# Supplementary materials

## S1 Mathematical description of log processing rates

Equations S1 to S5 estimate the volume of logs able to be processed by the spindleless lathe per hour ($LVPH_{ls}$). $LVPH_{ls}$ is then used to estimate the number of annual processing hours at the green veneering stage (Equation 7 in the main text). $LVPH_{ls}$ is a function of the volume of the log billets processed ($LogVol_{ls}$) and the time taken to process each billet into veneer ($TVT_{ls}$). $TVT_{ls}$ for a given log billet is the sum of time taken to load the logs into the lathe ($LLT_{ls}$) and the veneer peeling time ($PT_{ls}$). The formulas to estimate $LLT_{ls}$ and $PT_{ls}$ have been derived from Venn et al. (2020) and are outlined in Equations S4 and S5, respectively. $LVPH_{ls}$ increases with $SEDUB_{ls}$ since large logs take longer to peel and therefore do not need to be reloaded into the lathe as frequently as smaller diameter logs. The peeler core (*CD*) is a residual cylindrical core from the centre of the log from which, no veneer can be recovered. An overview of the variables expressed in Equations S1 to S5 are outlined in Table S1.

$$LVPH_{ls} = LogVol_{ls} * \left(\frac{3600}{TVT_{ls}}\right) \quad \text{(S1)}$$

$$LogVol_{ls} = \frac{\left(\frac{SEDUB_{ls}}{2}\right)^2 * \pi + \left(\frac{(LL * Taper_{ls} + SEDUB_{ls})}{2}\right)^2 * \pi}{2} * LL \quad \text{(S2)}$$

$$TVT_{ls} = LLT_{ls} + PT_{ls} \quad \text{(S3)}$$

$$LLT_{ls} = 6.3128 + 0.2285 * SEDUB_{ls} \quad \text{(S4)}$$

$$PT_{ls} = \frac{\pi * \left(\left(\frac{SEDUB_{ls}}{2}\right)^2 - \left(\frac{CD}{2}\right)^2\right)}{GVThickness_s * PS} \quad \text{(S5)}$$

Table S1. Derived parameters (Der), vector or matrix parameters (P), and scalar parameters (SP) for the parameters expressed in Equations S1 to S5.

| Name | Variable or parameter | Description |
|---|---|---|
| $LLT_{ls}$ | Der | Log loading time (sec) |
| $LVPH_{ls}$ | Der | Log volume processed per hour by the lathe ($m^3$) |
| $PT_{ls}$ | Der | Peeling time of a log billet (sec) |
| $TVT_{ls}$ | Der | Total veneering time of a log billet (sec) |
| $SEDUB_{ls}$ | P | Small-end diameter under bark of a log (cm) |
| $Sweep_{ls}$ | P | Log sweep (m/m) |
| $Taper_{ls}$ | P | Log taper (m/m) |
| $GVThickness_s$ | SP (3.2) | Green veneer thickness (mm) |
| $CD$ | SP (0.045) | Peeler core diameter (m) |
| $LL$ | SP (2.6) | Log length (m) |
| $PS$ | SP (0.67) | Lathe peeling speed (m/sec) |

## S2 Distribution of log sizes by log type

Within each log type, the model accounts for a distribution of logs that vary in their small-end diameter under bark ($SEDUB_{ls}$) which are outlined in Table S2. The distribution of coconut log sizes have been informed by Kuttankulangara et al. (2019) who found that the majority of coconut logs have a diameter between 20 cm and 28 cm. Log size distributions for mahogany and pine have been derived from data collected from Fiji Hardwoods and Fiji Pine, respectively, who are the largest growers of plantation resources in Fiji. The weighted average presented in the bottom row corresponds to the $SEDUB_{ls}$ values displayed in Table 4 within the main text.

Table S2. Distribution of logs within log type by small-end diameter under bark ($SEDUB_{ls}$) .

| $SEDUB_{ls}$ (cm) | Proportion of logs by $SEDUB_{ls}$ by log type (%) | | | | |
|---|---|---|---|---|---|
| | Coconut | Mahogany G3B & G3C | Mahogany G4B & G4C | Pine sawlog | Pine pulplog |
| 14 | | | | | 25.0 |
| 16 | | | | | 25.0 |
| 18 | | | | | 25.0 |
| 20 | 20.0 | | | | 25.0 |
| 22 | 20.0 | | | 3.6 | |
| 24 | 20.0 | | | 6.0 | |
| 26 | 20.0 | | | 9.9 | |
| 28 | 20.0 | | | 9.9 | |
| 30 | | | | 13.6 | |
| 32 | | | | 13.6 | |
| 34 | | | | 11.2 | |
| 36 | | | | 11.2 | |
| 38 | | | | 12.8 | |
| 40 | | | 20.0 | 3.0 | |
| 42 | | | 20.0 | 3.0 | |
| 44 | | | 20.0 | 0.9 | |
| 46 | | | 20.0 | 0.9 | |
| 48 | | | 20.0 | 0.4 | |
| 50 | | 20.0 | | | |
| 52 | | 20.0 | | | |
| 54 | | 20.0 | | | |
| 56 | | 20.0 | | | |
| 58 | | 20.0 | | | |
| Weighted average | 24.0 | 54.0 | 42.0 | 32.2 | 17.0 |

## S3 Comparison of green veneer recovery

Table S3 outlines the range of green veneer recovery rates ($GVR_{ls}$) by log type. The recoveries displayed were calculated using Equation 3 in the main text. The weighted average presented in the bottom row corresponds to the $GVR_{ls}$ values displayed in Table 4 within the main text. $GVR_{ls}$ was calculated by multiplying the green veneer recovery rates in Table S3 by the proportion of logs within each SEDUB category in Table S2 by log type.

Table S3. Green veneer recovery rates ($GVR_{ls}$) by log type.

| $SEDUB_{ls}$ (cm) | Recovery from log volume by SEDUB and log type (%) | | | | |
|---|---|---|---|---|---|
| | Coconut | Mahogany G3B & G3C | Mahogany G4B & G4C | Pine sawlog | Pine pulplog |
| 14 | | | | | 44.0 |
| 16 | | | | | 50.6 |
| 18 | | | | | 55.8 |
| 20 | 71.6 | | | | 60.1 |
| 22 | 74.4 | | | 63.6 | |
| 24 | 76.6 | | | 66.5 | |
| 26 | 78.5 | | | 69.0 | |
| 28 | 80.2 | | | 71.1 | |
| 30 | | | | 73.0 | |
| 32 | | | | 74.6 | |
| 34 | | | | 76.1 | |
| 36 | | | | 77.4 | |
| 38 | | | | 78.6 | |
| 40 | | | 71.5 | 79.6 | |
| 42 | | | 72.7 | 80.6 | |
| 44 | | | 73.8 | 81.4 | |
| 46 | | | 74.9 | 82.2 | |
| 48 | | | 75.9 | 82.9 | |
| 50 | | 76.8 | | | |
| 52 | | 77.6 | | | |
| 54 | | 78.4 | | | |
| 56 | | 79.1 | | | |
| 58 | | 79.8 | | | |
| Weighted average | 76.3 | 78.3 | 73.7 | 74.1 | 52.6 |

## S4 Harvestable volumes of pine

Communications with Fiji Pine, the sole pine plantation grower in Fiji, revealed that the standing log volume per hectare of pine ($SLV_{ils}$) ranged between 180 m$^3$/ha to 250 m$^3$/ha (a mean of 215 m$^3$/ha) in Viti Levu and between 350 m$^3$/ha to 400 m$^3$/ha (a mean of 375 m$^3$/ha) on Vanua Levu. Historical harvesting records of pine plantations in Fiji indicate that approximately 14.2% of the harvested volume of pine was sawlogs (logs exceeding a $SEDUB_{ls}$ of 20cm), with the remaining 85.8% of logs being pulplogs (logs equal to or less than a $SEDUB_{ls}$ of 20cm). Of the pulplogs, 33.3% of logs were considered too small for effective spindleless rotary veneering (i.e., < 14 cm $SEDUB_{ls}$) whilst 50% of the remaining logs (i.e., > 14 cm $SEDUB_{ls}$) are likely to have excessive sweep. Therefore, 28.5% of logs harvested by Fiji Pine represent pulplogs that are appropriate for veneering. These estimations derived a $SLV_{ils}$ of sawlogs and pulplogs of approximately 30.6 m$^3$/ha and 61.2 m$^3$/ha on Viti Levu, and 57.0 m$^3$/ha and 114.0 m$^3$/ha on Vanua Levu, respectively.

## S5 Log specifications

Table S4 outlines the range of sweep and taper characteristics of the mahogany and pine log types, as provided by Fijian plantation forest growers, and the adopted levels of these parameters for the case-study.

Table S4. Sweep and taper characteristics for mahogany and pine log types.

| Log characteristic | Log characteristics by species | | | |
|---|---|---|---|---|
| | Mahogany | | Pine | |
| | B-Grade | C-Grade | Pine sawlog | Pine pulplog |
| Sweep range (m/m) | 0.014-0.034 | 0.034+ | 0.015 – 0.019 | |
| Adopted sweep (m/m) | 0.024 | 0.043 | 0.016 | |
| Taper (m/m) | "Medium taper" | "Significant taper" | "Reasonably straight" | |
| Adopted taper (m/m) | 0.02 | 0.03 | 0.01 | |

## S6 Estimation of veneer prices

The market prices of the veneer products adopted in this analysis have been converted from engineered wood product (EWP) prices, supplied by a major veneering processor, via the residual value method. Equations S6 to S8 was used to estimate the market price of the veneer products. The variables used in the equations are described below and their values are presented in Table S5.

$$VeneerPrice = (EWPPrice - ProdCost - Tax - Profit) * Recovery \quad \text{(S6)}$$

$$Tax = EWPPrice * 9\% \quad \text{(S7)}$$

$$Profit = (EWPPrice - Tax) * 15\% \quad \text{(S8)}$$

where

*VeneerPrice* is the average price of the veneer (\$/m$^3$ veneer);
*EWPPrice* is the average price of the EWPs (\$/m$^3$ EWP);
*ProdCost* is the average cost of converting dry veneer into EWPs (\$/m$^3$ EWP);
*Tax* is the average tax paid (\$/m$^3$ EWP);
*Profit* is the average profit received (\$/m$^3$ EWP); and
*Recovery* is the recovery of EWP from dry veneer (%).

Table S5. Variables used to estimate the average price of veneer.

| Species | *EWPPrice* (\$/m$^3$ EWP) | *ProdCost* (\$/m$^3$ EWP) | *Tax* (\$/m$^3$ EWP) | *Profit* (\$/m$^3$ EWP) | *Recovery* (%) | *VeneerPrice* (\$/m$^3$ veneer) |
|---|---|---|---|---|---|---|
| Coconut | 2900 | 690 | 261 | 396 | 80.6 | 1252 |
| Mahogany | 3200 | 690 | 288 | 437 | 80.6 | 1439 |
| Pine | 2300 | 690 | 207 | 314 | 80.6 | 877 |

Note: For visual ease, *VeneerPrice* was rounded to the nearest \$5 in the main paper.

## S7 Impact of key parameters on gross margins

Table S6 presents the results of the multiple regression to test the impact of key model parameter levels on the gross margins per hour of veneer manufacture ($GM_{pz}$). As expected, variation in $GM_{pz}$ is well explained by the stochastic variables, with the R-squared varying from 0.862 to 0.891 under the six potential facility locations.

Throughout the majority of veneering location scenarios, changes in pine-specific variables (e.g., $MP_{s=pine}$, $MDLC_{s=pine}$, $SLV_{ils=pine}$) generally had a negligible effect on $GM_{pz}$ due to their relatively low volumes harvested. Mills with better access to a particular species were more impacted by changes in profitability or availability of that species. For example, the $GM_{pz}$ of mills on Vanua Levu, which are closer to coconut resources than mills on Viti Levu, were more sensitive to changes in the coconut veneer price and less impacted by changes in the market price of mahogany and pine veneer than mills on Viti Levu

$GM_{pz}$ is positively correlated to utilisation rates because an increase in the utilisation of the equipment increases the volume of veneer can be processed by the mill per hour. Since the spindleless lathe has a larger processing capacity than the veneer dryer, $GM_{pz}$ is more sensitive to a 1% increase in $URGreen$ than *URDry*. Since a greater volume of large diameter logs can be processed by the spindleless lathe per hour ($LVPH_{ls}$, as described in Table 4 in the main text), a 1% increase in its utilisation rate results in a correspondingly larger increase in $LVPH_{ls}$ (and therefore $GM_{pz}$) for mahogany than coconut or pine logs. Therefore, changes in *URGreen* impact $GM_{pz}$ to a larger extent at mills near large mahogany plantations such as Galoa and Lautoka. In contrast, since the veneer dryer processes green veneer at the same rate regardless of species, log types with lower rates of green veneer recovery, such as coconut logs, can be processed faster than large diameter mahogany logs. This is because the lower green veneer recovery rates of small diameter logs result in less green veneer that needs to be dried and therefore, corresponds to a larger volume of log equivalent that can be processed by the dryer per hour. As such, increases in *URDry* result in a relatively larger increase in $GM_{pz}$ at mills near coconut plantations, such as Qacavuio, Savusavu and Dreketi.

Table S6. Regression coefficients and significance levels of selected variables on the gross margin of veneer manufacture ($/h) ($GM_{pz}$) by facility location .

| Variable | Coefficient and level of statistical significance by facility location | | | | | |
|---|---|---|---|---|---|---|
| | Galoa | Lautoka | Rakiraki | Dreketi | Savusavu | Qacavuio |
| $Scale$ | -129*** | -127*** | -120*** | -170*** | -156*** | -154*** |
| $MP_{s=coco}$ | 0.73*** | 0.75*** | 0.81*** | 1.00*** | 1.01*** | 0.97*** |
| $MP_{s=mah}$ | 1.07*** | 1.03*** | 1.01*** | 0.83*** | 0.82*** | 0.86*** |
| $MP_{s=pine}$ | 0.05 | 0.07 | 0.06 | 0.04 | 0.02 | 0.00 |
| $MDLC_{s=coco}$ | -2.96*** | -3.03*** | -2.51*** | -1.59* | -1.57* | -2.54*** |
| $MDLC_{s=mah}$ | -6.07*** | -6.03*** | -5.63*** | -4.88*** | -4.97*** | -5.34*** |
| $MDLC_{s=pine}$ | -1.04 | -1.00 | -1.27. | -1.20. | -1.42* | -1.03 |
| $SLV_{ils=coco}$ | 0.84** | 0.88** | 1.19*** | 2.01*** | 1.95*** | 1.93*** |
| $SLV_{ils=mah}$ | 2.51*** | 2.18*** | 1.89*** | 1.25*** | 1.21*** | 1.35*** |
| $SLV_{ils=pine}$ | 0.73 | 0.75 | 0.68 | 0.55 | 0.48 | 0.46 |
| $URGreen$ | 30.2*** | 30.4*** | 28.1*** | 27.9*** | 26.6*** | 29.0*** |
| $URDry$ | 6.0. | 6.4. | 6.6. | 10.9* | 8.6* | 7.3* |
| $R^2$ | 0.870 | 0.862 | 0.891 | 0.884 | 0.887 | 0.865 |

Significance: '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$

## S8 Impact of key parameters on the volume of mahogany and pine procured

The results of the linear regression model on the volume of mahogany and pine procured are reported in Tables S7 and S8, respectively.

Table S7. Regression coefficients and significance levels of selected variables on the volume of mahogany harvested by facility location.

| Variable | Coefficient ($m^3$ harvested) and level of statistical significance by facility location | | | | | |
|---|---|---|---|---|---|---|
| | Galoa | Lautoka | Rakiraki | Dreketi | Savusavu | Qacavuio |
| $Scale$ | 11,741*** | 11,627*** | 11,991*** | 11,363*** | 11,498*** | 11,388*** |
| $MP_{s=coco}$ | -9.66*** | -9.65*** | -9.65*** | -7.41*** | -7.42*** | -7.48*** |
| $MP_{s=mah}$ | 10.89*** | 11.76*** | 10.99*** | 9.90*** | 8.97*** | 9.22*** |
| $MP_{s=pine}$ | -4.56*** | -3.94** | -4.39*** | -2.94** | -2.22** | -2.32** |
| $MDLC_{s=coco}$ | 42.09** | 44.66** | 34.52* | 21.15 | 24.46 | 26.64. |
| $MDLC_{s=mah}$ | -72.54*** | -80.39*** | -75.79*** | -75.59*** | -76.65*** | -67.99*** |
| $MDLC_{s=pine}$ | 10.48 | 12.01 | 15.06 | 3.74 | 7.59 | 9.88 |
| $SLV_{ils=coco}$ | -42.27*** | -43.84*** | -49.14*** | -59.69*** | -63.27*** | -62.24*** |
| $SLV_{ils=mah}$ | 71.79*** | 66.67*** | 67.55*** | 43.96*** | 41.20*** | 48.03*** |
| $SLV_{ils=pine}$ | -6.81 | -9.83 | -17.65 | -0.77 | -5.85 | -3.22 |
| $URGreen$ | 74.98 | 84.51. | 73.21 | 17.50 | 16.47 | 45.49 |
| $URDry$ | -69.06 | -82.89 | -107.31 | -74.15 | -35.88 | -146.24 |
| $R^2$ | 0.793 | 0.796 | 0.765 | 0.783 | 0.741 | 0.743 |

Significance: '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$

Table S8. Regression coefficients and significance levels of selected variables on the volume of pine harvested by facility location .

| Variable | Coefficient ($m^3$ harvested) and level of statistical significance by facility location | | | | | |
|---|---|---|---|---|---|---|
| | Galoa | Lautoka | Rakiraki | Dreketi | Savusavu | Qacavuio |
| $Scale$ | 354*** | 459*** | 372*** | 530*** | 399*** | 396*** |
| $MP_{s=coco}$ | -1.98*** | -2.29*** | -1.93*** | -0.52** | -0.30. | -0.16 |
| $MP_{s=mah}$ | -3.23*** | -3.24*** | -1.34** | -3.11*** | -2.56*** | -2.25*** |
| $MP_{s=pine}$ | 4.65*** | 5.68*** | 6.74*** | 3.62*** | 2.89*** | 2.64*** |
| $MDLC_{s=coco}$ | 18.19* | 19.33** | 21.33*** | 5.67 | 5.83 | 6.42 |
| $MDLC_{s=mah}$ | 32.13*** | 38.87*** | 37.99*** | 32.67*** | 28.26*** | 30.05*** |
| $MDLC_{s=pine}$ | -15.28* | -13.67. | -14.95 | -7.77 | -8.71 | -12.90* |
| $SLV_{ils=coco}$ | -15.81*** | -18.04*** | -17.66*** | -19.71*** | -17.74*** | -15.18*** |
| $SLV_{ils=mah}$ | -12.75*** | -12.97*** | -13.00*** | -10.84*** | -8.94** | -9.00** |
| $SLV_{ils=pine}$ | 6.00 | 5.12 | 7.54 | 3.00 | 2.78 | 2.45 |
| $URGreen$ | 19.04 | 13.12 | 17.76 | 18.43 | 17.23 | 24.97 |
| $URDry$ | -61.17 | -42.32 | -24.25 | -47.03 | -34.71 | -30.69 |
| $R^2$ | 0.478 | 0.551 | 0.483 | 0.519 | 0.466 | 0.440 |

Significance: '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$

## References


Kuttankulangara, M.S., Megalingam, R., Minz, S., Karmakar, S., & Kharb, L. (2019). Coconut Tree Structure Analysis-Background Work for an Unmanned Coconut Harvesting Robot Design. Information, Communication and Computing Technology. ICICCT 2018. Communications in Computer and Information Science.

Venn, T.J., McGavin, R.L., & Ergashev, A. (2020). Accommodating log dimensions and geometry in log procurement decisions for spindleless rotary veneer production. *BioResources*, *15*(2), 2385-2411.