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A Decision–Support Tool to Inform Coconut Log Procurement and Veneer Manufacturing Location Decisions in Fiji

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Abstract: Coconut plantations throughout the Asia–Pacific region are generally characterised by the presence of low-productivity senile palms over the age of 60, which have negative impacts on farming communities, coconut processors, and the wider economy. In Fiji, despite numerous senile coconut replacement programs, 60% of coconut palms are considered senile. The purpose of this study is to provide preliminary estimates of the financial viability of a market-based approach to senile coconut palm replacement in Fiji by utilising the palms as a feedstock, for the manufacture of rotary peeled veneer, along with plantation pine and mahogany. A mathematical model capable of supporting deterministic and stochastic dynamic optimisation was developed with an objective function to maximise the gross margin of marketable veneer manufacture per hour (GM_{pz}) by procuring the optimal allocation of logs throughout the landscape. The majority of facility location and log processing scale scenarios evaluated found that utilising large volumes of senile coconut palms for the manufacture of veneer was optimal, whilst veneering mills situated near the coconut plantations in Vanua Levu were found to maximise GM_{pz}. Overall, the results indicate that a coconut veneer and engineered wood product (EWP) value chain could present a financially viable opportunity to support large-scale senile coconut palm replacement in Fiji.

Keywords: financial modelling; stochastic dynamic programming; log procurement; processing scale; facility location; forest and wood products industry

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1. Introduction

Coconut palms (*Cocos nucifera*) are integral to the lives of many communities throughout the Asia–Pacific region, with approximately eight million farmers in the region relying on coconuts for essential income and food security [1]. Coconut palms are often referred to as 'the tree of life', since they provide almost all the necessities of life, including food, water, building materials, and ingredients for local medicines [2–5]. Coconut palms also offer environmental benefits to farming communities, such as coastal stabilisation and protection from extreme winds and tides (which are expected to become more frequent with climate change); their small canopy facilitates agroforestry with livestock rearing and other crops grown underneath [2,4,6,7]. Coconuts are generally considered a smallholder crop, with approximately 96% of the world's coconut palms having been grown on farms that are up to four hectares in area [8].

In many Asia–Pacific countries, coconut plantations are typically characterised by the presence of low-productivity senile palms over the age of 60, which represent large opportunity costs of foregone income, employment, food security, and foreign exchange earnings [9,10]. Landholders have been apprehensive about replacing senile palms due to the high costs of removing the palms and replanting the area with new crops; the duration of time before new crops yield fruit; insecure property rights; and the generally high risk-aversion and status-quo bias among coconut farmers in the region [11–15]. Many government and international aid programs have been trialled throughout the region to support senile palm replacement; however, these programs have generally been ineffective at reducing the high population of senile coconut palms due to a lack of funding and long-term incentives, as well as poor infrastructure and logistics [16–19].

An alternative approach to encourage the replacement of senile coconut palms could be to create private sector demand for the palms that would minimise costs to taxpayers and international aid agencies. For example, log processing facilities within the forest and wood products sector could utilise senile coconut palms as feedstock for the manufacture of veneer and veneer-based engineered wood products (EWPs). Although there is no coconut veneer being commercially produced globally, previous research has demonstrated that veneer and EWPs can successfully be produced from senile coconut palms and substitute as feasible alternatives to conventional timber species in many applications [11,20–22]. Market appraisals by Peters, et al. [23] and Faircloth, et al. [24] have indicated that the unique attractive appearance of coconut wood and its sustainable plantation origins could stimulate high levels of consumer demand for coconut wood products. Additionally, demand for old palms could provide landholders with immediate income for this previously low-value resource, whilst facilitating increased agricultural productivity and supporting rural development goals throughout the Asia–Pacific region [25–28].

In the Asia–Pacific region, Fiji is perhaps among the nations most likely to benefit from a coconut veneer and EWP market. In recent decades, rapid urbanisation and declining interest in agriculture have negatively impacted human health, food security, employment, poverty, and the economy [29]. This has been further hindered by Fiji's susceptibility to natural disasters and restrictive land tenure policies [26,30–32]. Agricultural land in Fiji is scarce since about 70 percent of the country's area is classified as hilly or mountainous and not conducive to mechanised agriculture. As such, improving the productivity of existing farmland has been a primary objective in various Fijian land management policies [33–35].

Fiji's coconut plantations represent a major component of the agricultural sector that could be dramatically improved to enhance the livelihoods of many rural communities and agricultural processors [12,36]. Since the 1960s, Fijian coconut exports have declined by 90%, whilst global coconut product exports have increased by over 400% during the same period [37]. Widespread senility has been recognised by the Fijian Government as the largest contributor to low coconut productivity in Fiji, with approximately 60% of Fiji's coconut palms being considered senile [9,11,12,38]. As a result, Fiji's average coconut yield per hectare is currently only 65% of the global mean, whilst in the neighbouring Solomon Islands and Samoa, where less than 20% of palms are senile, the number of coconut yields per hectare exceeds the world average by 45% and 32%, respectively [37,39].

Fiji also has an active veneer processing industry, which is likely to benefit from the additional timber feedstock senile coconut palms could offer, due to the decreasing availability of traditional native forest sawlogs, increasing harvest regulations, and a planned 2030 end date for native forestry [40]. If the Fijian forest and wood products sector are to finance the removal of senile coconut palms, coconut veneer and EWP manufacture need to be financially competitive; however, information regarding financial performance is scarce. The Fijian industry is therefore seeking answers to questions that are familiar in the forestry literature to support veneering investment decisions, including

- Where to harvest logs on the landscape;
- Which timber species and log types should be harvested;
- What is the impact of scale on a mill's financial performance?
- Where is the optimal location for a log processing facility?

The objective of this paper is to provide a preliminary investigation of the capacity for veneer manufacturing to facilitate large-scale senile coconut palm replacement in Fiji. A coconut wood value chain will rely on the potential for utilisation of coconut logs to enhance the financial performance of EWP manufacturers. Since private sector decision making is driven by optimising returns on investment, a spatial and stochastic operations research

(OR) model was developed to perform this financial evaluation. The paper estimates the potential scale of senile palm removal and evaluates the gross margins of veneer manufacture in Fiji under a range of facility location and log processing scale scenarios. This paper is limited to the evaluation of the financial performance of coconut veneer production since collaborative research arrangements with Fijian EWP manufacturers were still in the early stages of development and potential coconut EWPs are still being examined. Positive findings could justify further research to enhance this preliminary model to support tactical EWP manufacturing decisions about log procurement and final product manufacture, as well as improved strategic decisions about processing scale and facility location. The paper proceeds with a review of the Fijian veneering industry, followed by a description of the mathematical model developed for this case study and the modeled scenarios and variables. Financial performance results are then reported and veneering investment and senile coconut value chain implications are discussed. All financial values have been expressed in FJD (as of July 2024, FJD 1 = AUD 0.66 and USD 0.45).

2. Fijian Case Study

Forestry is an important contributor to the Fijian economy and accounts for FJD 160 million (1.4%) of Fiji's gross domestic product (GDP) [41]. However, Fiji is a net importer of timber products. Over the period 2013 to 2020, Fiji had an average annual trade deficit in timber and paper products of FJD 67.5 million, of which FJD 4.22 million was the average deficit in veneer and EWPs (EWPs traded by Fiji include plywood and laminated veneer lumber. The Fijian Ministry of Forestry also does not measure the imported volume of wood products) [41].

The Fijian veneer and engineered wood product (EWP) industry has historically been dependent on native timber harvesting, with approximately 75% of the industry's log processing volume from 2014 to 2018 having been sourced from native forests [42]. Popular native species utilised for veneer manufacture include kaudamu (*Myristica castaneifolia*.), vusavusa (*Gonystylus punctatus*), and kauvula (*Endospermum macrophyllum*). Over the last couple of decades, wood processing mills in Fiji have faced increased difficulties securing traditional native forest sawlogs because of decreased availability, increased costs, and stricter harvest regulations [11,20,40]. As a result, the average volume of native forest logs harvested by the forest and wood products industry decreased from 107,000 m^3 in 2000 to just 21,000 m^3 in 2020, representing an annual decrease of 4% per year [43]. The veneer processing industry in Fiji has also declined in the last few years, with the country's total annual log processing volumes having decreased from 35,315 m^3 in 2018 to 8904 m^3 in 2022, likely owing to the increasing difficulties in securing traditional native forest sawlogs [41]. The domestic veneering industry's challenge to secure sufficient feedstock will also be compounded by the existing policy to shut down native forest harvesting in 2030 [40]. As such, the Fijian veneering industry is likely to become increasingly reliant on timber plantations.

The two widely available plantation timber species in Fiji are Caribbean pine (*Pinus caribaea*) and mahogany (*Swietenia macrophylla*), which occupy areas of 32,504 ha and 38,322 ha, respectively, as outlined in Table 1 and illustrated in Figure 1. These plantation areas were calculated from spatial data supplied by pine and mahogany plantation growers in Fiji. Plantation pine and mahogany are log resources that the veneering industry is familiar with. Pine is commonly utilised in veneer production, particularly for core veneers in EWPs, accounting for approximately 25% of the veneer feedstock volume in Fiji [42]. Mahogany only accounts for a small fraction of the country's current veneer production but is generally used as a face veneer substitute for native species. Senile coconut palms could complement the supply of plantation pine and mahogany by offering additional log supply to mills running under capacity, whilst also offsetting Fiji's dependency on veneer imports.

Table 1. Area of forest types by island.

Forest Type	Area of Forest Type by Island (ha)			Total Area (ha)
	Viti Levu	Vanua Levu	Taveuni	
Coconut	643	14,795	1462	16,900
Mahogany	21,771	16,550	0	38,322
Pine	21,456	11,048	0	32,504
Total	43,870	42,393	1462	87,726

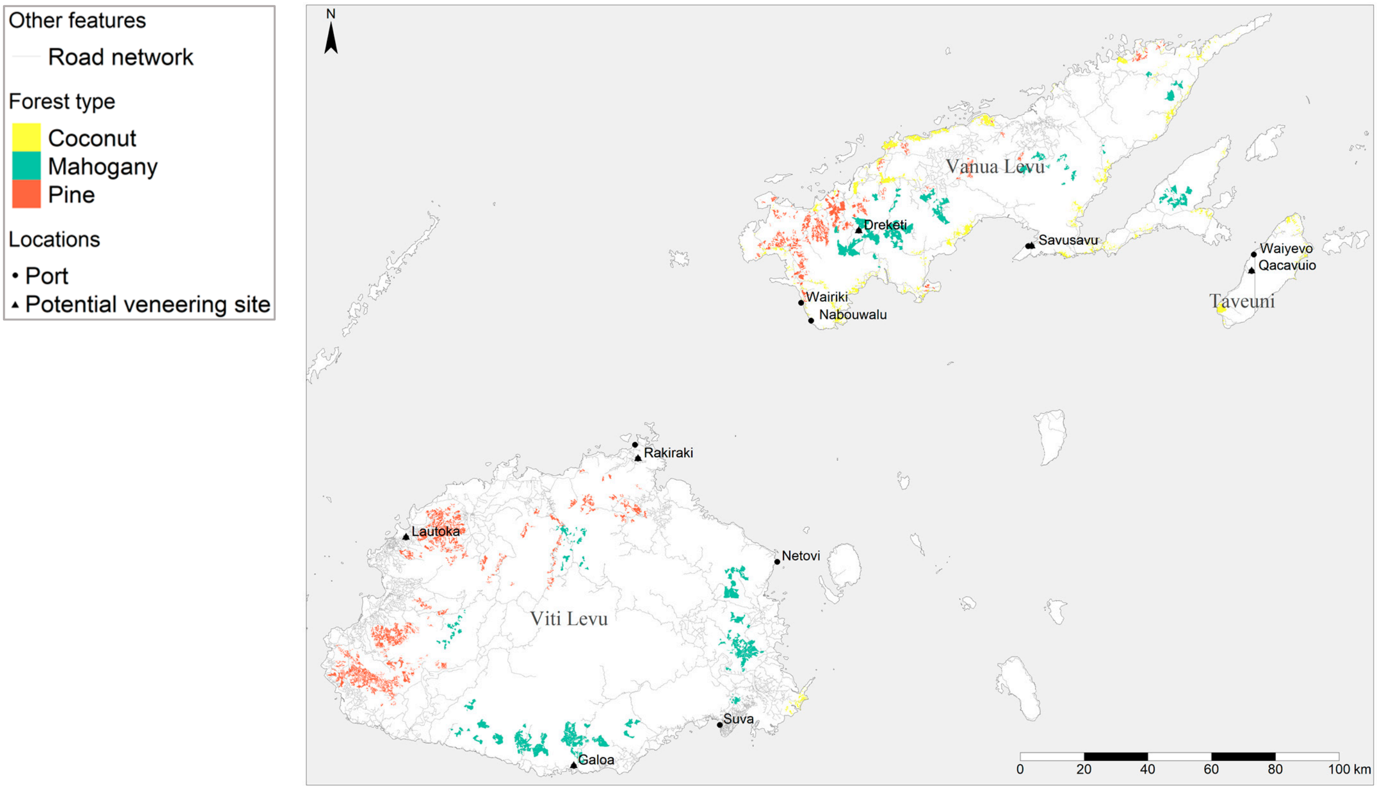


Figure 1. Distribution of forest types, potential veneering locations, ports, and roads in Fiji.

Although there is no commercial production of coconut veneer internationally, there has been a considerable amount of research conducted on its suitability for veneer and EWP manufacture [11,20,23,24,44]. Previous empirical studies have found that coconut logs have high variability in density, which presents challenges for traditional sawmilling that are also exacerbated by small log diameters [9,20,21]. Spindleless rotary veneering can produce coconut veneer and EWPs that are more uniform in density and mechanical properties than sawn wood products, whilst also minimising the volume of material lost during processing [11,20,44]. Nevertheless, the mechanical properties of coconut veneer and EWPs are generally lower than commercial wood species of similar density, reducing its ability to completely substitute for conventional timber in some structural applications [24]. Additionally, the surface has a natural roughness that requires careful gluing and moderate sanding of the final product, whilst the presence of thick-walled fibers puts additional stress on wood processing equipment [21,23]. While the properties of coconut veneer constrain its performance in some structural applications, its hardness, colour, and visual appeal are advantages for many appearance products and coconut can substitute for conventional wood in these applications [11,23].

There is a great deal of uncertainty regarding the area of coconut plantations in Fiji, with estimates ranging from 17,800 ha [36] to as much as 65,000 ha [38]. Shapefiles supplied by the Fijian Ministry of Agriculture and Ministry of Forestry suggested there are approximately 16,900 ha of coconut plantations on the three main islands in Fiji (Viti Levu, Vanua Levu, and Taveuni), with the majority of this area being in the southern region of Vanua Levu and the island of Taveuni, as displayed in Figure 1 [45]. The existing literature indicates that approximately 11% [36] to 25% [46] of Fiji's coconut plantations are located on the small islands in the Eastern Division; however, these areas are not considered in this analysis.

The Fijian veneering industry has requested information about coconut veneering investment opportunities, particularly how alternative processing scales, facility locations, and log procurement strategies could impact returns. OR methods are well-suited to supporting these kinds of decisions.

3. Materials and Methods

3.1. Mathematical Model

A non-linear mathematical programming model capable of supporting deterministic and stochastic dynamic optimisation was developed to support preliminary veneer and EWP manufacturing decision making with regard to log procurement, facility location, and processing scale in Fiji. The model was designed to be used by experienced decision makers in the wood processing industry and has been developed in R (ver. R-4.3.1) [47], a freely available software package that can accommodate large spatially-explicit datasets and facilitate deterministic and stochastic optimisation. While the base-case results are intended to reflect the most likely outcome for each facility location and log processing scale scenario, the stochastic analyses are intended to inform veneering mills of the possible distribution of GM_{pz} and optimal log procurement, given a range of potential parameter values.

The mathematical model provides a preliminary estimate of financial performance of utilising senile coconut palms and other commercial plantation logs, for the production of veneer, which could then be utilised as feedstock for the manufacture EWPs. Potential markets for coconut EWPs are being examined in collaboration with existing EWP manufacturers and will be the subject in a forthcoming study. The outputs of the model are designed to (i) reflect the relative financial performance of a range of potential veneer processing locations at alternative log processing scales; (ii) indicate which log types of a particular species should be targeted for veneering; and (iii) estimate the potential area of senile palm removal.

In Fiji, there is a dearth of information about the fixed and variable costs of veneer production, especially using spindleless lathe technology, which has precluded a discounted cash flow analysis of investment opportunities in this preliminary assessment. Therefore, as indicated in Equation (1), decisions in the model are made based on an objective function that maximises the gross margin of marketable dry veneer per hour of veneer processing (GM_{pz}—\$/h). The model is designed to maximise GM_{pz} by optimally selecting forest polygons (i), log types (l) and species (s) to harvest for pre-defined facility locations (z) and log processing scales (p) in a given year (t). GM_{pz} represents the revenues generated per hour to cover all fixed and variable costs of converting mill-delivered logs into marketable veneer at the processing facility, as well as an acceptable return to capital. The model accommodates uncertainty with model parameters by performing Monte Carlo simulations, where the model is run numerous times, with each run iteratively changing the value of specific parameters to generate alternative GM_{pz} estimates. Model users can select which parameters are stochastic, along with their distribution, such that a range of likely GM_{pz} can be modelled.

An overview of the decision variables solved by the model (Dec), binary parameters, scalar parameters and vector and matrix parameters (Bin, SP, P) that are requested from the model user, and derived parameters (Der), which are a function of Dec, Bin, SP and P, which are provided in Table 2. Index sets associated with variables and parameters in Table 2 are described in Table 3. Scalar and binary parameter levels used in the case study are reported in Table 2. The decision variable in the model is the volume of each log type and species to harvest from each forest polygon in a particular year (LV_{ilst}). The mathematical programming model formulation is as follows:

$$Maximise\ GM_{pz} = \sum_{t=1}^{T} \frac{AR_{pt} - MDLC_{ptz}}{PH_{pt}} \tag{1}$$

where AR_{pt}, $MDLC_{ptz}$, and PH_{pt} are defined below.

$$AR_{pt} = \sum_{s=1}^{S} \left(\sum_{i=1}^{I} \sum_{l=1}^{L} LV_{ilpst} * GVR_{ls} * DVR_{s} \right) * MP_{s} \tag{2}$$

The proportion of a log billet's volume that can be recovered as green veneer (GVR_{ls}—Equation (3)) is driven by the geometry of the log billets being processed ($LogVol_{ls}$), with large straight logs yielding higher levels of recoverable veneer. The equation to estimate $LogVol_{ls}$ is described in the Supplementary Materials and is a function of small-end diameter under bark ($SEDUB_{ls}$), log taper ($Taper_{ls}$), log sweep ($Sweep_{ls}$), and log length (LL). Because taper increases the difference between the large-end diameter under bark and the small-end diameter under bark, taper can potentially reduce the negative impact of sweep on the recovery of green veneer.

$$GVR_{ls} = \frac{\left(\frac{\left(SEDUB_{ls} - \left(\frac{Taper_{ls}}{2} - Sweep_{ls} \right) * LL \right)}{2} \right)^{2} * LL * \pi - CV_{s}}{LogVol_{ls}} \tag{3}$$

Total annual mill-delivered log costs are the costs of harvesting and transporting logs to the mill-gate ($MDLC_{ptz}$) and are estimated in Equations (4) and (5). $MDLC_{ptz}$ is equal to the summation of the costs of stumpage (S_{ls}), cut, snig, and load (CSL_{ls}), haulage from the forest to the mill ($HaulCost_{iz}$), and any other additional costs associated with harvesting particular log types (OLC_{ls}). The model enables the transport of logs to the mill either by road (road network illustrated in Figure 1) or by a combination of road and sea if the logs need to be transported from one island to another. RTA_{iz} is a binary variable, which identifies whether the logs are transported to the veneer processing mill by road only or by a combination of road and sea. If there is a direct route by road between the harvested polygon and the mill, then the value of RTA_{iz} is 1 and the log haul cost by road is calculated. Alternatively, if the harvested polygon and the location of the mill are on separate islands and require sea transport, the value of RTA_{iz} is set to zero. In this scenario, the total cost of hauling the logs to the mill is equal to the sum of the costs of hauling logs from the forest to the port of departure (x) by road, shipping the logs from the port of departure to the port of arrival (y) and then transporting the logs to the mill by road.

$$MDLC_{ptz} = \sum_{i=1}^{I} \sum_{z=1}^{Z} \sum_{l=1}^{L} \sum_{s=1}^{S} LV_{ilpst} * \left(S_{ls} + CSL_{ls} + OLC_{ls} + HaulCost_{iz} \right) \tag{4}$$

$$\begin{aligned} HaulCost_{iz} = \textstyle\sum_{x=1}^{X} \sum_{y=1}^{Y} (VHC_{ixyz} * Dist\_FM_{iz} + FHC_{ixyz}) * RTA_{iz} + (VHC_{ixyz} * \\ Dist\_FP_{ix} + FHC_{ixyz} + SeaFreight_{xy} + VHC_{ixyz} * Dist\_PM_{yz} + FHC_{ixyz}) * (1 - RTA_{iz}) \end{aligned} \tag{5}$$

Table 2. Decision variables (Dec), derived parameters (Der), vector or matrix parameters (P), binary parameters (Bin), and scalar parameters (SP) for the mathematical program.

Name	Variable or Parameter	Description	Name	Variable or Parameter	Description
LV_{ilpst}	Dec	Harvested log volume (m^3)	MP_s	P	Dry veneer market price (\$/m^3 of dry veneer)
AR_{pt}	Der	Annual revenue (\$)	OLC_{ls}	P	Other costs associated with harvesting logs (\$/m^3)
$DVPH_{pt}$	Der	Annual dry veneer processing hours	RTA_{iz}	P (Bin)	Variable that indicates whether there is a direct road route from the forest to the mill. If there is, this value is set to 1, otherwise it is set to 0.
$GVPH_{pt}$	Der	Annual green veneer processing hours	S_{ls}	P	Stumpage price paid to the landholder (\$/m^3)
GVR_{ls}	Der	Recovery of green veneer from log volume (%)	$SEDUB_{ls}$	P	Small-end diameter under bark of a log (cm)
$HaulCost_{iz}$	Der	Total cost of hauling logs to the mill (\$/m^3)	SLV_{ils}	P	Standing harvestable log volume (m^3/ha)
$LogVol_{ls}$	Der	Volume of a log billet (m^3)	$Scale_p$	P	Annual log processing scale (m^3/y)
$LVPH_{ls}$	Der	Log volume processed per hour by the lathe (m^3)	$SeaFreight_{xy}$	P	Cost of shipping logs between ports (\$/m^3)
$MDLC_{ptz}$	Der	Annual mill-delivered log cost (\$)	$Sweep_{ls}$	P	Log sweep (m/m)
PH_{pt}	Der	Annual processing hours	$Taper_{ls}$	P	Log taper (m/m)
$Area_i$	P	Harvestable area within each forest polygon (ha)	VHC_{ixyz}	P	Variable cost of hauling logs by road (\$/m^3/km)
CF_{ils}	P	Competition factor, i.e., the percent of harvestable log volume within each forest polygon available to the veneering facility (%)	DVR_s	SP (75)	Recovery of dry veneer from green veneer (%)
CSL_{ls}	P	Cut, snig and load cost of logs (\$/m^3)	CV	SP (0.004)	Peeler core volume (m^3)
$Dist\_FM_{iz}$	P	Return distance from the forest to the mill (km)	$GVVPH$	SP (4.8)	Green veneer volume processed by the dryer per hour (m^3/h)
$Dist\_FP_{ix}$	P	Return distance from the forest to the departure port (km)	LL	SP (2.6)	Log length (m)
$Dist\_PM_{yz}$	P	Return distance from the arrival port to the mill (km)	$URDry$	SP (85)	Utilisation rate of equipment at the dry veneering stage (%)
FHC_{ixyz}	P	Fixed cost of hauling logs by road (\$/m^3)	$URGreen$	SP (55)	Utilisation rate of equipment at the green veneering stage (%)

Table 3. Index sets used in the mathematical programming model.

Name	Description
$i \in I$	Unique forest polygon identifier
$l \in L$	Log type of a particular species
$p \in P$	Processing scale
$s \in S$	Tree species
$t \in T$	Time period
$x \in X$	Departure port
$y \in Y$	Destination port
$z \in Z$	Facility location

The total processing hours (PH_{pt}) is determined by the green and dry veneering hours. As described in Equation (7), green veneer processing hours ($GVPH_{pt}$) is equal to the volume of the feedstock in a particular year (t), divided by the log volume that can be processed per hour ($LVPH_{ls}$). $LVPH_{ls}$ is a function of the volume of the log billets processed and the time taken to process each billet into veneer and is defined in the Supplementary Materials. $LVPH_{ls}$ 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. Dry veneering hours ($DVPH_{pt}$) is determined by the volume of green veneer input and the processing capacity of the dryer ($GVVPH$). Utilisation rates ($URGreen$ and $URDry$) represent the fraction of operating time that the equipment at each stage of production is being utilised.

$$PH_{pt} = GVPH_{pt} + DVPH_{pt} \tag{6}$$

$$GVPH_{pt} = \sum_{l=1}^{L} \sum_{s=1}^{S} \frac{\sum_{i=1}^{I} LV_{ilpst}}{LVPH_{ls} * URGreen} \tag{7}$$

$$DVPH_{pt} = \frac{\sum_{s=1}^{S} \sum_{i=1}^{I} \sum_{l=1}^{L} LV_{ilpst} * GVR_{ls}}{GVVPH * URDry} \tag{8}$$

subject to the following constraints:

$$0 \leq LV_{ilpst} \leq SLV_{ils} * Area_i * CF_{ils} * Available_{ilst} \tag{9}$$

$$\sum_{i=1}^{I} \sum_{l=1}^{L} \sum_{s=1}^{S} LV_{ilpst} \leq Scale_p \tag{10}$$

Equation (9) ensures that the log volume harvested from each forest polygon cannot exceed the log volume available for harvest within forest polygon. SLV_{ils} represents the standing harvestable log volume of each log type and species per hectare, whilst $Area_i$ is the harvestable area within each forest polygon in hectares. In the absence of information regarding the existing and future competition for log resources in Fiji, the model accounts for the competition of logs by assuming that within each polygon, only a proportion of the standing log volume is commercially available for rotary veneer processing by the veneering mill evaluated in the model (CF_{ils}). $Available_{ilst}$ is a binary variable that determines when particular forest polygons are available for harvesting. When the log resources in a particular forest polygon become mature and ready for harvest, the value of the binary variable, $Available_{ilst}$, is 1 and the expression $SLV_{ils} * CF_{ils}$ exceeds zero. Once logs are harvested from the forest polygon, the value of $Available_{ilst}$ returns to zero and the expression $SLV_{ils} * CF_{ils}$ becomes zero and no additional log volume of that species and log type can be procured until the newly planted forest resources reach maturity and become ready for harvesting again. Equation (10) permits the harvesting of logs each year until the annual log processing scale that is being evaluated is reached.

3.2. Scenarios and Parameters for the Case Study Application

This section describes the veneer production scenarios and the parameter levels adopted to facilitate application the of the mathematical model to inform veneering decisions in Fiji. To estimate gross margins of veneer production per hour of manufacture (GM_{pz}), a base-case deterministic analysis and a stochastic analysis were performed over a 30-year period. All financial values have been expressed in FJD (as of July 2024, FJD 1 = AUD 0.66 and USD 0.45).

3.2.1. Log Processing Scale Scenarios

The veneer manufacturing case study considers two log volume processing scales ($Scale_p$): (i) 15,000 m^3/y and (ii) 30,000 m^3/y. Empirical evidence in Australia suggests that 15,000 m^3/y of log throughput is achievable with one full-time spindleless rotary veneering line [48]. The 30,000 m^3/y scale is modelled as two full-time spindleless rotary veneering lines.

3.2.2. Facility Location Scenarios

The spatial resource information available to the authors was restricted to Viti Levu, Vanua Levu, and Taveuni. Six potential veneering locations identified in Figure 1 were selected for evaluation as they either already have existing log processing facilities or are situated in towns and cities with good access to ports and are proximate to forest resources, as follows:

1. Galoa, Viti Levu;
2. Lautoka, Viti Levu;
3. Rakiraki, Viti Levu.
4. Dreketi, Vanua Levu;
5. Savusavu, Vanua Levu;
6. Qacavuio, Taveuni.

3.2.3. Model Parameters

A comprehensive literature review revealed scarce published information about Fijian log resources, mill-delivered log costs, and veneer and EWP processing costs and market prices. Consequently, parameter estimates for the mathematical model were largely informed through discussions with key informants in the Fijian wood processing industry. Interviews were conducted with two Fijian plywood manufacturers, two plantation growers, three harvest contractors, and numerous research academics and government agency representatives to parameterise the model. Spatial datasets used in this case study, including plantation areas, the road network, and the location of key ports, were collected from plantation forest growers, government ministries, and fellow industry researchers within Fiji.

3.2.4. Forest and Log Types Available for Harvesting

The three commercially important forest types considered in this analysis are senile coconut plantations, mahogany plantations, and pine plantations, which cover the areas indicated in Table 1 and Figure 1. The Fijian EWP industry is presently reliant on native forest resources [42]. With the expected foreclosure of native forest harvesting in 2030, optimal log procurement for EWP manufacture requires an understanding of the profitability of processing alternative plantation log types and senile coconut palms. To maximise GM_{pz}, the model can choose to acquire none, one, or multiple log types from each polygon of each forest type. The seven following log types potentially utilised for veneering have been examined:

- Senile coconut peeler logs;
- Mahogany G3B logs;
- Mahogany G3C logs;
- Mahogany G4B logs;
- Mahogany G4C logs;
- Pine sawlogs; and
- Pine pulp logs.

Due to their small diameter range and relatively uniform log geometry throughout the bole, only one coconut log type has been considered. Fiji Hardwoods, the major mahogany plantation grower in Fiji, recognises five mahogany log grades according to the centre log diameter, G1 (largest) to G5 (smallest), and, for each log grade, there are three log qualities, A (best) to C (worst). Discussions with managers of Fiji Hardwoods revealed that grades G3B, G3C, G4B and G4C are marketed as veneering logs and thus have been accommodated in the analysis. G1, G2, G3A and G4A logs were considered to have higher value as sawlogs. G5 logs have been excluded from selection as they are currently not being commercially sold in Fiji due to their generally poor log quality. Fiji Pine, the major pine plantation grower in Fiji, classifies pulp logs as any pine log with a small-end diameter under bark ($SEDUB_{ls}$) below 20 cm, whilst sawlogs are logs with a $SEDUB_{ls}$ of at least 20 cm. Although pine pulp logs are not commonly veneered in Fiji due to their small diameter, some veneer processing facilities internationally utilise logs with a $SEDUB_{ls}$ as low as 10 cm [49]. In addition, their relatively lower mill-delivered log cost and greater availability than pine sawlogs in Fiji warrant their inclusion in this analysis.

Standing log volume per hectare estimates (SLV_{ils}) for the log types considered are outlined in Table 4. $SEDUB_{ls}$ specifications in Table 4 are the expected means for the seven log types evaluated, with log size distributions used in the analysis presented in the Supplementary Materials. SLV_{ils} has been estimated as follows for coconut plantations. The Fijian Ministry of Agriculture recommends a planting density of 100 coconut palms per ha [36], of which approximately 30% of palms on any given farm have been destroyed due to cyclones [45]. Given that 60% of palms in Fiji are estimated to be senile and without spatially explicit data regarding the ages of coconut palms in Fiji, the analysis assumes that 42 senile palms are present and available for harvesting per hectare. Approximately six 2.6 m logs can be recovered from one senile coconut palm [45]. The $SEDUB_{ls}$ of senile coconut logs is assumed to be uniformly distributed between 20 cm and 28 cm, consistent with previous empirical research [11,20,50]. From these assumptions, the log volume of each senile coconut palm was estimated to be 0.725 m^3, corresponding to a SLV_{ils} of 30.5 m^3/ha in year zero (the SLV_{ils} of coconut in year zero was calculated as follows: $\left(\frac{SEDUB_{ls}}{2}\right)^2 \times \pi \times 2.6$ m/log × 6 logs/tree × 42 senile trees/ha). To account for current productive palms becoming senile in the future, the model assumed an additional 1/60th of the productive palms in year zero becomes available for harvesting in each year of the analysis, increasing SLV_{ils} by 0.338 $\text{m}^3/\text{ha/y}$. The increase in SLV_{ils} of coconut per year was calculated as follows: 28 productive palms/ha in year zero × 1/60 × 0.725 m^3/palm = 0.338 m^3/ha.

SLV_{ils} for mahogany and pine were revealed through interviews with experienced forest managers in Fiji. Experts revealed that pine SLV_{ils} is substantially higher on Vanua Levu than Viti Levu due to higher rainfall and site quality. Further details about how SLV_{ils} of pine were calculated and are described in the Supplementary Materials. SLV_{ils} levels for mahogany are averages of historic harvest data from Viti Levu. Harvesting operations of mahogany plantations have yet to commence on Vanua Levu and in the absence of data, SLV_{ils} for mahogany on Viti Levu has been adopted for plantations on Vanua Levu.

To determine the harvestable volume available per hectare for veneering at a particular mill, SLV_{ils} was multiplied by the competition factor estimates (CF_{ils}) in Table 4. CF_{ils} represents the percent of harvestable logs potentially available to veneer processing mills, due to competition with other mills in the study area. To account for the small number of senile coconut palms currently being harvested for small-scale furniture manufacture, in addition to any senile coconut wood being utilised on-farm (e.g., fencing); CF_{ils} for coconut was set to 90%. The values of CF_{ils} for pine and mahogany were estimated in collaboration with experienced forest managers in Fiji. Consistent with current industry target rotation ages in the study area, the rotation age for pine and mahogany has been set at 20 and 35 years, respectively. Spatially explicit stand age data were provided for mahogany and pine by plantation owners in Fiji and used to determine when each forest polygon would be mature and ready for harvest. Values of log sweep and taper have been collected from interviews with plantation growers and other industry experts in Fiji. Additional information regarding log specifications is provided in the Supplementary Materials.

Table 4. Case study log specifications, costs, and vector parameters.

Log Specification or Model Parameter and Units	Log type by Species						
	Coconut	Mahogany ^{1}				Pine	
		G3B	G3C	G4B	G4C	Sawlog	Pulp
SLV_{ils} (m^3/ha) ^{2}	30.5	100.0	19.8	77.6	34.0	30.6; 57.0	61.2; 114.0
CF_{ils} (%)	90	25	25	25	25	10	10
$SEDUB_{ls}$ (cm)	24.0 [a]	54.0	54.0	42.0	42.0	32.2	17.0
$Taper_{ls}$ (m/m)	0.005 [b]	0.02	0.03	0.02	0.03	0.01	0.01
$Sweep_{ls}$ (m/m)	0.01 [c]	0.024	0.043	0.024	0.043	0.016	0.016
Green density (kg/m^3)	1100 [d]	700 [f]	700 [f]	700 [f]	700 [f]	990 [e]	990 [e]
S_{ls} (\$/m^3 log) ^{3,4,5}	28	20	7	6	1	48	9
CSL_{ls} (\$/m^3 log)	21.5	45.6	45.6	45.6	45.6	28	28
OLC_{ls} (\$/m^3 log) ^{6}	0	261	165	136	97	12	6
GVR_{ls} (%)	76.3	78.3	64.1	73.7	57.4	74.1	52.6
$LVPH_{ls}$ (m^3/h)	13.8	18.9	19.8	18.4	19.6	16.2	12.2
MP_s (\$/m^3 dry veneer)	1250	1440	1440	1440	1440	875	875

Notes: [1]. Total SLV_{ils} of mahogany was estimated to be approximately 389 m^3/ha when including all other mahogany log types not considered in this analysis. [2]. SLV_{ils} is estimated throughout the landscape for coconut and mahogany forests. Pine plantation managers did provide estimates of SLV_{ils} on Viti Levu and Vanua Levu, which are indicated in the table, respectively. [3]. In addition to stumpage payments from plantation logs, other payments made to landholders include goodwill and a proportion of lease costs paid to the iTaukei Land Trust Board (TLTB). These are accommodated within the OLC_{ls} costs. [4]. Stumpage payments are distributed as follows. Stumpage payments for coconut logs are distributed between the TLTB and farmers whose senile coconut palms are harvested. Stumpage payments for pine logs are distributed between the pine plantation managers and the TLTB. Stumpage for mahogany logs is paid to the TLTB only. [5]. For comparison, mahogany log type, G1A, has a stumpage price of \$33/m^3. [6]. OLC_{ls} include costs associated with licensing and reforestation fees, tax, lease costs, loading and unloading of logs, goodwill payments made to landholders that can be in addition to stumpage, a profit margin to plantation forest managers, and other management costs. It is not clear whether these types of costs will be incurred for coconut plantations. Sources: [a]. Kuttankulangara, Sakthiprasad and Kannan [50]; [b]. Fathi [51]; [c]. Nolan, McGavin, Blackburn and Bulai [11]; [d]. Killmann [52]; [e]. Bootle [53]; [f]. Anoop, et al. [54].

3.2.5. Stumpage, Harvest, and Haul Costs

Mill-delivered log costs are the costs of harvesting and transporting logs to the mill-gate and are equal to the sum of cut, snig, and load costs (CSL_{ls}), stumpage (S_{ls}), haul costs ($HaulCost_{iz}$), and any other additional costs associated with harvesting particular log types (OLC_{ls}). Interviews with Fijian harvest contractors revealed CSL_{ls} for each of the log types reported in Table 4. Stumpage prices paid to landholders (S_{ls}) for mahogany and pine logs were provided by plantation growers. In Fiji, stumpage prices for plantation logs grown on mataqali land are guided by the iTaukei Land Trust Board (TLTB) who set a percentage of the gross margin of each log type (mill-delivered log price minus mill-delivered log cost (excluding stumpage)) as S_{ls} [55]. It was reported that farmers near Savusavu, Vanua Levu, currently receive a stumpage of \$20 per senile coconut palm from a small-scale coconut furniture manufacturer, which has been converted into a dollar per cubic metre equivalent for this analysis.

Tables 5 and 6 are used to calculate the log haul costs ($HaulCost_{iz}$). A network analysis was performed in R to calculate the shortest return distance from each harvestable forest polygon to each facility location, each forest polygon to each shipping port, and each shipping port to each facility location using the road network displayed in Figure 1. Table 5 lists industry-provided parameter levels for road haul costs. Due to truck weight limit restrictions within Fiji, the haul costs provided represent average 2023 contract rates paid to several haul contractors by a major plantation owner in the study area for a generic truck with a carrying capacity of ten tonnes. Fixed haul costs (FHC_{ixyz}) represent the average costs of maintaining the trucks and paying drivers' wages. Variable haul costs (VHC_{ixyz}) are the costs of diesel consumption per cubic metre per kilometre. The total haul cost per cubic metre was calculated by multiplying the return haul distance by the variable haul cost and adding the fixed haul cost.

Table 5. Road haul costs in Fiji.

Return Haul Distance (km) [1]	FHC_{ixyz} (\$/m^3) [2]	VHC_{ixyz} (\$/m^3/km) [3]
01–60	9.25	0.156
61+	30.96	0.156

Notes: [1]. Haul distance levels are relevant for model parameters: $Dist\_FM_{iz}$, $Dist\_FP_{iz}$, and $Dist\_PM_{iziz}$. [2]. Fixed haul costs increase with haul distance since fewer trips can be made per day once return haul distances exceed 60 km. [3]. Variable costs of log haulage (VHC_{ixyz}) (\$/m^3/km) generally decline with haul distance since longer journeys often involve driving on a higher proportion of paved roads (and a lower proportion on slow unpaved forestry tracks), which reduces fuel consumption per kilometre [48]. In Fiji, these fuel economy benefits are not as evident because of the mountainous terrain and relatively low-speed limits. In the absence of a road spatial layer with information about speed limits and road quality, the analysis has assumed a constant variable haul cost.

Table 6. Costs of various shipping routes in Fiji by log species.

Shipping Route		Shipping Cost (\$/tonne)	$SeaFreight_{yz}$ (\$/m^3 of log)		
From	To		Coconut	Mahogany	Pine
Suva	Savusavu	125	138	88	124
Suva	Waiyevo	167	184	117	165
Savusavu	Waiyevo	42	46	29	42
Rakiraki	Wairiki	83	91	58	82
Nabouwalu	Netovi	83	91	58	82

Note: $SeaFreight_{yz}$ (\$/m^3 of log) = Shipping cost (\$/tonne) × Green log density (tonnes/m^3—Table 4).

The costs of shipping logs between ports are expressed in Table 6. The costs of shipping a truck with a 10-tonne carrying capacity to the ports included in the case study were supplied by a major Fijian shipping company and converted into a dollar per cubic metre of log equivalent. To calculate the shipping costs per cubic metre of log ($SeaFreight_{yz}$), the cost of transporting one tonne of logs (Table 6) was divided by the green density of each log type (Table 4). When the forest polygon and the facility location are located on the same island, the total haul cost is the road haul cost from the forest to the mill. However, if a forest polygon was located on a separate island from the mill, then the total haul cost would be equal to the cost of transporting logs from the forest to a port, the shipping costs from the port of departure to the destination port, and the secondary road haul cost from the destination port to the mill. In many cases, there are multiple possible sea routes that could deliver logs from one island to another. In these circumstances, the model selects the route with the lowest aggregate cost of road haul and sea transport.

3.2.6. Veneer Recovery and Processing Rates

Table 4 reports green veneer recovery (GVR_{ls}) and log volume processed by the spindleless lathe per hour ($LVPH_{ls}$) by log type. The analysis assumes that 75% of the green veneer produced is recovered as marketable dry veneer (DVR_s). This is based on empirical studies by McGavin, et al. [56], McGavin, et al. [57] and McGavin and Leggate [58], on *Eucalyptus* and *Corymbia* logs in Australia, and Nolan, McGavin, Blackburn and Bulai [11] on coconut logs in Fiji. The loss of veneer volume is due to defects in the veneer sheets (from imperfections inside the log), trimming the veneer to marketable dimensions, and shrinkage during drying.

Spindleless lathe utilisation ($URGreen$), is typically well below 100% due to issues such as delays in log loading, waste removal, and lathe knife changes for sharpening. Other factors affecting the utilisation rate include labour skill and processing automation [48]. A time and motion study was carried out at a wood processing facility in Fiji to observe the veneer processing operation. Following this study, the utilisation rate of spindleless lathes ($URGreen$) in Fiji was estimated to be around 55%. In the model, log processing rates per hour ($LVPH_{ls}$) provided in Table 4 are multiplied by $URGreen$ to estimate the true log processing rate at the green veneering stage. This paper adopts the green veneer throughput rates of a three-deck veneer dryer described in Venn, Dorries and McGavin [48], with a green veneer drying capacity ($GVVPH$) of 4.8 m^3/h and a dry veneer utilisation rate ($URDry$) of 85%. Each dryer is, therefore, capable of processing 4.08 m^3 of green veneer per hour when accounting for the utilisation of the veneer dryer ($URDry$). The 30,000 m^3/y scale is assumed to have twice the drying capacity of the 15,000 m^3/y scale, which is either achieved by having two dryers or one dryer with twice the drying capacity.

3.2.7. Veneer Market Prices

Since veneer is not widely traded in Fiji and information regarding the potential value of dry veneer is scarce, the market prices of veneer adopted in this study (MP_s) have been estimated from EWP prices via the residual value method. Interviews with wood product manufacturers in Fiji revealed market prices and average costs of production for a suite of EWPs. To transform these prices into veneer prices, the costs of the operation past the dry veneering stage were subtracted from the final EWP price, in addition to an average profit margin of 15%. Further information describing the process of calculating veneer prices is outlined in the Supplementary Materials. Mahogany and pine dry veneer prices in Table 4 reflect their relative value in the wood products market, with mahogany generally being used in high-value aesthetic applications, and pine typically being utilised in low-value applications. Interviews with EWP manufacturers and other industry experts indicated that coconut EWPs could be used in a variety of low to high-value applications. As such, the coconut veneer price adopted for this case study is the mean value of these scenarios.

3.3. Stochastic Programming

To help guide investment decisions and validate the robustness of the model, Monte Carlo analyses were performed with 1000 simulations for each combination of facility location and log processing scale. Each iteration of the model adjusted the value of key parameters listed in Table 7 which affected optimal log procurement decisions and generated a distribution of possible GM_{pz}. Minimum, maximum, and standard deviation values were guided by trial data and expert opinion to reflect likely ranges in the parameter values. The base-case analysis adopts the mean parameter estimates in Table 7 to reflect the most likely outcome, given the range of potential parameter values.

Table 7. Values and standard deviations of the variables assessed in the Monte Carlo simulations.

Variable	Species	Units [1]	Distribution (N/U) [2]	Variable Levels Considered			Standard Deviation
				Mean	Minimum	Maximum	
MP_s	Coconut	\$/m^3 dry veneer	U	1250	685	1815	
	Mahogany		U	1440	1065	1815	
	Pine		U	875	685	1065	
$MDLC_s$	Coconut	Percentage change in MDLC (%)	N	0			10
	Mahogany		N	0			10
	Pine		N	0			10
SLV_{ils}	Coconut	Percentage change in SLV_{ils} (%)	U	0	−43	43	
	Mahogany		U	0	−33	33	
	Pine		U	0	−15	15	
$URGreen$		Utilisation rate (%)	N	55			3
$URDry$			N	85			1.5

Notes: [1]. Stochasticity was accommodated in the model in one of two ways. The absolute values of MP_s, $URGreen$ and $URDry$ were varied. Percentage changes in base-case estimates were modelled for $MDLC_s$ and SLV_{ils}. For example, a $MDLC_s$ of 20 represents an increase of 20% over the base-case cost of S_{ls}, CSL_{ls}, OLC_{ls}, and $HaulCost_{iz}$. [2]. N: Normal distribution; U: Uniform distribution.

Accommodating parameter uncertainty within the model is particularly warranted within the forestry industry in Fiji given the country's volatile economic conditions, which have impacted harvesting and manufacturing costs [59]. Costs of veneer manufacture (e.g., capital, labour, and other operating costs at the mill) are not directly considered in this analysis, however, changes in the veneer market price can be regarded as a proxy for potential changes in the costs of production. Additionally, SLV_{ils} and the utilisation rates of the equipment are likely to vary over space and time, respectively, which can be accommodated within the stochastic analyses to facilitate improved decision making under uncertainty. The distribution of SLV_{ils} of mahogany and pine were provided by plantation forest growers. Industry experts indicated that the total number of standing coconut palms per hectare (productive and senile) could vary between 40 and 100 which represents a potential 43% change in the base-line SLV_{ils} of coconut. Mill-delivered log costs ($MDLC_s$) in Table 7 represents the change in the costs of harvesting and delivering logs to the mill and therefore can be considered as the net change in the costs of stumpage, cut, snig and load, haul costs or other costs associated with harvesting logs (S_{ls}, CSL_{ls}, OLC_{ls}, or $HaulCost_{iz}$).

Multiple linear regression models were fitted to explain GM_{pz} and the log volume harvested of each species as a function of the eleven variables listed in Table 7, and the log processing scale, at each log processing location. Coefficients and *p*-values for each independent variable at each facility location were derived to determine their significance in explaining the dependent variables, thus highlighting model parameters decision makers should be cautious about.

3.4. Relative Performance of Coconut Logs

To better inform coconut procurement decisions, an investigation was conducted to determine the willingness of veneering mills to acquire coconut logs. The analysis estimates how much the base-case MDLC of coconut logs would need to vary in order for a log procurement officer to be indifferent between acquiring coconut logs or the alternative log types, over the range of coconut veneer market prices listed in Table 7. Changes in the MDLC of coconut could be interpreted as changes in the costs of stumpage, cut, snig and load, haul costs, or other costs associated with harvesting logs (e.g., administrative costs). A break-even analysis was also performed to evaluate at what market price of coconut veneer does procuring coconut logs become indifferent to alternative log types, using the base-case MDLCs in Table 4.

4. Results

The results of the mathematical model are now presented, including the distribution of gross margins (GM_{pz}); the relative financial performance of the evaluated log types; the optimal log procurement for each veneering location and log processing scale scenario; and the statistical significance of model parameters in determining the volume of coconut logs harvested. The results of this paper are intended to offer a preliminary assessment into whether utilising senile coconut palms in the manufacture of veneer could drive senile palm replacement in Fiji. While the base-case results are intended to reflect the most likely outcome for each facility location and log processing scale scenario given the anticipated parameter values previously described, the stochastic analyses are intended to inform veneering mills of the possible distribution of GM_{pz} and optimal log procurement, given the potential range of parameter values considered in this paper (Table 7).

4.1. Gross Margins of Veneer Manufacture

The base-case and stochastic distribution of the gross margins of veneer manufacture per hour (GM_{pz}) by processing scale and facility location are presented in Table 8 and Figure 2. Among all locations, processing at Dreketi was found to maximise GM_{pz} (a base-case of \$2266/h at 15,000 m^3/y and \$2098/h at 30,000 m^3/y), whilst Lautoka generated the lowest GM_{pz} among all facility location scenarios (\$2046/h and \$1916/h).

Table 8. Base-case and stochastic distribution of gross margins of veneer manufacture (GM_{pz}) ($/h) by log processing scale and facility location.

Facility Location	GM_{pz} ($/h) by Log Processing Scale (m^3/y) by Base-Case and Probability Percentile (%)											
	15,000						30,000					
	Base-Case	1	25	50	75	99	Base-Case	1	25	50	75	99
Galoa	2097	1302	1800	2120	2395	2810	1966	1197	1675	1970	2243	2710
Lautoka	2046	1244	1746	2087	2312	2764	1916	1152	1635	1933	2194	2638
Rakiraki	2096	1283	1773	2140	2390	2794	1975	1185	1687	1986	2255	2691
Dreketi	2266	1341	1943	2280	2607	3107	2098	1264	1813	2125	2387	2875
Savusavu	2232	1299	1918	2260	2571	3068	2078	1232	1785	2103	2374	2849
Qacavuio	2104	1171	1786	2118	2451	2955	1950	1102	1665	1966	2240	2730

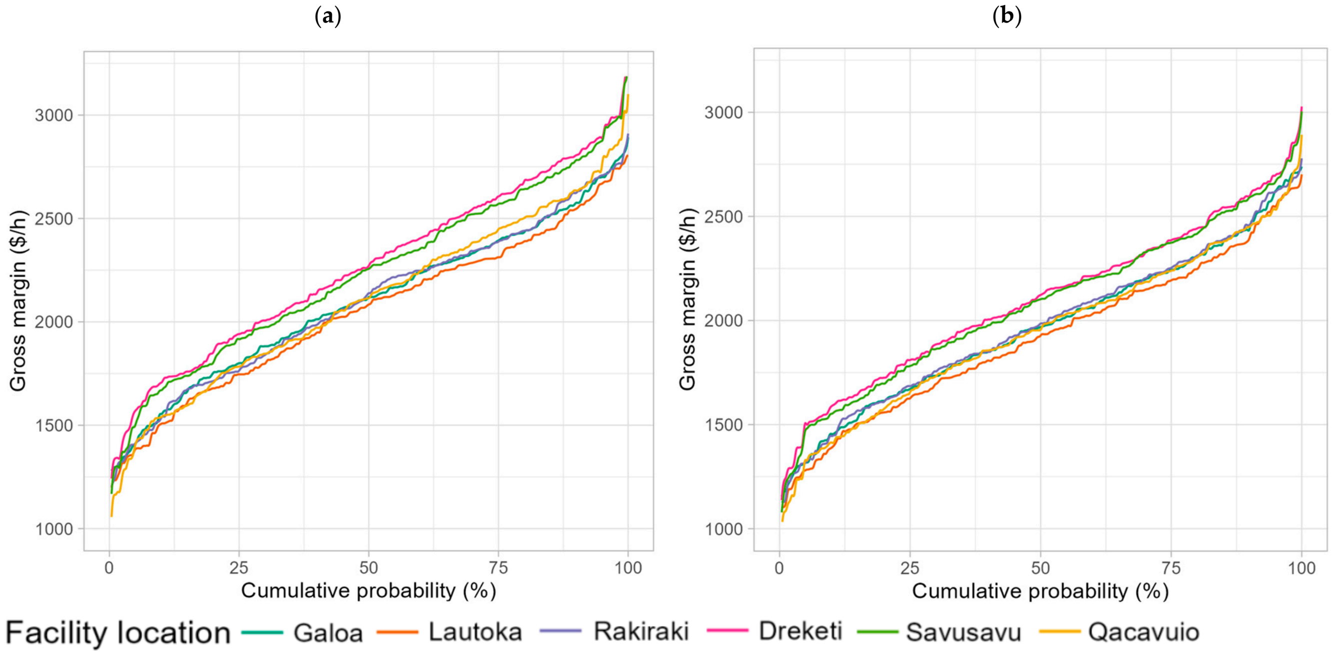


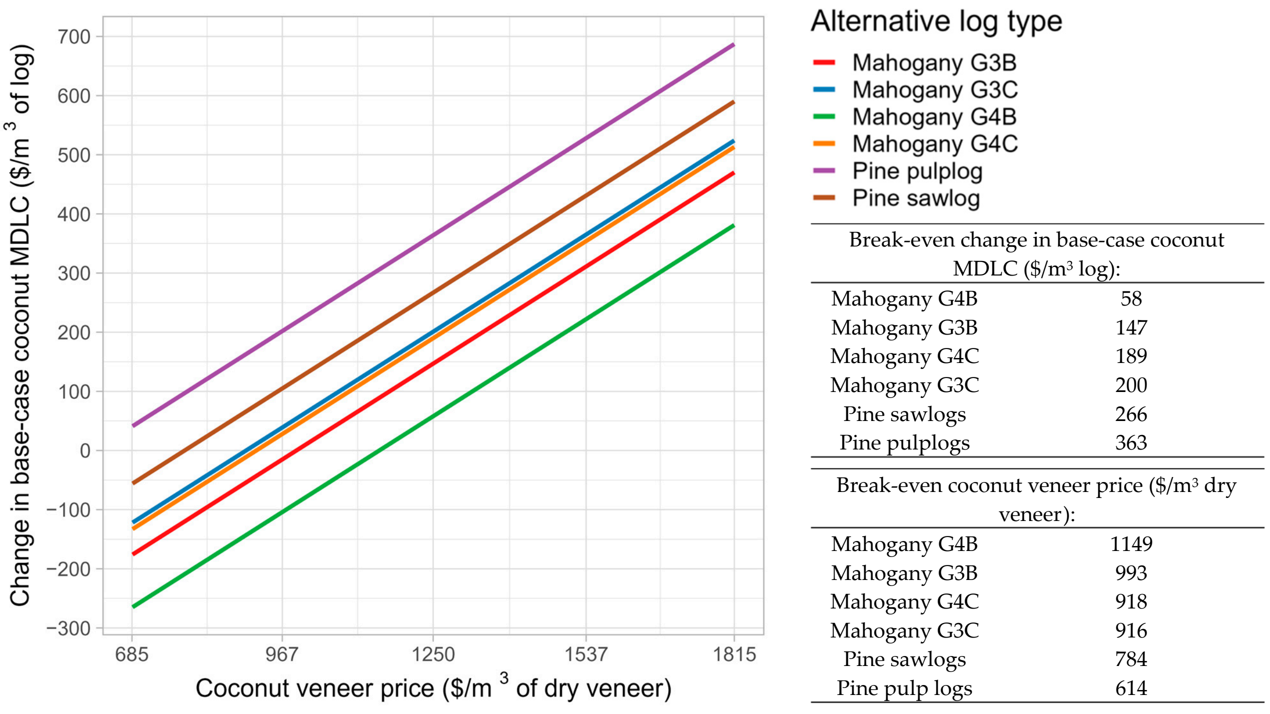
Figure 2. Distribution of gross margins of veneer manufacture (GM_{pz}) ($/h) for a log processing scale of (**a**) 15,000 m^3/y and (**b**) 30,000 m^3/y by facility location.

The stochastic simulations revealed that mills with good access to multiple forest types could more effectively respond to changes in the profitability of procuring particular logs from forest types since these mills could adjust the volume of each species harvested without incurring high haul costs. For example, in the case study, the mills in Dreketi and Savusavu, which were situated close to large areas of coconut, mahogany, and pine plantations, performed the best. The other mills, whilst being centrally located to large areas of a particular species (such as Galoa being close to mahogany or Qacavuio being close to coconut), often shipped logs from Vanua Levu to reach their log processing scale target, which contributed to their relatively low GM_{pz}.

GM_{pz} was found to decrease with log processing scale for all facility locations. In the base-case model, increasing the log processing scale from 15,000 m^3/y to 30,000 m^3/y, led to a reduction in GM_{pz} of $121/h to $168/h (Table 8). This is because at the larger processing scale, mills face increased resource scarcity and therefore, must either haul more profitable log types over longer distances at higher costs or procure less profitable log types from plantations near the mill. Out of the potential veneering locations, mills on Vanua Levu and Taveuni were impacted the most by an increase in log processing scale due to a comparatively larger increase in their average MDLC (the sum of S_{ls}, CSL_{ls}, OLC_{ls}, or $HaulCost_{iz}$). This is further described in the next section.

4.2. Evaluation of Log Types and Optimal Log Procurement

Figure 3 outlines the relative performance of each log type considered in the analysis. The figure illustrates the change in the base-case MDLC (the sum of S_{ls}, CSL_{ls}, OLC_{ls}, and $HaulCost_{iz}$) of coconut logs (\$/m^3 of log) that results in veneering mills being indifferent between coconut logs and alternative log types throughout the potential coconut veneer market prices considered in the stochastic analysis. For example, at the base-case coconut veneer price of \$1250/m^3, mills could pay an additional \$58/m^3 above the base-case MDLC of coconut and be indifferent between procuring coconut and mahogany G4B logs. Figure 3 also reports the market price of coconut veneer where a log procurement officer could be indifferent between procuring coconut logs or an alternative log type for the manufacture of dry veneer. For example, mills would be indifferent between acquiring coconut and mahogany G4B logs when the coconut veneer market price is \$1149/m^3. The results of these analyses indicate that at base-case levels of MDLCs and veneer prices (Table 4), coconut logs were the optimal log type to procure for veneer manufacture, whilst pine logs were least profitable. Among the mahogany log types considered, G4B and G3B logs were more favourable than G4C and G3C, respectively, despite their relatively higher MDLC, due to their superior veneer recovery rates.



Break-even change in base-case coconut MDLC (\$/m³ log):	
Mahogany G4B	58
Mahogany G3B	147
Mahogany G4C	189
Mahogany G3C	200
Pine sawlogs	266
Pine pulplogs	363

Break-even coconut veneer price (\$/m³ dry veneer):	
Mahogany G4B	1149
Mahogany G3B	993
Mahogany G4C	918
Mahogany G3C	916
Pine sawlogs	784
Pine pulp logs	614

Figure 3. Change in base-case mill-delivered log cost of coconut (\$/m^3 of log) that would result in a log procurement officer being indifferent between acquiring coconut logs or alternative log types for a range of potential coconut veneer market prices (\$685/m^3 to 1815/m^3).

Figure 4 illustrates the percentage contribution of each log type to the total veneer log throughput over 30 years for the base-case scenario and stochastic simulations of the model. Consistent with findings from Figure 3, coconut and mahogany were by far, the most harvested log species under all facility location and log processing scale scenarios. Among the base-case analyses, senile coconut palms accounted for 16% to 93% of the annual log processing scale, with mahogany comprising the majority of the annual log volume intake. Interestingly, in all facility location and log processing scale scenarios, no pine pulp logs and very few pine sawlogs were veneered due to their relatively low green veneer recovery (GVR_{ls}) (especially pulp logs) and veneer price (MP_s) and smaller available log volumes per hectare (SLV_{ils} * CF_{ils}), compared to coconut and mahogany (Table 4). Mahogany G4B logs were generally preferred over the other mahogany log types since they are less expensive than G3B and G3C logs, while still offering higher veneer recovery rates than G3B and G4C logs.

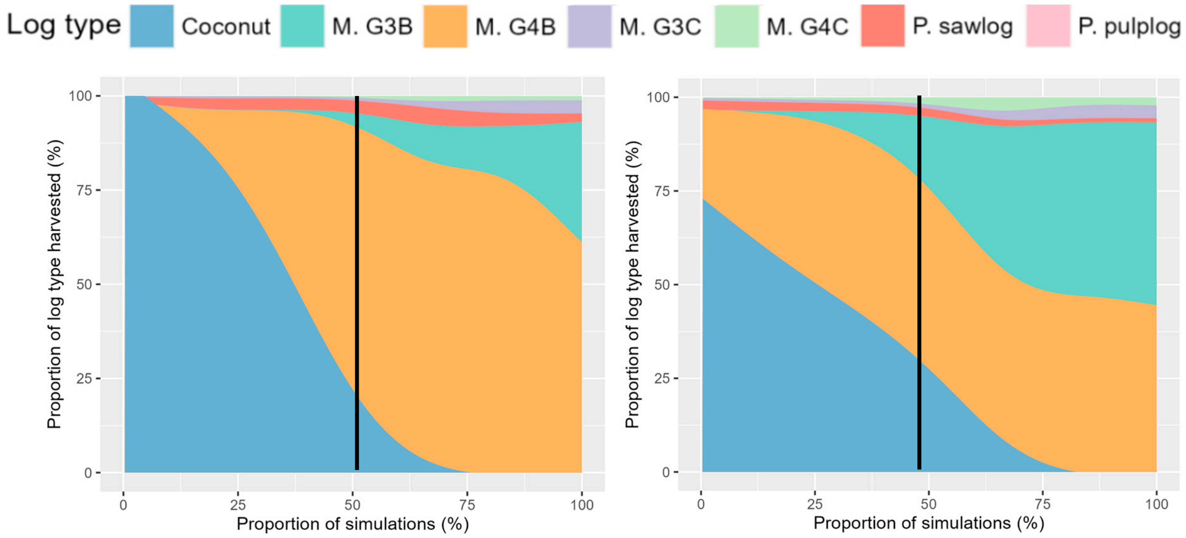
As shown in Figure 4, the optimal procurement of log types varied considerably throughout the stochastic iterations of the model. This was more evident at the 15,000 m^3/y scale since, at this scale, mills face less resource scarcity and therefore can be more selective about which logs on the landscape are harvested. At the 30,000 m^3/y scale, mills procured a greater proportion of less profitable log types (identified in Figure 3) and highly profitable log types were hauled from farther away.

As previously described, the level of increase in a mill's average MDLC ($\$/m^3$ of log) between log processing scales was the largest contributor to the decrease in GM_{pz}. For example, the mills on Vanua Levu and Taveuni (Dreketi, Savusavu, and Qacavuio), where GM_{pz} declined the most as a result of the increase in scale, experienced the greatest increase in their average MDLC. In the base-case analysis and at the 15,000 m^3/y scale, over 90% of these mills' log volume was sourced from nearby coconut plantations (Figure 4), which contributed to their relatively low average MDLC and superior GM_{pz}. However, when the log processing scale increased to 30,000 m^3/y, these mills were unable to continue to source their logs from coconut plantations and, as a result, the contribution of coconut to the log volume intake fell to approximately 50% (Figure 4). The majority of the additional log volume had to therefore be sourced from more expensive (and less profitable) mahogany logs, which contributed to their large increase in MDLC and decrease in GM_{pz}. Table 9 reports the average MDLC of the seven log types by facility location and scale.

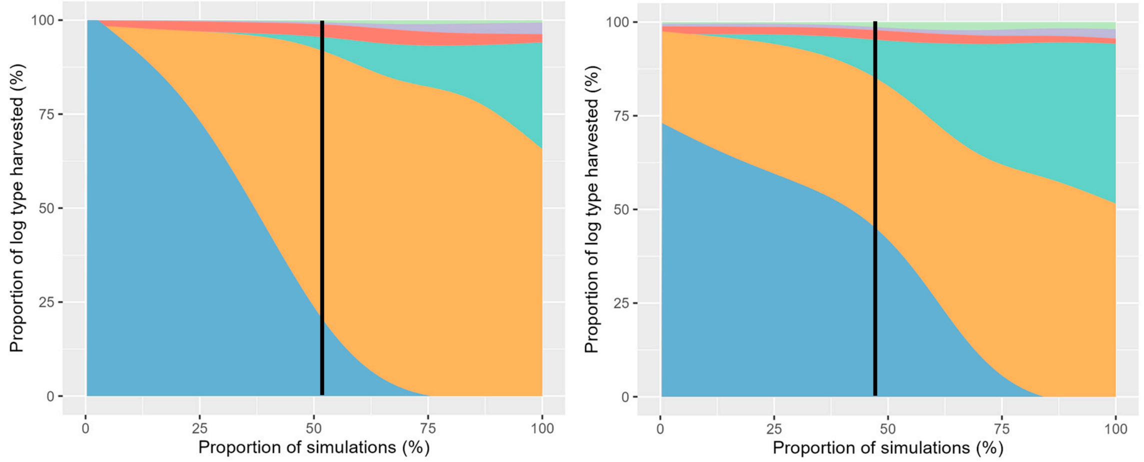
Table 9. Base-case average mill-delivered log costs ($\$/m^3$ of log) by log type for each facility location and log processing scale [a,b].

Log Type	**Scale (m^3/y)**	**Average MDLC ($/$m^3$) and Proportion Contribution of Annual Veneer Feedstock by Mill Location (%) by Mill Location**					
		Galoa	**Lautoka**	**Rakiraki**	**Dreketi**	**Savusavu**	**Qacavuio**
Coconut	15,000	179	187	167	84	85	129
	30,000	215	223	184	92	91	134
Mahogany G3B	15,000					369	
	30,000	362	394		336	370	
Mahogany G3C	15,000	250	292		255	267	313
	30,000	255	295	319	259	272	317
Mahogany G4B	15,000	234	256	256	203	241	281
	30,000	235	258	265	210	251	289
Mahogany G4C	15,000						
	30,000	153		254	202		277
Pine sawlog	15,000	140	108	135	111	150	191
	30,000	145	113	139	116	159	222
Pine pulplog	15,000						
	30,000						
Weighted average	15,000	235	240	218	92	102	141
	30,000	265	257	224	168	172	205

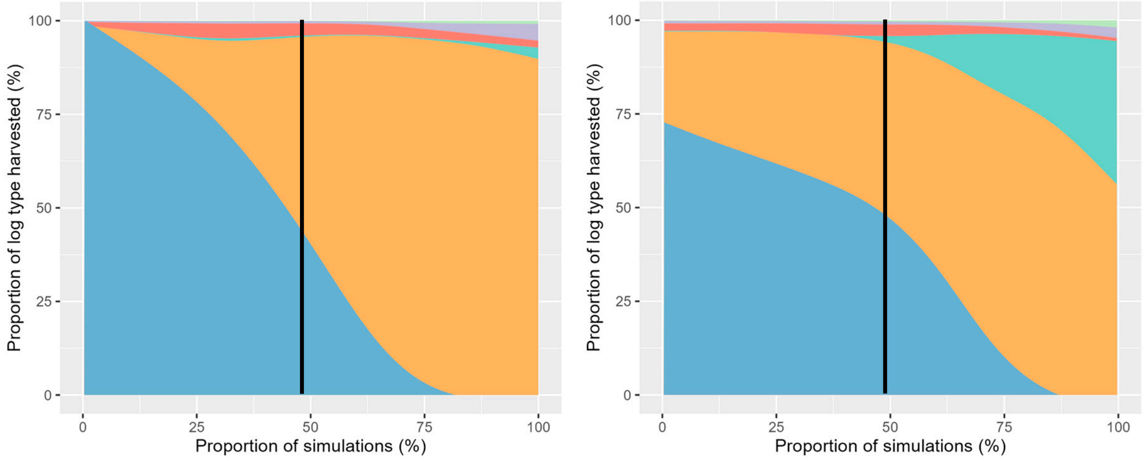
Note: [a]. Empty cells represent log types not harvested for veneering by that veneering location. [b]. Weighted average MDLCs are equal to the average MDLC of each log type multiplied by the proportion of log volume each log type comprises over the 30-year period.



(Galoa—15,000 m^3/y) (Galoa—30,000 m^3/y)

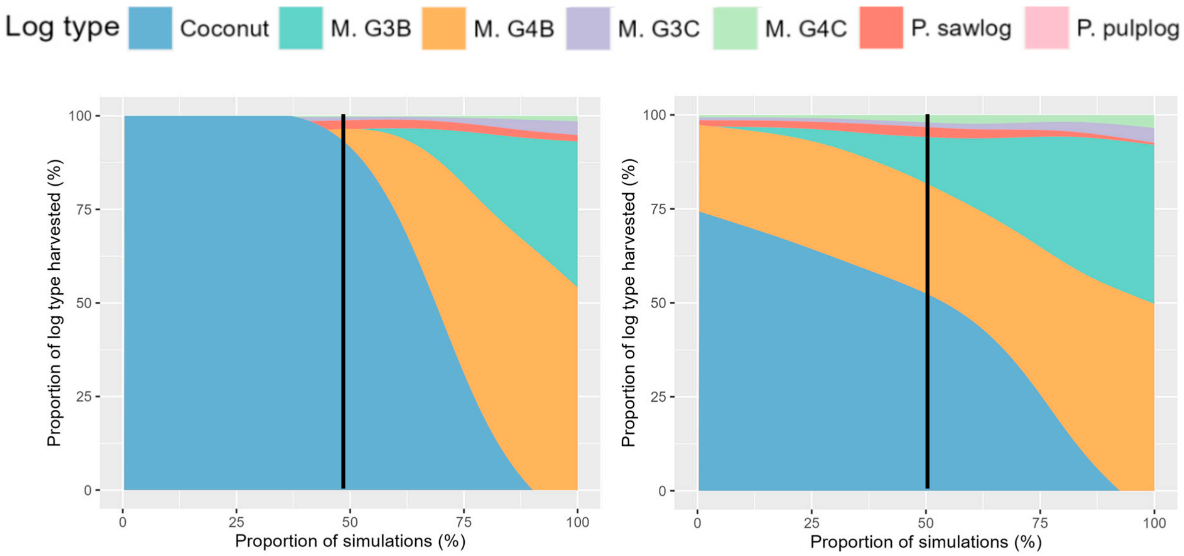


(Lautoka—15,000 m^3/y) (Lautoka—30,000 m^3/y)

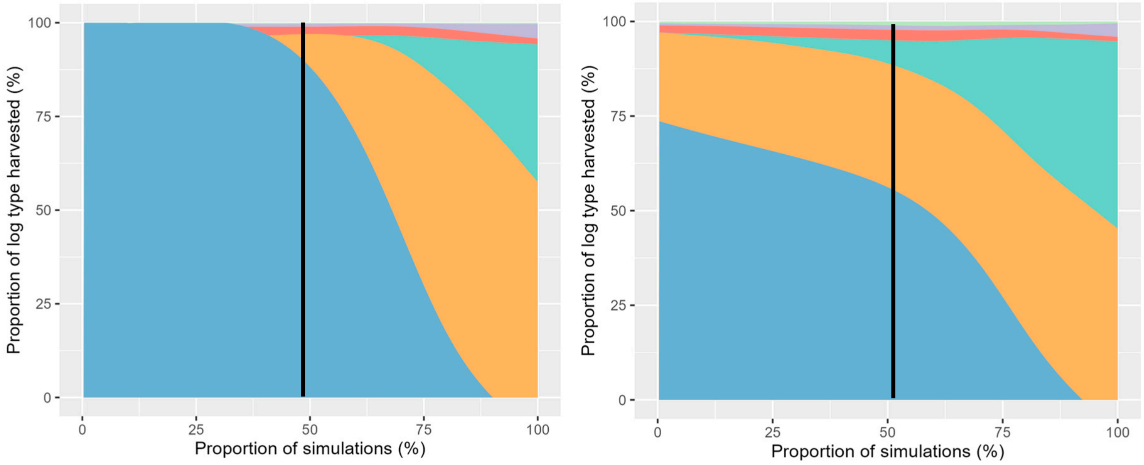


(Rakiraki—15,000 m^3/y) (Rakiraki—30,000 m^3/y)

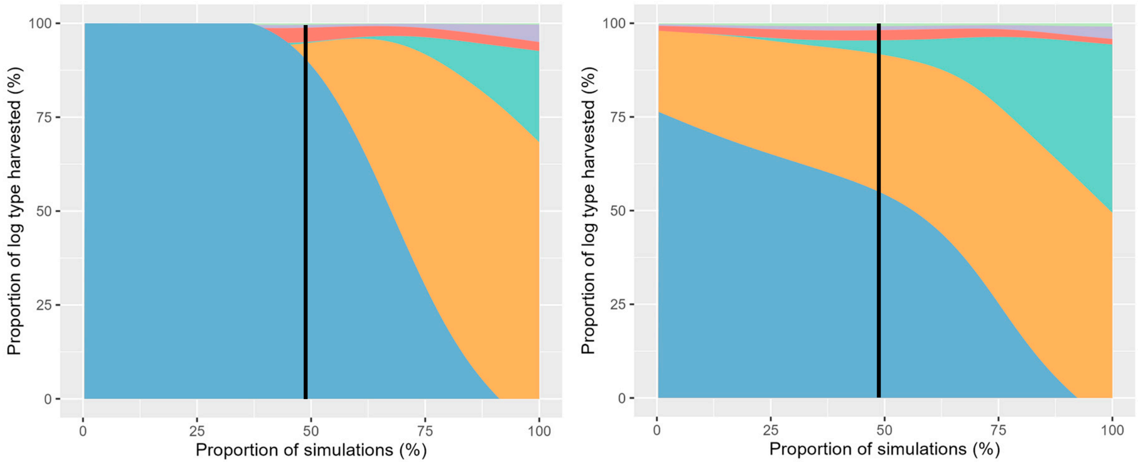
Figure 4. *Cont.*



(Dreketi—15,000 m³/y) (Dreketi—30,000 m³/y)



(Savusavu—15,000 m³/y) (Savusavu—30,000 m³/y)



(Qacavuio—15,000 m³/y) (Qacavuio—30,000 m³/y)

Figure 4. The proportion of log types harvested by facility location and log processing scale [a,b]. Note: [a]. For the purposes of display, the proportion of log volumes harvested has been adjusted using a moving average to smooth out large fluctuations associated with stochasticity. [b]. Base-case log procurement results are identified by the black vertical line.

As expected, the volume of each species harvested was dependent on the mill's proximity to each of the three forest types considered, particularly at the 15,000 m^3/y scale. For example, in the base-case model and at the small-scale of production, the mills on Vanua Levu and Taveuni procured substantially more coconut than the mills on Viti Levu due to the abundance of coconut plantations surrounding these mills. The impact of facility location on the mills' optimal log procurement is further illustrated in Figure 5, which displays the frequency that each forest polygon was harvested throughout the 1000 stochastic simulations at a log processing scale of 15,000 m^3/y for the Galoa, Rakiraki, and Dreketi mills. As illustrated, Galoa generally procured large volumes of mahogany from the nearby plantations whilst Rakiraki, which is relatively distant to many of the harvestable forest areas and located near a port with access to Vanua Levu, harvested coconut and mahogany on both of the main islands. Although Dreketi is located proximate to large areas of pine and mahogany plantations, GM_{pz} was maximised by procuring large volumes of coconut, despite the longer haul distances. The proximity of each mill to each forest type is also highlighted in Table 9, which highlights that mills located near particular forest types could procure the log types of that forest type at a relatively lower cost.

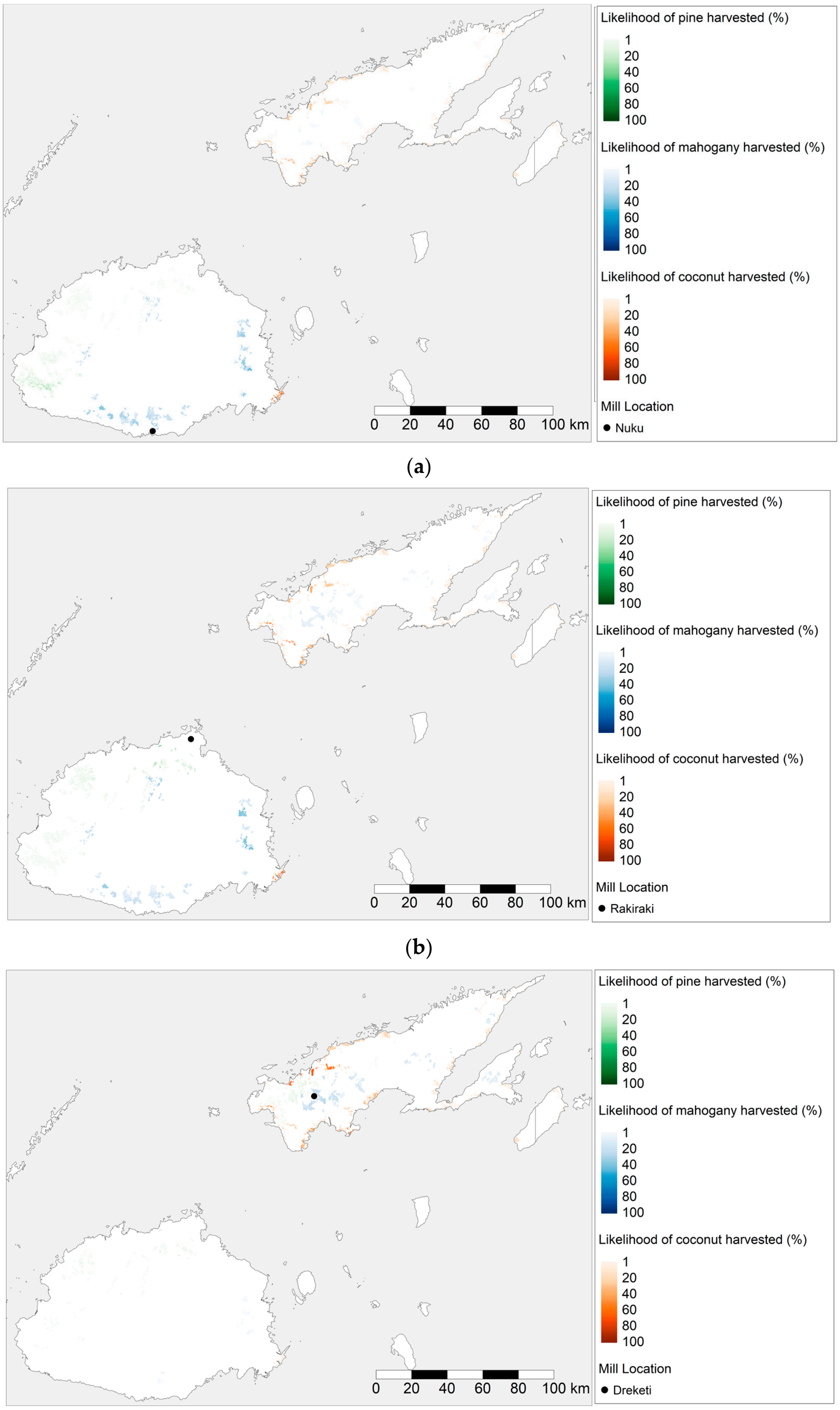
Table 10 presents the results of the multiple regression on the annual volume of senile coconut logs procured by each potential mill, averaged over the 30-year period. Tabulated results of the multiple regression on the procurement of mahogany and pine are provided in the Supplementary Materials. Table 10 reports the change in the average volume of coconut logs harvested per year, as a result of a one-unit change in the key variables assessed. The stochastic simulations found that the parameters in the model explain 62% to 76% of the variation in optimal coconut log procurement, suggesting parameter levels of these variables should be investigated carefully to maximise the utility of the decision–support tool.

Table 10. Regression coefficients and significance levels of selected variables on the average annual volume of coconut harvested over the 30-year analysis by facility location.

Variable [1]	Coefficient (m^3 Harvested per Year) and Level of Statistical Significance by Facility Location [2,3]					
	Galoa	Lautoka	Rakiraki	Dreketi	Savusavu	Qacavuio
$Scale$	2902 ***	2912 ***	2635 ***	3167 ***	3122 ***	3215 ***
$MP_{s=Coco}$	11.64 ***	11.84 ***	11.25 ***	7.93 ***	7.85 ***	7.99 ***
$MP_{s=Mah}$	−8.66 ***	−8.67 ***	−8.82 ***	−6.79 ***	−6.78 ***	−6.87 ***
$MP_{s=Pine}$	−2.09 .	−1.43	−1.54	−0.33	−0.71	−0.48
$MDLC_{s=Coco}$	−60.32 ***	−60.95 ***	−65.98 ***	−26.80 .	−27.03 .	−32.03 *
$MDLC_{s=Mah}$	40.34 **	39.93 **	37.13 *	42.91 **	44.19 **	49.19 **
$MDLC_{s=Pine}$	15.78	11.47	14.51	1.29	2.36	5.98
$SLV_{ils=Coco}$	58.10 ***	64.09 ***	62.68 ***	79.40 ***	80.57 ***	73.83 ***
$SLV_{ils=Mah}$	−59.00 ***	−55.32 ***	−49.15 ***	−33.12 ***	−35.47 ***	−41.19 ***
$SLV_{ils=Pine}$	−17.74	−10.16	−14.70	3.72	−0.83	−3.20
$URGreen$	−84.09 .	−78.33	−65.24	−10.91	−40.37	−36.17
$URDry$	130.36	126.18	171.33 .	121.06	112.63	126.79
R^2	0.761	0.754	0.713	0.655	0.626	0.616

Notes: [1]. Species index: "*Coco*" = coconut and "*Mah*" = mahogany. [2]. Significance: '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; and '.' $p < 0.1$; [3]. For example, a $1 increase in the market price of coconut veneer, $MP_{s=coco}$, increased the volume of coconut logs procured by 7.9 m^3/y to 11.8 m^3/y, depending on the facility location.

As expected, increasing the log processing scale significantly increased the average volume of coconut logs harvested by 2900 m^3/y to 3200 m^3/y. The majority of the variables that impact the profitability of veneer manufacture, such as veneer market prices and MDLCs, were found to have a greater impact at mills in Viti Levu than those in Vanua Levu or Taveuni. Due to the high haul costs associated with shipping coconut logs from Vanua Levu and Taveuni, mills in Viti Levu generally utilised a greater mix of coconut, mahogany, and pine than mills in Vanua Levu, although this was less pronounced at the 30,000 m^3/y scale (Figure 4). As such, changes in the financial performance of particular species had a larger impact on log procurement decisions for sites on Viti Levu than those for Vanua Levu and Taveuni.



(**a**)

(**b**)

(**c**)

Figure 5. Harvested areas by forest type at a 15,000 m^3/y processing scale at (**a**) Galoa; (**b**) Rakiraki; and (**c**) Dreketi over the Monte Carlo simulations.

The impact of changes in the standing log volume per hectare by species (SLV_{ils}) was largely dependent on the mill's proximity to coconut and mahogany plantations. For example, the mills at Galoa and Lautoka, which are located relatively closer to mahogany plantations than coconut plantations, were impacted the least by changes in the SLV_{ils} of coconut but were impacted the most by changes in the SLV_{ils} of mahogany. In contrast, for mills that are proximate to coconut plantations, such as Qacavuio, Savusavu, and Dreketi, changes in the SLV_{ils} of coconut impacted the volume of coconut and mahogany harvested substantially, whilst changes in the SLV_{ils} of mahogany had a smaller impact than on mills on Viti Levu.

Increasing the utilisation rate of the spindleless lathe (*URGreen*) leads to a greater incentive to utilise large-diameter logs due to their relatively higher hourly log throughput rates than small-diameter logs. Therefore, increases in *URGreen* insignificantly decreased the volume of coconut harvested. Alternatively, increases in *URDry* resulted in an insignificant increase in the volume of coconut harvested.

5. Discussion

This paper has introduced a stochastic OR model that can maximise the gross margins of veneer manufacture in Fiji whilst accommodating uncertainty within model parameters. An extensive international review of the literature did not reveal published gross margin estimates of veneer manufacture against which the findings of this study could be compared. The model described in this paper has been targeted at decision makers who have knowledge of wood processing costs against which the hourly gross margin estimates (GM_{pz}) can be compared. The decision-making environment of a particular wood processing firm may not be perfectly represented by any of the facility locations or log processing scale scenarios reported in this paper. Whilst the model has been demonstrated to Fiji, the methodology utilised within this paper could be feasibly applied to other Asia–Pacific nations, so long as spatial data on forest areas, road networks, and potential veneering sites are available.

By summarising studies on facility location and raw-material procurement problems in general, Melo et al. [60] indicated that the objective function in the majority of published papers is to minimise cost, which contradicts the fact that investments are usually made on the basis of profitability. Cost minimisation also seems to have been the focus of many forestry decision–support tools [61–64]. While cost minimisation can be appropriate when log properties do not significantly impact the volume or value of the end product, it is worth noting that internationally, veneer production utilizes logs spanning a diameter range from under 10 cm [49] to 90 cm [65]. An objective function that maximises gross margins of veneer manufacture per hour of production accounts for the processing efficiencies that arise from utilising large straight logs, as well as differences in the market value and mill-delivered log costs.

The results of the mathematical model suggest that utilising senile coconut palms for the manufacture of veneer can potentially enhance the financial performance of log processing facilities, whilst also facilitating senile palm replacement in Fiji. Out of the seven log types evaluated in this paper, senile coconut palms were found to be the most profitable for veneer manufacture, given the parameter values assumed (Figure 3). As such, GM_{pz} was found to be maximised at mills when large volumes of coconut logs were procured (Figure 4) and the distances over which the logs were hauled were minimised (Figure 5). For example, out of the six facility location scenarios considered, processing at Savusavu and Dreketi (which are located near large areas of coconut and procured large volumes of senile coconut palms) generated the highest GM_{pz}, whilst Galoa and Lautoka, only situated near mahogany and pine, respectively, performed the worst.

Taveuni has been proposed as an ideal veneering location given the accessibility of coconut plantations on the island. However, the assessment revealed that this location was sub-optimal due to the large volumes of coconut, mahogany, and pine logs that needed to be shipped from Vanua Levu to achieve the remaining log volume input. The shapefiles supplied by the Fijian Ministry of Agriculture and Ministry of Forestry (which are used in this case study) only indicates 1462 ha of coconut on the island (Table 1), which equates to approximately 40,132 m^3 of senile coconut logs in year zero (or about 2.7 years of continuous log supply at a log processing scale of 15,000 m^3/y). However, anecdotal evidence suggests there may be substantially greater areas of coconut plantations on the island. Further research should be dedicated towards verifying the area of coconut plantations on Taveuni.

Based on the 16,900 ha of coconut plantations considered in this analysis and the base-case parameter estimates of SLV_{ils} and CF_{ils} (Table 4), there is approximately 464,000 m^3 of coconut logs that could be devoted to veneer manufacture. This could be a sufficient volume to fully sustain a 15,000 m^3/y operation for approximately 31 years. In the base-case analyses, the area of senile coconut palms harvested ranged from 2400 ha (15,000 m^3/y scale at Galoa) to 16,700 ha (30,000 m^3/y scale at Savusavu), which represents a total stumpage payment to landholders of \$2.02 million to \$14.03 million over the 30-year period. These estimates are based on an average stumpage payment of \$840/ha, derived from rates paid by small-scale harvesting operations (\$20/tree for an average of 42 senile trees per hectare in year zero). Furthermore, the estimates in Figure 3 indicate that, under base-case veneer prices, wood processors could potentially pay up to \$58/m^3 to \$363/m^3 more than the base-case coconut MDLC and still remain competitive with the alternative log types. This indicates the potential for farmers to negotiate higher stumpage prices for their senile palms.

Expanding veneer manufacture is likely to generate additional socio-economic benefits to the broader Fijian economy that are outside the scope of this paper. These include reducing the country's dependence on timber imports, improving incomes, reducing unemployment, increasing government tax revenue, and generating carbon sequestration benefits from substituting carbon-intensive building products such as concrete, steel, and brick. Commercialising coconut veneering in Fiji may stimulate the large-scale removal of senile coconut palms at little to no cost to the government or farmers, which, after replanting, could provide additional income and food security to local communities.

Low-productivity senile coconut palms generate private, social, and environmental benefits that might be temporarily degraded after harvesting. These include carbon sequestration, mitigation of soil erosion including coastal stabilisation, protection from extreme winds, shade and cooling, and the provision of income and food to farmers [2,6,7,66]. Due to limited road infrastructure within many coconut farms, harvesting senile palms could potentially damage additional crops under the coconut canopies, further impacting farmer's food and income generation. The Pacific Community, an international development organisation, has recently published a code of practice guideline for the responsible harvesting of senile coconut palms that can minimise the environmental, social, and economic impacts of the harvesting of senile coconut palms [67]. However, further research should be dedicated towards quantifying the costs and benefits, which can help evaluate whether a coconut wood value chain is socio-economically beneficial to Fiji.

There are several limitations of the model that will be addressed in future work. First, the model estimates GM_{pz} on the basis of mill-delivered log costs and residual value estimates of wholesale veneer market prices because collaborative research arrangements with EWP manufacturers in Fiji were in the early stages of development. This precluded a discounted cash flow analysis of veneer opportunities. The model also relies heavily on preliminary estimates of veneer processing parameters (e.g., recovery rates and utilisation rates) due to the lack of comprehensive localised data. A disadvantage of evaluating veneer manufacture using gross margins is that gross margins decrease with increasing processing scale due to higher haul costs; the potential economies of scale with larger facilities cannot be captured. Ongoing research is addressing the dearth of fixed and variable cost estimates for rotary veneer manufacture in Fiji. When these data are available, Equation (1) can be modified to capture economies of scale and enable estimation of the net present value of veneering investments.

Second, there is presently no large-scale commercial harvesting of senile coconuts, and further research is required to estimate appropriate stumpage prices and validate the harvest costs described in this paper. For example, the model does not currently account for the costs of top and stump disposal, which may be necessary to avoid outbreaks of the invasive rhinoceros beetle (*Oryctes rhinoceros*). There may also be other administrative costs (e.g., environmental management plans or goodwill payments to landholders) that have not been accommodated in this analysis.

Third, the model accounts for uncertainty within specific parameters by adopting a wide range of potential values, which resulted in large variations in GM_{pz} and optimal log procurement decisions. This variability conveys investment risk, which may discourage coconut veneering. Further research to verify and validate model parameters will facilitate more precise estimates of the financial performance of coconut veneer manufacturing.

Fourth, the analysis assumes a constant level of competition for logs throughout the analysis since plantation owners in Fiji were unable to specify how CF_{ils} varies throughout the landscape or may vary in the future. If the ban on native forest harvesting is implemented in 2030, it is likely that the competition for plantation logs and alternative timber resources such as senile coconut wood will increase.

Fifth, while this case study does account for variability in the small-end diameter under bark ($SEDUB_{ls}$) by log type (distributions provided in the Supplementary Materials), the model assumes uniformity in the other characteristics of the logs (e.g., sweep, taper, density, and quality), which may not accurately reflect the variability encountered in forestry operations. Future amendments to the model could better accommodate variability in log characteristics.

Sixth, the analyses performed in this paper have assumed that 60% of all coconut palms on each hectare are senile, in lieu of accurate distributions of coconut age profiles. This is unlikely in reality since the age distribution of coconut palms does vary between plantations, resulting in differences in SLV_{ils} throughout the landscape. This may result in a disparity between the GM_{pz} and optimal log procurement results reported in this paper and what may feasibly be achieved. Further research should be undertaken to improve estimates of the age profile of coconut plantations in Fiji to better account for the availability of senile coconut palms throughout the landscape.

Seventh, the spatial model calculates road distance based on the shortest distance by road from the forest to the mill and does not account for road quality, speed limits, and bridge weight restrictions. These factors can be a large contributor to haul costs and can greatly influence which forest regions are harvested and the optimal location for a facility [68,69]. This information was not available for the road network data collected. If road characteristics data become available, the network analysis described in this paper can be adjusted to better account for the true costs of hauling logs throughout the landscape.

Eighth, this paper assumes there is sufficient shipping capacity to facilitate inter-island movements of logs. Future research should be carried out to validate the existing capacity of barges and opportunities to hire private barges for log transport.

Ninth, since the model evaluates GM_{pz} of veneer manufacturing, the potential to value-add by utilising multiple species within a single EWP has been ignored. For example, the model has adopted a relatively low pine veneer market price, resulting in limited procurement of pine. However, pine can be used as a core veneer within a high-value EWP with mahogany or coconut face veneer. This will increase the desirability of pine procurement and will be further investigated in a future paper.

6. Conclusions

Like many countries in the Asia–Pacific region, Fiji's coconut plantations are largely characterised by the presence of unproductive senile coconut palms over the age of 60, which present financial and social difficulties in the form of reduced income and employment, food insecurity, and increased reliance on processed and imported foods. A mathematical model capable of accommodating deterministic and stochastic analyses was developed to assess the financial performance of spindleless rotary veneer production in Fiji and evaluate the potential for coconut veneer production to encourage the harvest of senile coconut palms. Coconut and mahogany were the most profitable and most harvested species for all facility location and log processing scale scenarios. GM_{pz} was found to be highest for veneering mills on Vanua Levu, which have close access to coconut plantations, whilst the mills on Viti Levu, which are distant from the majority of coconut plantations, generated the lowest GM_{pz}. Among the base-case analyses, approximately 2400 ha to 16,700 ha of senile coconut palms were harvested over the 30-year period, which indicates the potential for a coconut veneer and EWP value chain to facilitate large-scale senile palm replacement. The volume of coconut logs harvested by the mills was found to be significantly impacted by log processing scale, market prices of coconut and mahogany veneer, MDLC of coconut and mahogany logs, and the SLV of coconut and mahogany.

Overall, the results of the analyses indicate that coconut veneer manufacture is likely to be a profitable venture; however, further research should be targeted towards expanding the model by incorporating fixed and variable costs of spindleless lathe veneering and EWP manufacture. This will facilitate discounted cash flow analysis and estimation of the net present value of alternative veneer and EWP investments. By including these additional elements, wood processors could gain a better understanding of their ability to pay for senile coconut logs, in addition to other wood resources, to support efficient investments in EWP manufacturing and potentially facilitate large-scale senile palm removal. Additional research should also investigate financially optimal veneer and EWP manufacturing scenarios, including which products to manufacture, and the potential for distributed EWP manufacture, whereby veneer may be processed in one or more locations and transported to a central facility for EWP manufacture.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15081442/s1: Table S1: Derived parameters (Der), vector or matrix parameters (P), and scalar parameters (SP) for the parameters expressed in Equations (S1) to (S5); Table S2: Distribution of logs within log type by SEDUB; Table S3: Green veneer recovery rates by log type; Table S4: Sweep and taper characteristics for mahogany and pine log types; Table S5: Variables used to estimate the average price of veneer; Table S6: Regression coefficients and significance levels of selected variables on GM_{pz} by facility location; Table S7: Regression coefficients and significance levels of selected variables on the volume of mahogany harvested by facility location; and Table S8: Regression coefficients and significance levels of selected variables on the volume of pine harvested by facility location. Reference [70] is cited in supplementary materials.

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