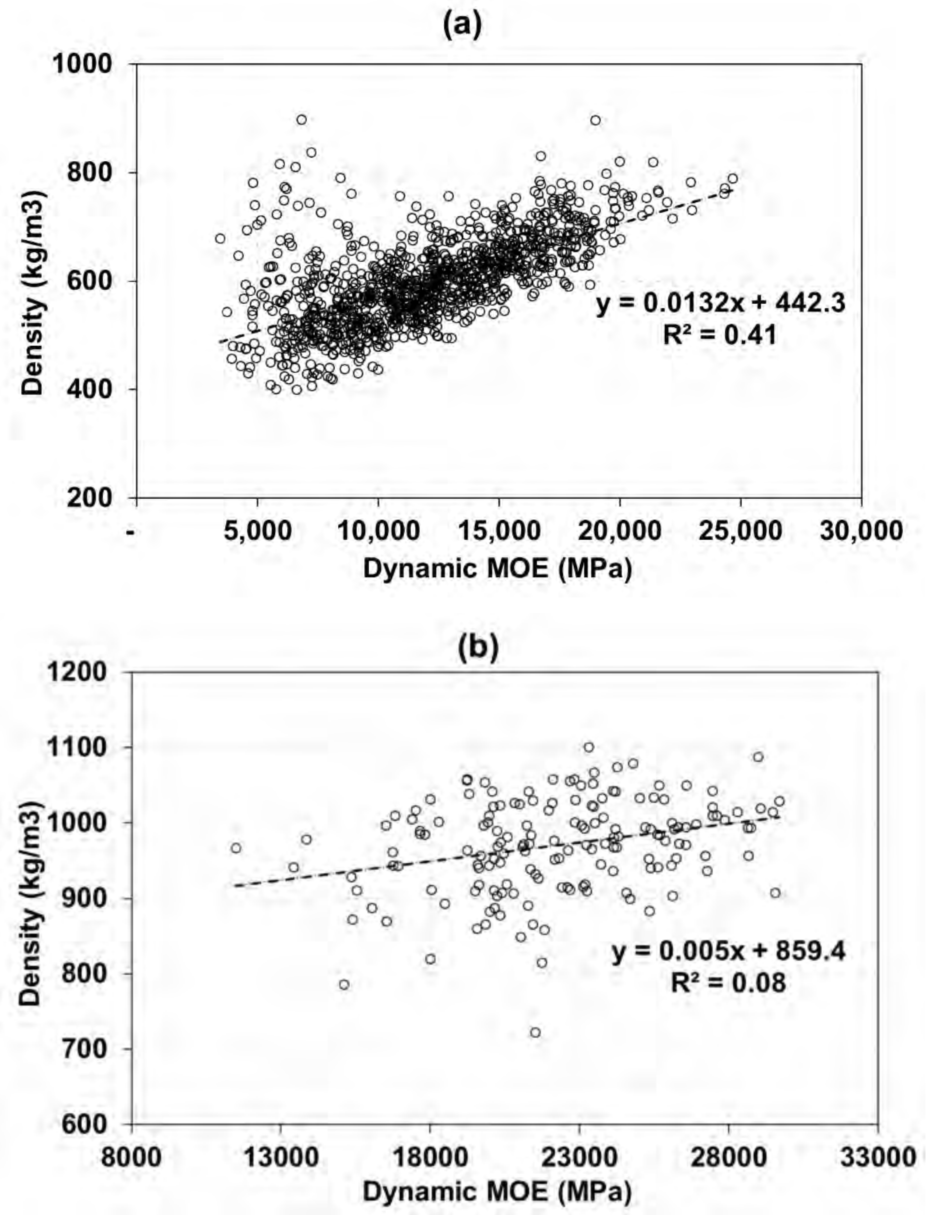

Fig. 2 The relationship between density and MOE of SP species (a) and SPG species (b)

Optimisation problem

General

The optimisation problem in this research consists of identifying construction strategies for a family (i.e. several types of product manufactured from the same veneered stock) of three symmetric 15-ply LVL or LVL-C products, manufactured from mixing SPG and SP veneers, which limit the use of SPG veneers while achieving given target structural grades. Optimising for a family of products allows a more efficient use of the veneered stock than if a single product was manufactured from the same stock. The construction strategy of each product in a family must satisfy two constrains representing (i) a targeted edge bending stiffness (MOE) and (ii) a targeted dowel connection embedment strength. Additionally, the number of SPG veneers used in the overall family is capped. Each product in the family is set to represent different manufacturing volume (P_v).

Modulus of elasticity

The MOE often represents one of the reference properties considered when selecting a timber structural product as there is typically a strong correlation between the MOE and strength (JCSS 2006). The edge bending stiffness of a final product is calculated herein from the dynamic MOE value of each individual veneer (taken as the average value of the veneer grade in Table 1) and the transformed cross-section method (Bodig and Jayne 1982). Considering a 15-ply LVL beam of height *h*, with each veneer of equal thickness *t*, the method consists of transforming each veneer *i* into a veneer of thickness t_i and of a reference MOE, taken herein as the MOE of the first veneer MOE_1, t_i is calculated as,

$$t_i = t(\frac{MOE_1}{MOE_i}) \tag{1}$$

where MOE_i is the MOE of the i^{th} veneer. This results in the MOE of the 15-ply LVL beam in edge bending (MOE_b) being simply calculated as the average of the veneer MOE as,

$$MOE_b = \frac{1}{15}\sum_{i=1}^{15} MOE_i \tag{2}$$

Note that only the veneer MOE value parallel to the grain was measured and the MOE value perpendicular to the grain also needs to be known to calculate the edge bending stiffness of LVL-C. Herein, the MOE perpendicular to the grain of the SPG and SP veneers were taken as 1/11 and 1/20 of the MOE parallel to the grain, respectively, based on the equation established in Guitard and El Amri (1987).

Embedment strength

Embedment strength is an important material parameter to evaluate the strength of timber joints. The embedment strength of VBP is calculated herein from the 5%-offset of bolt diameter method (ASTM D5764-97a 2018) of computed embedment stress-displacement curves. These curves are derived for each product from the representative stress-displacement curves of each veneer, which are defined below when the veneers are loaded parallel and perpendicular to the grain.

Based on the experimental observations in Franke and Quenneville (2011), Sawata and Yasumura (2002) and Sandhaas et al. (2013), the embedment stress-displacement curve of a timber element loaded parallel to the grain is approximated herein by a trilinear curve (Fig. 3a). The initial stiffness K_0 of the curve is calculated from the equation developed and validated on various types of engineered wood products (EWPs) in Hwang and Komatsu (2002) as,

$$K_0 = MOE_0 / (3.16 + 10.9d) \tag{3}$$

where MOE_0 = the MOE of the veneers parallel to the grain (in MPa) and d = bolt diameter (in mm).

Also based on experimental observations, when loaded perpendicular to the grain, the embedment stress-displacement curve of a timber element is approximated in this study by a bilinear curve (Fig. 3b). The initial stiffness K_{90} is taken as 1/3 of K_0 based on the values derived from the studies reported in Table 2.

The embedment strengths $f_{h,0}$ and $f_{h,90}$ when loaded parallel and perpendicular to the grain, respectively, are estimated from the Hankinson formula in the Eurocode 5 (EN1995-1-1 2004) as,

$$f_{h,\alpha} = 0.082(1-0.01d)\rho_k / (k_{90}\sin^2\alpha + \cos^2\alpha) \tag{4}$$

where α = the load to the grain angle, ρ_k = the mean timber density (in kg/m^3), d = the bolt diameter (in mm) and k_{90} = the reduction factor (equal to 1.35 + 0.015d for SP (Softwood) and 0.90 + 0.015d for SPG (Hardwood)).

In Eq. (4), the wood density is determined herein from the reference dynamic MOE parallel to the grain, as there is theoretically some correlation between the two values (JCSS 2006). The relationships between the dynamic MOE of the veneers and their density are given in Fig. 2 for the two species of interest and extracted from the data collected. While a strong correlation exists between the two properties for the SP species (R^2 = 0.41), this correlation is significantly weaker for the SPG species (R^2 = 0.08). Nevertheless, the density of a veneer is estimated herein from its dynamic MOE using the linear interpolations shown in Fig. 2 as, for the SPG and SP species respectively.

$$\rho_{SPG} = 0.005MOE_0 + 860 \tag{5}$$

$$\rho_{SP} = 0.0132 MOE_0 + 442 \quad (6)$$

where ρ_{SPG} = the density of SPG (kg/m^3) and ρ_{SP} = the density of SP (kg/m^3).

In this paper, and to illustrate the methodology employed, the density value needed to predict the embedment strength is solely estimated based on the dynamic MOE of veneers. For SPG veneers, the correlation between density and MOE is weak which may affect the accuracy of the model and therefore of the "optimised" construction strategies and associated estimated optimised properties. However, a manufacturer has the possibility to use more accurate prediction equations than Eqs (5, 6) based on other properties recorded in-line. Note that the prediction equation for the SP veneers (Eq. (6)) is affected by a large number of measurements with low MOE and high-density, as shown in Fig. 2(a). However, all measurements shown in Fig. 2 represent the actual distribution of veneers expected in a mill and all data points were kept in the prediction equation.

All other parameters to plot the embedment stress-displacement curves of a given veneer are given in Fig. 3. The stress-displacement curve of a 15-ply LVL is constructed herein by combining the stress-displacement curves of all its 15 single veneers as shown in Fig. 4. During an embedment test, the displacement of each veneer is the same and the load F applied on a 15-ply LVL at any displacement δ can be calculated from the stress-displacement curve of each veneer as,

$$F(\delta) = dt \sum_{i=1}^{15} f_i(\delta) \quad (7)$$

where d = bolt diameter, t = veneer thickness and $f_i(\delta)$ = embedment stress of veneer i at displacement δ obtained from the curves in Fig. 3.

Table 2 Initial stiffness ratio between loading parallel and perpendicular to the grain

Author	Species	Products	Average ratio K_0/K_{90}	CoV (%)
Santos et al. (2010)	Maritime pine	Solid wood	3.05	-
Dos Santos et al. (2015)	Maritime pine	Solid wood	3.04	-
Franke and Quenneville (2011)	Radiata pine	LVL	3.43	17.0
Franke and Magnière (2014a)	Beech	Solid wood	2.98	20.1
Franke and Magnière (2014b)	Spruce	Solid wood	4.33	-
Awaludin et al. (2007)	Balau (*Shorea obtusa*)	Solid wood	2.77	-
Schweigler et al. (2016)	Spruce	Solid wood	2.14	1.6
Karagiannis et al. (2016)	Scandinavian Spruce (*Picea Abies*)	Glulam	3.52	31.0
Hwang and Komatsu (2002)	-	Solid wood	3.4	-
	Douglas fir	PSL*	3.38	-
	Radiata pine	LVL100E	2.33	-
		LVL80E	1.46	-
Average			**2.98**	
* Parallel strand lumber				

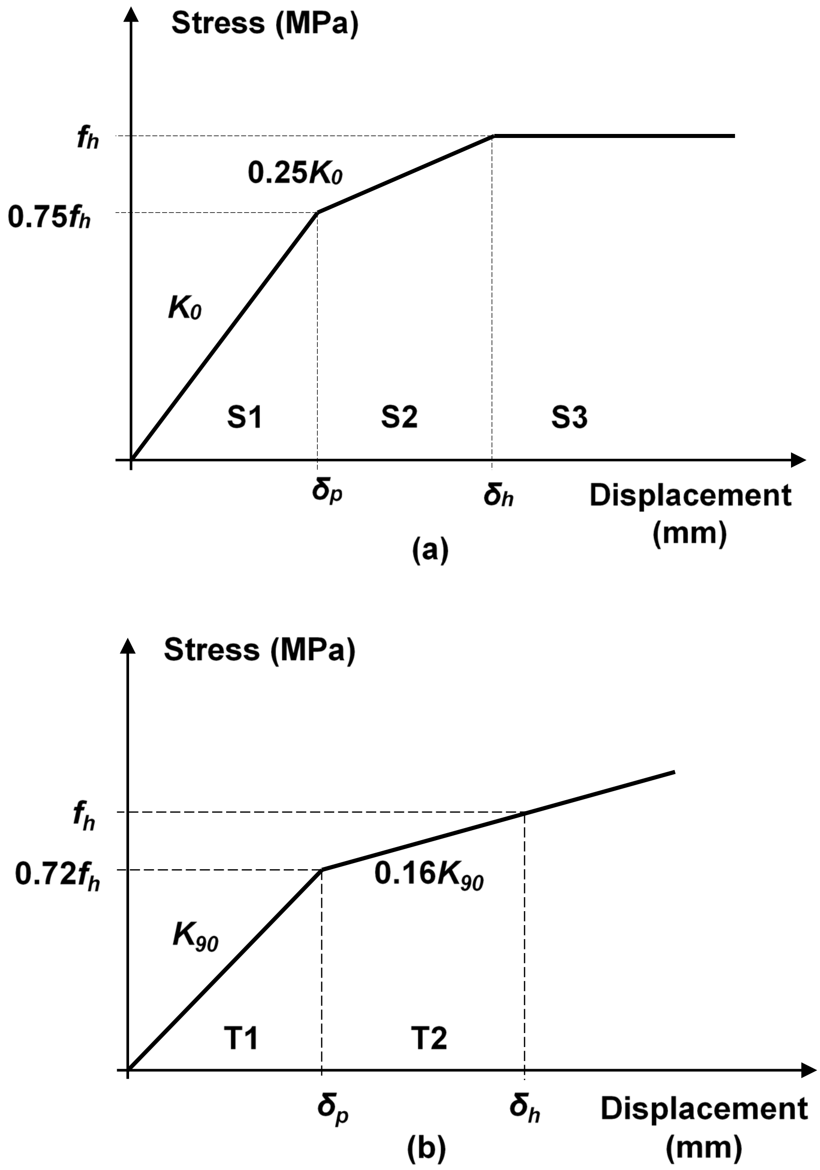

Fig. 3 (a)Tri-linear model when loaded parallel to grain and (b) Bi-linear model when loaded perpendicular to grain

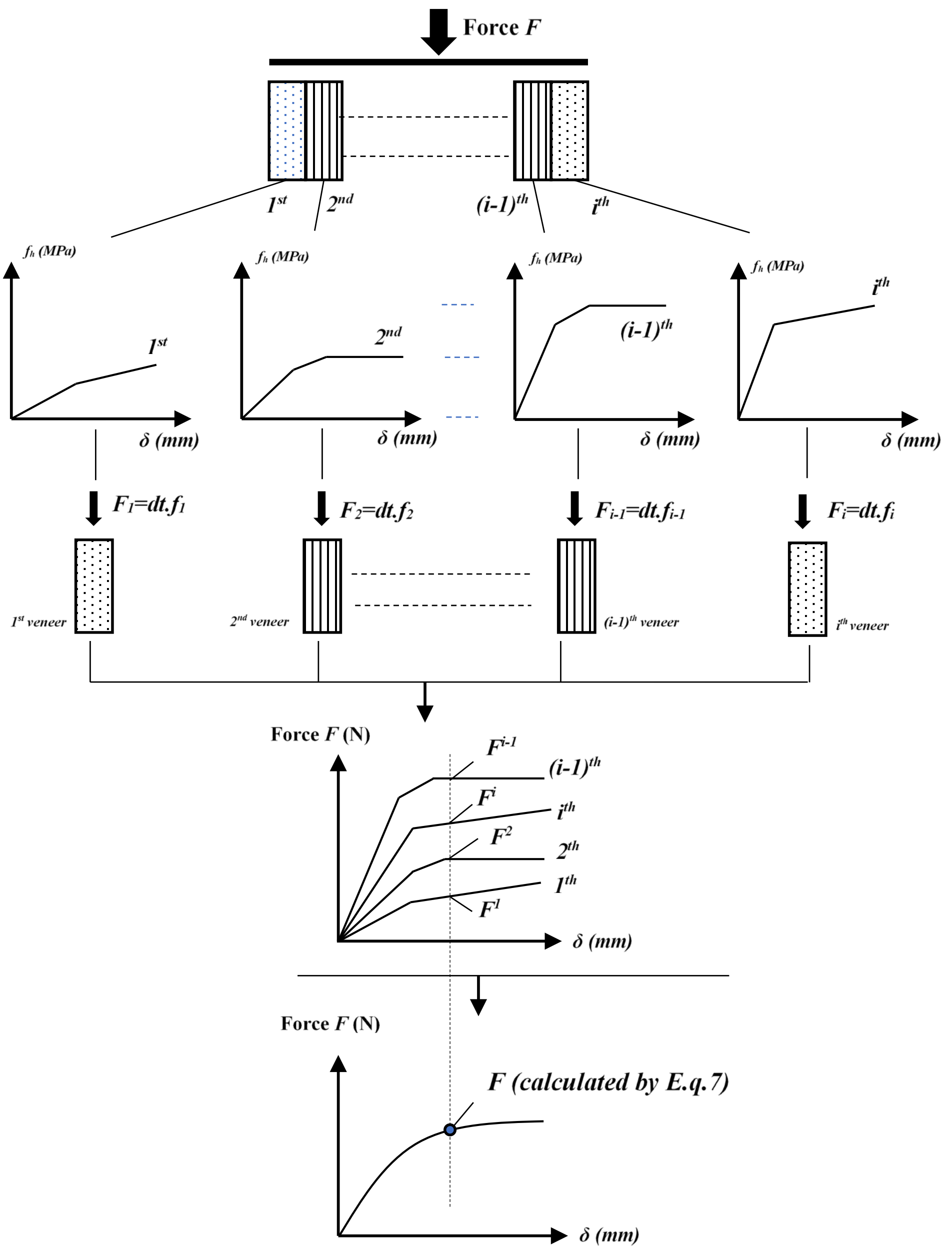

Fig. 4 The load-displacement curve of a *i*-ply LVL

Maximum number of SPG constraint

The total number of SPG veneers used (h_c) is introduced in the algorithm to limit the use of SPG veneers and to reflect the potential limited availability of this resource. This value is calculated as:

$$h_c = \sum_{i=1}^{3} P_{vi} . h_i \quad (8)$$

where h_c = total number of SPG veneers used in a family, P_{vi} = percentage of manufacturing volume of product i, h_i = number of SPG veneers in product i.

Case studies

In this study, different families are optimised representing different targets of manufacturing volume, edge bending stiffness and embedment strength. In total, 10 cases (Case I to X) of 3 families each are optimised. In each case, the 1st, 2nd and 3rd product have a target edge bending stiffness of 14 GPa, 16 GPa and 18.5 GPa, respectively, to reflect various grades in the AS/NZS 2269.0 (2012).

All the families in Cases I to IV (detailed in Table 3) have targeted embedment strengths $f_{h,T}$, for a 16 mm diameter bolt, of 27 MPa, 28.5 MPa and 30 MPa for the 1st, 2nd and 3rd product in each family, respectively. These embedment strengths correspond to the expected strengths of commercialised softwood LVL beams of MOE equal to 14 GPa, 16 GPa and 18.5 GPa, and therefore, the optimised products could directly compete with these existing products. The maximum number of SPG veneers is targeted to be 35% of total volume and the manufacturing volume of each product in a family varies among Cases as follows:

- Case I: the 1st, 2nd and 3rd product in each family are set to represent 20%, 30%, and 50% of the manufacturing volume, respectively.
- Case II: the 1st, 2nd and 3rd product in each family are set to represent 20%, 60%, and 20% of the manufacturing volume, respectively.
- Case III: the 1st, 2nd and 3rd product in each family are set to represent 40%, 30%, and 30% of the manufacturing volume, respectively.
- Case IV: the 1st, 2nd and 3rd product in each family are set to represent 45%, 45%, and 10% of the manufacturing volume, respectively.

In Cases V to VII (detailed in Table 3), the 1st, 2nd and 3rd product in a family represent 40%, 30%, and 30% of manufacturing volume, respectively, and the maximum number of SPG veneers is targeted to be 35% of total volume. However, the embedment strengths vary as follows.

- Case V: The embedment strength of each product in a family is targeted to be 15% higher than the expected strength of currently commercialised softwood LVL beams. The embedment strength of the 1st, 2nd and 3rd product in a family is therefore targeted to be 31 MPa, 33 MPa and 34.5 MPa, respectively.
- Case VI: The embedment strength of each product in a family is targeted to be 20% higher than the expected strength of currently commercialised softwood LVL beams. The embedment strength of the 1st, 2nd and 3rd product in a family is therefore targeted to be 32.5 MPa, 34 MPa and 36 MPa, respectively.
- Case VII: The embedment strength of each product in a family is targeted to be 25% higher than the expected strength of currently commercialised softwood LVL beams. The embedment strength of the 1st, 2nd and 3rd product in a family is therefore targeted to be 34 MPa, 35.5 MPa and 37.5 MPa, respectively.

Cases VIII to X (detailed in Table 3) are the same as Cases V to VII, respectively, but the maximum number of targeted SPG veneer is set to 45% of total volume instead of 35%.

Table 3 Case studies

Cases	Target values			
	MOE (GPa)	$f_{h,T}$ (MPa)	P_v (%)	h_T(%)
I	14	27	20	35%
	16	28.5	30	
	18.5	30	50	
II	14	27	20	35%
	16	28.5	60	
	18.5	30	20	
III	14	27	40	35%
	16	28.5	30	
	18.5	30	30	
IV	14	27	45	35%
	16	28.5	45	
	18.5	30	10	
V	14	31	40	35%
	16	33	30	
	18.5	34.5	30	
VI	14	32.5	40	35%
	16	34	30	
	18.5	36	30	
VII	14	34	40	35%
	16	35.5	30	
	18.5	37.5	30	
VIII	14	31	40	45%
	16	33	30	
	18.5	34.5	30	
IX	14	32.5	40	45%
	16	34	30	
	18.5	36	30	
X	14	34	40	45%
	16	35.5	30	
	18.5	37.5	30	

Genetic algorithm

Overview

Genetic algorithm (GA) is an optimisation tool which has been developed from the inspiration of biological evolution (Goldberg 1989; Holland 1975). It has the ability to solve non-linear problems without the need of solving complex equations. In GA, a constrained optimisation problem must be transformed into an unconstrained problem by including penalty functions. GA has been widely applied to solve many engineering optimisation problems such as strength (Park *et al.* 2001), stacking sequence design (Park *et al.* 2001) , stiffness (Potgieter and Stander 1998; Todoroki *et al.* 1995) and deflection (Walker and Smith 2003).

Fitness function

For the analysis, the optimisation algorithm was subjected to three constraints, representing the targeted edge bending stiffness and dowel connection embedment strength, and the maximum number of allowable hardwood veneers. The constrained optimisation problem, aiming at minimising the fitness function *f*, is transformed into an unconstrained problem as:

$$f = \sum_{i=1}^{3} P_{vi} . \sum_{j=1}^{6} w_j . n_{ij} + \sum_{i=1}^{3} P_{vi} . \left[\alpha_e . \max\left(0, 1 - \frac{MOE_i}{MOE_{Ti}}\right) + \alpha_f . \max\left(0, 1 - \frac{f_{h,i}}{f_{h,T,i}}\right)\right] + \alpha_h . \max\left(0, \frac{h_c}{h_T} - 1\right) \quad (9)$$

where: f = the fitness function, w_j = weight of j^{th} veneer grade (Section "Wood species and characteristics"), n_{ij} = number of veneers of grade j in i^{th} product in the family of three, P_{vi} = percentage of manufacturing volume of product i, α_f, α_e, α_h = penalty factors associated with each constraint, MOE_i and MOE_{Ti} = actual and targeted MOE, respectively, of product i, $f_{h,i}$ and $f_{h,T,i}$= actual (see Section "Embedment strength constraint") and targeted embedment strengths, respectively, of product i, h_c and h_T = actual (see Eq. (8)) and maximum allowable number of hardwood veneers, respectively.

GA flowchart

Figure 5 shows the flowchart of the algorithm, following the main characteristics of GA-based design (Goldberg 1989):

- The initial population in the GA is randomly generated with the structure of each individual given in Section "Chromosome structure".
- Half of the population is permitted to enter the mating pool and the roulette wheel selection method is used.
- Crossover and mutation operators are performed to create the next generation from combining the fittest individuals in the population, as detailed in Sections "Crossover operator" and "Mutation operator".
- To avoid individual with the same construction strategy but different chromosome structures, the chromosomes are ranked in each individual, so two identical construction strategies have the same chromosome structure (see Section "Chromosome structure").
- Elitism is also applied to the optimisation process, *i.e.* the best two construction strategies in each generation are automatically copied to the next generation.

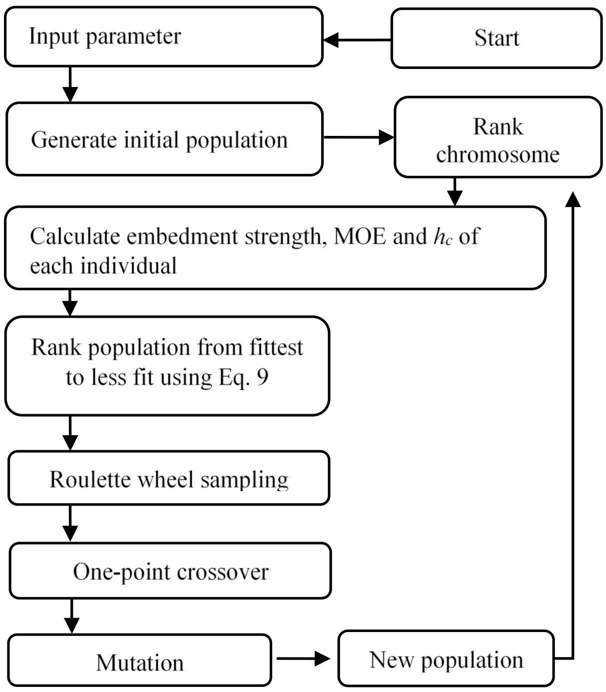

Fig. 5 GA optimisation flowchart

Chromosome structure

Each individual in the population is encoded by two chromosomes, with one chromosome (C1) representing the orientation of each veneer (0° or 90°), and the other one (C2) representing the veneer grade. As symmetric VBP are considered, only half of the products needs to be encoded, so the total number of genes in a chromosome is eight (seven symmetric veneers + one middle veneer). Table 4 shows the coding system. The orientation genes for veneer orientation (angle of 0° or 90°) are represented by the numbers "1" and "2", respectively, and the numbers "1" to "6" are used to code the veneer grades.

Table 4 Chromosome coding

Veneer orientation chromosome (C1)		
Angle	0°	90°

Code	1			2		
Veneer Grade chromosome (C2)						
Grade	H_H	H_M	H_L	S_H	S_M	S_L
Code	1	2	3	4	5	6

One example of a chromosome of one individual and its signification is shown in Fig. 6.

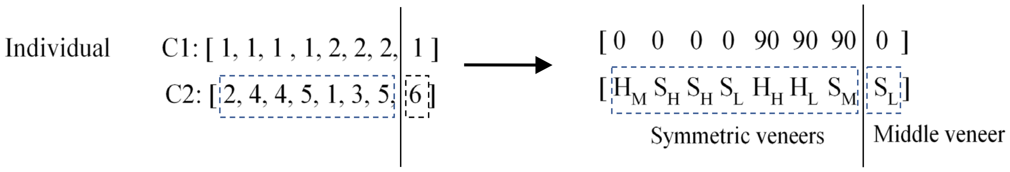

Fig. 6 Example of chromosome decoding

Note that all the genes of each chromosome of an individual are ranked with the exception of the last gene. The first seven genes represent the symmetric veneers and the last gene the unique middle veneer, as seen in Fig. 6. Particularly, the first seven genes of chromosome C1 are first ranked from the lowest to highest number ("1" and "2"), then, within each veneer orientation of C1, the corresponding numbers of chromosome C2 are also ranked from the lowest to highest grade.

Crossover operator

In this work, a one-point crossover is used, in which the crossover point is randomly generated and is the same for the two chromosomes of an individual, as shown in Fig. 7. A typical cross-over rate of 80% is chosen in this work.

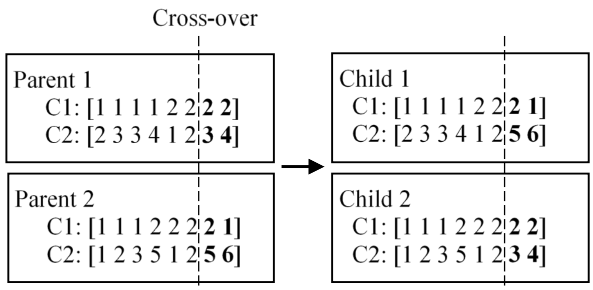

Fig. 7 Example of crossover operation

Mutation operator

For the mutation, a classical mutation is applied to both chromosomes. Each gene (integer number) in a chromosome has a probability of 1% to change to any other permissible integer number in its code system (excepting its current number). An example of a mutated individual is shown in Fig. 8.

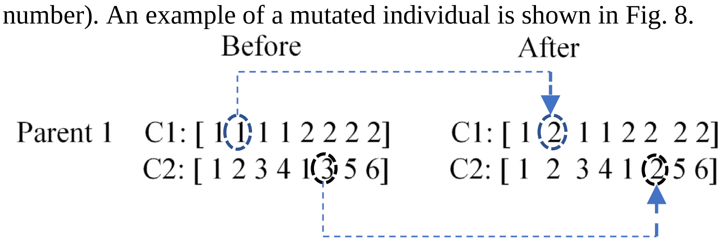

Fig. 8 Example of mutation operation

Other parameters used

The parameters used in the GA were determined by performing parametric studies, not reported in this paper. The number of individuals is set to 3,000 per generation. Values of penalty factors α_{fe}, α_e, α_h associated with each constraint were set to 50, 50 and 100, respectively. The algorithm is run 10 times to verify its robustness and stopped after 150 generations when convergence is always obtained.

RESULTS AND DISCUSSION

Convergence

The average fitness functions *f* given in Eq. (9) over 10 runs for Cases I-X to demonstrate the convergence and robustness of the algorithm are displayed in Fig. 9. Generally, Fig. 9 shows that about 50 generations are sufficient for the algorithm to converge to an optimised solution. The algorithm converged for at least 5 to 6 runs out of 10 to the same solution. Note that for Cases VIII to X, the algorithm converged to 7 to 8 out of 10 to the same optimized solution.

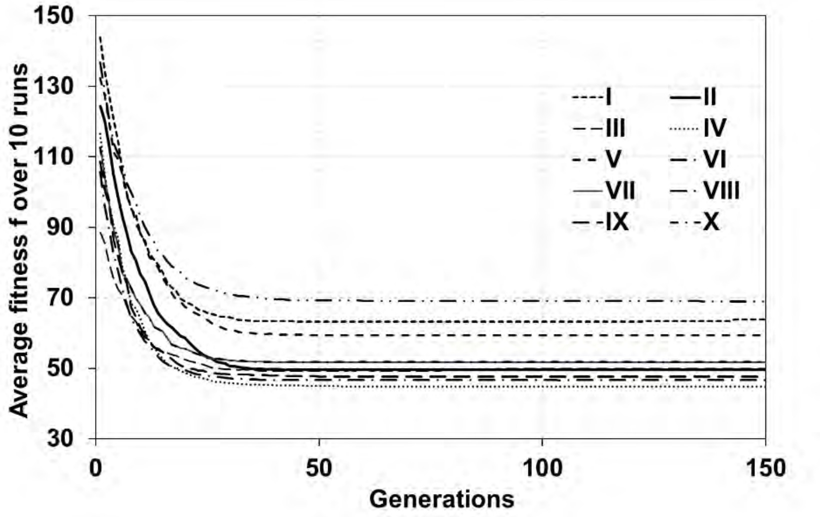

Fig. 9 Average fitness *f* for parametric study for Cases I to X

Optimal construction strategies

Cases I to IV

Table 5 shows the values of the MOE and embedment strength of the fittest family out of 10 runs for Cases I to IV. The algorithm typically satisfied the MOE constraint, with an error of less than 3%, except for Case I and the product with a target MOE of 18.5 GPa. The constraint on the embedment strength is always satisfied, with the embedment strength exceeding the target by up to 43%. The optimum solutions fully satisfied the maximum number of SPG veneers set to 35% of the total volume with the exception of Case IV (46% of SPG veneers).

The fittest construction strategies for all cases are presented in Table 6. No cross-banded plies have been found for the investigated cases, and the majority of veneers in the LVL products are of “High” graded SPG and SP, with an average percentage of up to 46% and 66%, respectively. The higher the target MOE and embedment strength required, the higher the percentage of SPG veneer used.

Table 5 Fittest values for Cases I to IV and SPG and SP products

Case	Target values				Fittest values out of 10 runs		
	MOE(GPa)	$f_{h,T}$(MPa)	P_v (%)	h_T(%)	MOE(GPa)	f_h(MPa)	h_c(%)
I	14	27	20	35%	13.989 (-0.07%)	28.7 (6%)	35 (0%)
	16	28.5	30		16.043 (0%)	31.4 (10%)	
	18.5	30	50		17.057 (-7.8%)	33.4 (11%)	
II	14	27	20	35%	13.989 (-0.1%)	28.7 (6.2%)	35 (0%)
	16	28.5	60		16.043 (0%)	31.5 (10%)	
	18.5	30	20		18.070 (-2.3%)	35.4 (18%)	
III	14	27	40	35%	14.017 (0.2%)	27.5 (2%)	35 (0%)
	16	28.5	30		16.043 (0.3%)	31.5 (10.4%)	
	18.5	30	30		18.676 (0.93%)	37.0 (23%)	
IV	14	27	45	35%	14.013 (0.1%)	28.6 (6%)	46 (31%)
	16	28.5	45		16.043 (0%)	31.4 (10%)	
	18.5	30	10		18.564 (0%)	42.8 (43%)	
Error (%) on MOE, h_c and f_h is presented in brackets. A negative value indicates that the value is below the targeted value							

Table 6 Optimum construction strategies for Cases I to III and SPG and SP products

Case	Fittest solution out of 10 runs		Grade percentage (%)					
	Cross-layers	Non-cross layers	H_H	H_M	H_L	S_H	S_M	S_L
I	-	2x(H_H), 2x(H_L),11x(S_H)	13	-	13	73		-
	-	5x(H_H),10x(S_H)	33	-	-	67	-	-
	-	6x(H_H),9x(S_H)	40	-	-	60	-	-
II	-	2x(H_H), 2x(H_L),11x(S_H)	13	-	13	73	-	-
	-	5x(H_H),10x(S_H)	33	-	-	67	-	-
	-	7x(H_H),8x(S_H)	47	-	-	53	-	-
III	-	3x(H_H),12x(S_H)	20	-	-	80	-	-
	-	5x(H_H),10x(S_H)	33	-	-	67	-	-
	-	8x(H_H),4x(S_H),3x(S_M)	53	-	-	27	20	-
IV	-	4x(H_H),6x(S_H),3x(S_M),2x(S_L)	27	-	-	40	20	13
	-	5x(H_H),10x(S_H)	33	-	-	67	-	-
	-	4x(H_H), 8x(H_L), 3x(S_H)	27	-	53	-	20	-

Cases V to VII

The fittest values for optimisation Cases V to VII are given in Table 7. The algorithm typically satisfied the constraints with a maximum error of less than 8.5% on the MOE and up to 10% on the embedment strength. The optimum solution fully satisfied the SPG proportion target of 35%.

Table 8 shows the optimum construction strategies for Cases V to VII. Cross-banded layers (LVL-C) are found in these cases and are generally made of “Low” and “High” graded SP veneers. Non-crossbanded plies are mainly made of “high “graded SP and SPG veneers. For Cases V to VII, the third product in a family does not need cross-banded plies to satisfy their constraints.

Table 7 Fittest values for Cases V to VII and SPG and SP products

Case	Target value				Fittest values out of 10 runs		
	MOE (GPa)	$f_{h,T}$(MPa)	P_v (%)	h_T (%)	MOE (GPa)	f_h (MPa)	h_c (%)
V	14	31	40	35%	14.330 (2.3%)	30.6 (-1.2%)	35 (0%)
	16	33	30		16.522 (3.2%)	33.0 (0%)	
	18.5	34.5	30		17.057 (-7.8%)	33.4 (-3%)	
VI	14	32.5	40	35%	13.643 (-2.5%)	31.6 (-2.7%)	35 (0%)
	16	34	30		14.625 (-8.5%)	33.4 (-1.7%)	
	18.5	36	30		18.070 (-2.3%)	35.4 (-1.6%)	
VII	14	34	40	35%	13.643(-2.5%)	31.6 (-7%)	35 (0%)
	16	35.5	30		15.638(-2.2%)	35.3 (-0.3%)	
	18.5	37.5	30		17.057(-7.8%)	33.4 (-10%)	
Error (%) on MOE,h_c and f_h is presented in brackets; a negative value indicates that the value is below the targeted value							

Table 8 Optimum construction strategies for Cases V to VII and SPG and SP products

Case	Fittest solution out of 10 runs		Grade percentage (%)					
	Cross-layers	Non-cross layers	H_H	H_M	H_L	S_H	S_M	S_L
V	2x(S_L)	4x(H_H),9x(S_H)	27	-	-	60	-	13
	1x(S_L)	6x(H_H),6x(S_H),2x(S_M)	40	-	-	40	13	7
	-	6x(H_H), 9x(S_H)	40	-	-	60	-	-
VI	2x(S_H)	4x(H_H), 9x(S_H)	27	-	-	73	-	-
	2x(S_L)	5x(H_H), 8x(S_H)	33	-	-	53	-	13
	-	7x(H_H), 8x(S_H)	47	-	-	53	-	-
VII	2x(S_H)	4x(H_H), 9x(S_H)	27	-	-	73	-	-
	2x(S_L)	6x(H_H), 7x(S_H)	40	-	-	47	-	13
	-	6x(H_H), 9x(S_H)	40	-	-	60	-	-

Cases VIII to X

Table 9 shows the fittest values for optimisation Cases VIII to X. The algorithm typically satisfied the constraints with a maximum error of less than 3% for MOE. The embedment strength constraints are always satisfied, and the obtained values are up to 6.6% greater than the targets. The optimum solutions always fully satisfied the number of maximum SPG veneers, set to 45%.

The optimum construction strategies for Cases VIII to X are given in Table 10. Although the “High” grade is predominant in the SPG and SP veneers, there is an increase in the “Medium” and “Low” graded SP veneers found in each construction strategy when compared to Cases I to VII. The “Medium” and “Low” graded SP veneers represent on average up to 24% and 13% of the total number of veneers, respectively.

Table 9 Fittest values for Cases VIII to X and SPG and SP products

Case	Target value				Fittest values out of 10 runs		
	MOE (GPa)	$f_{h,T}$(MPa)	P_v (%)	h_T (%)	MOE (GPa)	f_h (MPa)	h_c (%)
VIII	14	31	40	45%	14.020 (0.2%)	31.4 (1.3%)	45 (0%)
	16	33	30		16.076 (0.4%)	34.2 (3.6%)	
	18.5	34.5	30		18.500 (0%)	36.8 (6.6%)	
IX	14	32.5	40	45%	14 (0%)	33.0 (1.5%)	45 (0%)
	16	34	30		16.076 (.04%)	34.0 (0%)	
	18.5	36	30		18.5 (0%)	36.8 (2.2%)	
X	14	34	40	45%	13.643 (-2.5%)	34.0 (0%)	45 (0%)
	16	35.5	30		15.638 (-2.2%)	35.5 (0%)	
	18.5	37.5	30		18.374 (-1%)	38.3 (2.1%)	
Error (%) on MOE,h_c and f_h is presented in brackets; a negative value indicates that the value is below the targeted value							

Table 10 Optimum construction strategies for Cases VIII to X and SPG and SP products

Case	Fittest solution out of 10 runs		Grade percentage (%)					
	Cross-layers	Non-cross layers	H_H	H_M	H_L	S_H	S_M	S_L
VIII	-	2x(H_H), 4x(H_L),2x(S_H), 7x(S_M)	13	-	27	13	47	-
	1x(S_L)	6x(H_H),6x(S_H),2x(S_M)	40	-	-	40	13	7
	-	8x(H_H),4x(S_H),2x(S_M),1x(S_L)	53	-	-	27	13	7
IX	1x(S_L)	2x(H_H), 2x(H_L),6x(S_H), 2x(S_M)	13	-	27	40	13	7
	1x(S_L)	6x(H_H),6x(S_H),2x(S_M)	40	-	-	40	13	7
	-	8x(H_H),4x(S_H),2x(S_M),1x(S_L)	53	-	-	27	13	7
X	2x(S_L)	4x(H_H), 2x(H_L),4x(S_H), 2x(S_M),1x(S_L)	27	-	13	27	13	20
	2x(S_L)	6x(H_H),7x(S_H)	40	-	-	47	-	13
	-	8x(H_H), 6x(S_H), 1x(S_L)	53	-	-	40	-	7

Methodology validation

In this section, the accuracy of the proposed methodology is verified on 12-ply LVL and 12-ply LVL-C "optimised" mixed species SPG and HP products. Note that at the start of the collaborative project between the industry and the QLD Government (see Section "Wood species and characteristics"), the industry incentive was to use SPG and SP logs. The methodology presented in this paper was developed and the algorithm therefore extensively ran to optimise for these two species, as illustrated in the paper. However, when time to manufacture the "optimised" products came, there was a shift in the project scope and an industrial need to now utilise the same SPG veneers but mixed with plantation Hoop Pine veneers. Therefore, the developed methodology was applied to these two species but only selected optimisation cases were run. The optimised products were manufactured and tested in edge bending and embedment strength at a load-to-grain angle of 0°.

First, the material properties of the HP veneers used in the algorithm and manufacture are presented for information. Second, the "optimised" manufactured strategies are presented. Finally, the edge bending, and embedment strength of the "optimised" manufactured products are compared to the "optimised" targeted properties.

Hoop pine veneers

246 HP veneer sheets of 3.0 mm nominal thickness were used to find the distribution of veneers to be expected in the mill and the relationship between the dynamic MOE and density. These sheets were selected from the production line of a commercial veneer manufacturer and estimated to come from eight different logs. Similar to the SPG and SP veneers, the dynamic MOE of the veneers was measured using a non-destructive acoustic resonance method (CIRAD 2018)

The density ρ_{HP} of a HP veneer (in kg/m^3) is estimated herein from its dynamic MOE using the linear interpolations shown in Figure 10. The correlation (R^2 = 0.03) is significantly weaker than the SP species and this would affect the accuracy of the model

$$\rho_{HP} = 0.0025 MOE_0 + 446 \tag{10}$$

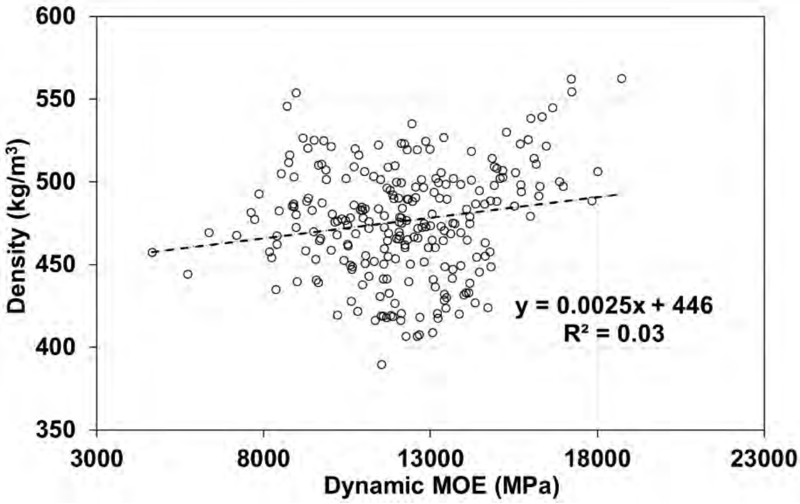

Fig. 10 The relationship between density and dynamic MOE of HP species

For HP species, the cut-off values between the Low-Medium and Medium-High grades represent the 33th and 66th percentile values of the MOE cumulative distribution function and are given in Table 11. The grades are referred to as "Low", "Medium" and "High" of which are termed similarly to the SP veneers "S_L", "S_M" and "S_H". The average MOE value per grade used as input value in the model are also given in Table 11.

Table 11 MOE cut-off values based on dynamic MOE for each wood species

Species	Grade	MOE threshold (MPa)	Average MOE (MPa)
Hoop pine	Low	MOE < 11,300	9,600
	Medium	11,300 ≤ MOE < 13,100	12,150
	High	13,100 ≤ MOE ≤18,716	14,700

Optimised strategies

To manufacture the products, optimisation Cases III and V given in Table 3 were run with the SPG and HP veneers. The fittest values for both cases are given in Table 12. The algorithm always satisfied the constraints on the MOE, embedment strength and maximum number of SPG veneers. The optimum construction strategies are given in Table 13.

Validation of the algorithm

Only the 1st "optimised" product of each Case in Table 13 was chosen to be manufactured. Three LVL panels of dimensions equal to 1,200 mm × 1,200 mm for each construction strategy were hot-pressed using a melamine urea formaldehyde (Hexion M8188) structural adhesive. For each panel, the veneers in a grade were randomly chosen. Note that one panel for Case V experienced gluing problems during the manufacturing process and was disregarded. After manufacturing, two beams (1,200 mm × 60 mm) were cut from each panel and tested on edge bending following the Australian New-Zealand standard AS/NZS 4357.2 (2006). i.e. with a distance between supports of 1,080 mm. Two 120 mm × 85 mm samples were also cut from each panel and tested for embedment strength at a load-to-grain angle of 0° and a dowel diameter of 16 mm, following the half-hole embedment strength recommendations in the ASTM D5764-97a. Before testing, all test samples were conditioned at 20°C and 65% relative humidity

Table 12 gives the average measured static apparent edge bending MOE (MOE_{static}), bending strength (MOR) and 5%-offset embedment strength $f_{h\text{-}test}$ per product type. The coefficient of variation for each type of test is also given in the table.
The measured static MOE of the two products satisfies the targeted MOE and is on average 15% and 8.5% higher than the targeted MOE for Cases III and V, respectively. In terms of the embedment strength, the experimental results were found to fully satisfy the targeted embedment strengths and be 110% and 83% higher than the targeted

values for Cases III and V, respectively. This significant difference may be due to (i) the accuracy of the embedment strength equations in the EC5 which have not been verified yet for mixed species LVL and LVL-C, (ii) the conservatism of the EC5 equations when used to calculate the embedment strength of SPG veneered-based products and (iii) the low correlation between the MOE and density (Eqs 5, 10). The embedment strength predicting equations could be refined in the algorithm when more accurate equations are available for the veneered-based products under consideration in the paper. Anyhow, the manufactured products fully satisfied the constraints, validating the methodology.

Table 12 Comparison of the experimental and fittest value of the model for selected products

Case	Target values			Fittest values out of 10 runs			Experimental values		
	MOE (GPa)	$f_{h,T}$(MPa)	h_T (%)	MOE(GPa)	f_h(MPa)	h_c(%)	MOE_{static} (GPa)	MOR (MPa)	$f_{h\text{-}test}$ (MPa)
III	14	27	35%	14.680 (5%)	28.5 (5%)	35 (0%)	16.097 (6%)	94.3 (4.5%)	56.5 (7%)
	16	28.5		15.982 (-0.1%)	28.97 (1.5%)		-	-	-
	18.5	30		18.524 (0.2%)	29.95 (-0.2%)		-	-	-
V	14	31	35%	14.034 (0.2%)	30.7 (-1%)	35 (0%)	15.180 (4%)	93.4 (3%)	56.7 (3%)
	16	33		16.154 (1%)	32 (-3)		-	-	-
	18.5	34.5		18.099 (-2%)	30 (-13%)		-	-	-

Fittest values: Error (%) on MOE, h_c and f_h is presented in brackets. A negative value indicates that the value is below the targeted value
Experimental values: Coefficient of variation (%) presented in bracket

Table 13 Optimum construction strategies for selected products

Case	Fittest solution out of 10 runs		Grade percentage (%)					
	Cross-layers	Non-cross layers	H_H	H_M	H_L	S_H	S_M	S_L
III	-	2x(H_H), 2x(H_L),2x(S_H), 6x(S_L)	16.6	16.6	-	16.6	-	50
	-	4x(H_H),2x(S_H), 6x(S_L)	33.3	-	-	16.6	-	50
	-	4x(H_H), 8x(S_H)	33.3	-	-	66.6	-	-
V	2x(S_L)	4x(H_H), 2x(S_M),4x(S_L)	33.3	-	-	-	16.7	50
	2x(S_L)	4x(H_H),6x(S_H)	33.3	-	-	50	-	16.6
	-	4x(H_H), 6x(S_H),2x(S_M)	33.3	-	-	50	16.6	-

Conclusion

The paper presented a tool, using genetic algorithm, to optimise the construction strategy of mixed-species LVL and LVL-C. The objective is to minimise the cost of a family of products subjected to different targeted stiffness and embedment strength, and a maximum allowable number of hardwood veneers. SPG and SP veneers were used to illustrate the potential of the algorithm. In total, three main construction strategies were analysed and consisted of (i) products with a maximum of 35% of SPG veneers in the overall manufacturing volume and having similar stiffness and embedment strength to commercially available products (Cases I to IV), (ii) products with and a maximum of 35% of SPG veneers in the overall manufacturing volume and having similar stiffness to commercially available products but higher embedment strength (Cases V to VII) and (iii) same as (ii) but with a maximum of 45% of SPG veneers in the overall manufacturing volume (Cases VIII to X). The main conclusions are summarised below and may provide guidance on manufacturing structural LVL and LVL-C from SPG and SP veneers in further research.

1. For all cases, the robustness of the algorithm was demonstrated by the consistency of the construction strategies of the optimized products over 10 runs.
2. Regarding the different investigated cases, the construction strategy depends on the choice of the input parameters. Only LVL products were found when optimising for Cases I to IV. However, LVL-C was solely found in all other investigated cases. The cross-banded veneers generally consisted of "Low" and "High" graded SP veneers. For all cases, the "high" MOE graded SPG and SP veneers were found to be predominant in the final products.

3. Results showed that increasing the number of hardwood veneers to 45% of the overall manufacturing volume (Cases VIII to X) instead of 35% (Cases I to VII) resulted in an increased utilization of the “Medium” and “Low” graded SP veneers. The “Medium” and “Low” graded SP veneers represented on average up to 24% and 13% of the total number of veneers, respectively.
4. The accuracy of the algorithm was verified against manufactured “optimised” LVL and LVL-C from which the edge bending and 5%-offset embedment strength was determined. The manufactured products were found to fully satisfy the constraints.

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