ACIAR PROJECT FST/2019/128

Financial and Economic Modelling Report 3:

Development of the 'Forest to Mill' module in R Software for the Mathematical Programming Model to Support Engineered Wood Product Manufacturing Decisions

Coconut and other non-traditional forest resources for the manufacture of Engineered Wood Products (EWP)

Prepared by
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Development of the 'Forest to Mill' module in R Software for the Mathematical Programming Model to Support Engineered Wood Product Manufacturing Decisions

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Executive Summary

Financial information to support engineered wood product (EWP) manufacturing investment decisions in Fiji is limited, particularly with coconut. It is critical that financial evaluations of investment opportunities accompany research activities that assess resource availability, technical aspects of EWP processing and potential markets. This project report summarises the development of a mathematical model in R software that generates optimal log acquisition strategies over space and time to maximise gross margins per cubic metre of a generic EWP product. The model is demonstrated for two processing locations and accounts for cut, snig and load costs, the cost of delivering logs to processing locations via road networks, veneer recovery rates from logs of different sizes and differences in market value of final products manufactured from alternative species. Due to COVID travel restrictions internationally and within Fiji, Fijian data was not available to parameterise the model for this project report, and data from southern Queensland has been utilised for model development. The spatial distribution of two forest types was accommodated spotted gum (*Corymbia citriodora*) and Queensland blue gum (*Eucalyptus tereticornis*) and (for illustrative purposes) it was assumed that spotted gum EWPs achieved a higher market price.

The road network analysis built into the model produced sensible haul distance and haul cost estimates for the two processing locations that were clearly superior to analyses based on Euclidean distance. The model also generated rational optimal log procurement strategies over space and time. For example, at each of the two processing locations the model demonstrated clear preferences for (a) harvesting forests closer to the mill; (b) harvesting more spotted gum forest (the higher value forest type) than Queensland blue gum forest; and (c) hauling logs from spotted gum forests further than logs from Queensland blue gum forests. Necessary future improvements of the forest to mill module in the mathematical programming model includes the option to optimise the procurement of specific log types from particular forest types over space and time, optimising the location of the processing facility relative to the resource, and parameterisation of the model for Fiji. These developments will be described in future project reports.

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1. Introduction

The aim of the broader ACIAR project is to deliver and validate wood processing technologies to transform coconut and other currently low-value forest resources in Fiji into high-value engineered wood products (EWPs) suitable for local and international markets. Financial information to support EWP manufacturing investment decisions in Fiji is extremely limited, and a financial evaluation of investment opportunities is a critical complementary research activity to accompany assessments of resource availability, technical aspects of EWP processing and potential markets.

The objective of the financial and economic research in FST/2019/128 is to develop a mathematical programming model to support decision-making with respect to investments in coconut and hardwood EWP manufacture in Fiji. Dorries et al. (2021) details the rationale and guiding framework for the model. The objective function of the model will be to maximise the net present value (NPV) of investment in EWP manufacture. The decision variables that the model will optimise to maximise NPV will provide valuable information to potential investors, including:

- Which final products should be produced?;
- Where to establish an EWP manufacturing facility?;
- Whether veneering and EWP manufacture should occur at the same location or whether veneering should be performed closer to the resource in a decentralised business model?;
- What is the economically efficient scale of operation?;
- Which forest resources should be harvested (e.g. coconuts and mahogany) and from where on the landscape?; and
- Where there is variation in log size and quality, which log types should be procured from the forest resources (e.g. small diameter versus large diameter logs, and short length versus longer logs)?

The purpose of this project report is to summarise progress on development of the 'forest to mill' module of the mathematical model in R software. This module accounts for the:

- spatial distribution of the resource;
- the temporal distribution of the resource (i.e. when the forest is available to harvest and potentially re-harvest);
- log volumes per hectare by log type; and
- harvest and haul costs to a processing facility.

2. Research Method

The authors have developed a non-linear mathematical programming model in Excel to support native forest hardwood EWP manufacturing decisions in southern Queensland (Venn *et al.*, 2020; Venn *et al.*, 2021; Venn and McGavin, 2021). While the model was fit for purpose, it had three major limitations. First, the Excel Solver platform had a limit of only 200 decision variables (i.e. the spreadsheet cells where values can be changed by Solver when searching for the optimal solution). This severely constrained the range of variables that could be optimised in a single run of the model, and necessitated multiple, time-consuming parallel runs of the model to explore the decision space. Second, due to the first limitation, the model was aspatial, meaning it had limited ability to account for spatial complexities in resource availability and mill-delivered log costs. Third, Excel cannot efficiently run stochastic mathematical programming models. Consequently, the model was deterministic and could not explicitly account for parameter uncertainty, nor test for statistically significant differences between simulated scenarios. Reviewers of this suite of research encouraged the authors to address these limitations. All of these limitations will be addressed in the economics research performed in this project

The mathematical programming model is being developed in R software, which is freely available and capable of overcoming all limitations associated with the model developed by Venn et al. (2021). In the early part of the broader ACIAR project, while project partners are collecting Fijian data, the model framework will be developed using data from southern Queensland. The model framework will be readily transferable to alternative geographic and economic contexts, although time will be required to parameterise the model appropriately.

2.1 Mathematical model

When the mathematical model is complete, the model will harvest forest resources to maximise the NPV of EWP manufacture. Until then, the 'forest to mill' module will have a preliminary objective function to maximise gross margins (GM). The following description of the model will continue to be refined as improvements to the model are made.

$$Maximise \quad GM = \frac{R - MDLC - MOC}{\sum_{p=1}^{P}\sum_{t=1}^{T} PVol_{pt}} \qquad \text{[eq. 1]}$$

where

$$R = \sum_{p=1}^{P}\sum_{t=1}^{T}\sum_{s=1}^{S} PVol_{pt} * MP_{sp} \qquad \text{[eq. 2]}$$

$$MDLC = \sum_{t=0}^{T}\sum_{i=1}^{I}\sum_{f=1}^{F}\left[AH_{itf} * \left(\sum_{l=1}^{L}\sum_{s=1}^{S} LV_{itls} * \left(S_{ils} + CSL_{lf} + HFC_i + \left(HVC_i * Dist_i\right)\right)\right)\right] \qquad \text{[eq. 3]}$$

$$MOC = LC + \left(\sum_{p=1}^{P} NLC_p + \left(\sum_{t=1}^{T} PVol_{pt} * F_p\right)\right) \qquad \text{[eq. 4]}$$

$$LC = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{m=1}^{M} FTE_{jm} * HL_{jm} * \left(\sum_{f=1}^{F}\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{p=1}^{P} \frac{AH_{itf} * LV_{itls} * RF_{lsmp}}{UR_m * PR_{ml}}\right) \qquad \text{[eq. 5]}$$

subject to constraints:

$$0 \le LV_{itls} \le SLV_{il}, \forall\, l, i \qquad \text{[eq. 6]}$$

$$0 \le AH_{itf} \le \frac{HA_i}{HRI} * CF_i, \forall\, i \qquad \text{[eq. 7]}$$

$$0 \le \sum_{i=1}^{I}\sum_{l=1}^{L} AH_{itf} * LV_{itls} \le Scale \qquad \text{[eq. 8]}$$

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, are provided in Table 1. Index sets associated with variables and parameters in Table 1 are described in Table 2. Scalar and binary parameter levels used in the case study are reported in Table 1. Vector and matrix parameter levels used in the case study are reported in the next section.

Table 1. 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
LV_{itls}	Dec	Harvested log volume (m^3 ha^{-1})
AH_{itf}	Dec	Area harvested (ha)
$PVol_{pt}$	Dec	Final product volume manufactured (m^3 of final product). In this case study, only one product type can be produced
R	Der	Total product revenue ($)
$MDLC$	Der	Total mill-delivered log cost ($)
MOC	Der	Total mill operating cost ($)
LC	Der	Total labour costs ($)
RF_{lsmp}	P	Recovery of final product from log volume (%)
UR_m	P	Utilisation rate of equipment and machinery (% of work hours)
PR_{ml}	P	Processing rate of inputs per hour at a 100% utilisation rate of equipment and machinery (m^3 h^{-1})
GR_g	P	Veneer grade recovery (%)
S_{ils}	P	Stumpage price paid to the landholder ($ m^{-3})
CSL_{lf}	P	Cut snig and load cost ($ m^{-3})
HFC_i	P	Haul fixed cost ($ m^{-3}). See Table 4
HVC_i	P	Haul variable cost ($ m^{-3} km^{-1}). See Table 4
$Dist_i$	P	Haul distance from each forest polygon, *i*, to the processing facility calculated via network analysis in R (km)
Scale	P 15000 m^3 y^{-1}	Veneer plant processing scale examined (m^3 y^{-1} of log)
FTE_{jm}	P	Number of full-time equivalent workers
HL_{jm}	P	Hourly cost of labour ($ h^{-1})
NLC_p	P	Non-labour operating costs ($ m^{-3} of final product)
SLV_{il}	P	Standing harvestable log volume (m^3 ha^{-1})
HA_i	P	Total area of commercially important and harvestable forest for each facility location scenario (ha)
CF_i	P	Competition factor, defined as the percent of total commercially important and harvestable forest area potentially available to the veneer production facility (%).
MP_{sp}	P	Final product market price ($ m^{-3} of final product)
F_p	P	Freight cost to market ($ m^{-3} of final product)
HRI	Bin 20 and 30 years	Harvest return interval (years). Silviculturally treated forests are 20 years, otherwise 30 years

The model is designed to be run separately for each combination of log procurement, facility location and processing scale scenarios that are of interest. The decision variables in the model are the area to harvest per annum, AH_{itf}, the volume of logs to harvest per hectare, LV_{itls}, and the volume of alternative final product types manufactured $PVol_{pt}$. In this milestone report, the only 'active' decision variable is AH_{itf}. Future versions of the model will accommodate the other two decision variables.

In addition to mill-delivered log costs, *MDLC*, and Final product market price, MP_{sp}, important parameters that determine GM in the model include utilisation rates of equipment and machinery UR_m, processing rates per hour, $PR_{ml,}$ and recovery of final product from log volume, RF_{lsmp}. Levels for the last two parameters tend to increase with log diameter, and accounting for them allows the model to accommodate the trade-off between *MDLC* and the processing efficiencies that often arise with larger logs.

Table 2. Index sets used in the mathematical programming model

Name	Description
$i \in I$	Unique forest polygon identifier
$t \in T$	Time period from 0 (initial investment) to 30 years
$f \in F$	Forest type. In this case study these are spotted gum forest and Queensland blue gum forest
$l \in L$	Log type. In the case study these are: A-grade sawlog; B-grade sawlog; small peeler log; and top log.
$s \in S$	Tree species harvested (i.e. some forest types can produce logs from multiple species). This has not been applied in this case study
$g \in G$	Veneer product grade quality. Grade quality will affect potential marketable products In this case study, this has not been applied. In the FWPA project, veneer grading was compliant with A, B, C and D-grades in the Australian and New Zealand Standard AS/NZS 2269.0:2012 (Standards Australia, 2012).
$p \in P$	Final product type. Only one-stage EWP considered in this case study
$j \in J$	Position or job type
$m \in M$	Manufacturing stage. In this case study there are four. Administration is considered a stage of production for analysis purposes. There is also green veneer production, dry veneer production and one-stage LVL manufacture

Equations 2 to 5 are the mathematical definitions of the derived parameters introduced in Table 1. The term in brackets in equation 5 calculates the number of processing hours by stage of production to produce the volume of final products. The hours are then multiplied by the numbers of different types of workers and their hourly labour rates to calculate labour costs for the operation.

Equation 6 ensures no more than the standing harvestable volume is harvested from any given hectare. In the absence of detailed information about the spatial distribution of the forest resource, equation 7 requires that the harvested area per annum by haul zone does not exceed the sustainable annual level that can be harvested from that haul zone. The sustainable annual level accounts for the harvest return interval (*HRI*) and competition for logs with other processing facilities (CF_i). Equation 8 requires that the log volume processed does not exceed the processing scale scenario volume.

Before the optimisation model is run, private native forest (PNF) polygons are assigned as being either managed for timber production or not. In the absence of actual records, the model has a feature that allows to user to select a random proportion of PNF polygons to be available to harvest. 'Unavailable' polygons are removed from further analysis.

The model allows manual assignment of a time period to each forest polygon from which time the polygon is mature and available for harvest. However, in Queensland there are no harvest records for private native forests, so it is not possible to know precisely when a particular forest area will be available for harvest. The model allows the user to assign a proportion of the total forest area for each forest type that is mature and available to harvest immediately in year 1. The model will then randomly assign forest polygons as available to harvest immediately to meet that defined proportion. The remainder of the forest area is then randomly assigned a time period of maturity (available to harvest) over years 2 to 30. In this case study analysis, 25% of the forest area was assumed to be available for immediate harvest.

The user can specify whether a harvest is accompanied by a silvicultural treatment to increase the merchantable growth rate of the forest. The user can choose from silvicultural treatment settings: (1) no harvested forests are treated; (2) all harvested forests are treated; and (3) a proportion of the forests are treated at random. In this case study analysis, silvicultural treatment setting 3 has been selected, with 50% of all harvested areas silviculturally treated. Growth in merchantable wood volume between harvests can be calculated by the model in one of two ways: (a) the same harvestable volume as the initial harvestable volumes by log type (as reported in Table 4 for the case study) will be available at the next harvest; or (b) harvestable volume will be calculated from estimates of mean annual increment (MAI). In this case study, forest growth method (a) has been adopted. The model allows the user to set the harvest return interval with and without silvicultural treatment, which determines the year in which the forest will next be available to harvest. Typical harvest return intervals for southern Queensland have been adopted here; 20 years for silviculturally treated forest and 30 years for untreated forests. For example, a forest polygon harvested without silvicultural treatment in year 2 will next be available to harvest in year 32, whereas a polygon harvested and silviculturally treated in year 7 will next be available to harvest in year 27.

2.2 Parameters for the southern Queensland case study

Ten EWP manufacturing scenarios have been examined to demonstrate the 'forest to mill' module, consisting of two facility locations in southern Queensland (Gympie and Esk), and five log procurement scenarios. All scenarios assume an annual processing scale of 15,000 m^3/y.

Log procurement scenarios

Four hardwood log types potentially utilised for veneering in the study area have been examined, namely A grade sawlogs, B grade sawlogs, small peeler logs and top logs. A and B grade sawlogs are traditional log types with which the hardwood industry is familiar. Small peeler logs and top logs are proposed new log types with which the industry has limited to no experience. Small peeler logs are from the bole of small diameter and suppressed trees. Top logs would typically be left among the residue following a traditional native forest harvest. These logs could be in the bole of a felled tree above a sawlog, but below crown break, or could be within the crown. The following six log procurement scenarios will be evaluated, although only results for the first five are reported below:

1. small peeler logs;
2. small peeler logs and top logs;
3. small peeler logs, top logs and B-grade sawlogs;
4. small peeler logs, top logs, B-grade sawlogs and A-grade sawlogs; and
5. B-grade sawlogs and A-grade sawlogs.
6. optimal procurement of logs to maximise GM.

The first five scenarios require that the listed log types are purchased by the veneering facility from every harvested hectare. Therefore, the only decision variable for the first five scenarios is AH_{itf}, because if a hectare is harvested, the log types specified in the log procurement scenario are harvested. These log procurement scenarios are regarded as 'near feasible' for the study area, because the contractual arrangements necessary to achieve them are no more burdensome for contracted parties than current operations.

An additional log procurement scenario remains under development, but will be reported in the next milestone report. This will optimise log types harvested per hectare, LV_{itls}, as well as AH_{itf}, to maximise GM.

That is, different log types can be procured from alternative harvested areas across the landscape. This is less likely to be achievable in practice, because of additional transaction costs with landholders, harvesting contractors, and other processors (for buying desired logs or on-selling less-desired logs). Nevertheless, the optimal solution provided by this scenario would provide an aspirational performance level, and is useful for evaluating 'near feasible' solutions and for estimating the contribution of different log types to GM.

The timber resource

Lewis (2020) reported the private native forest (PNF) mapping methodology, which removed forests that are not harvestable under the code of practice (Department of Natural Resources and Mines, 2014), and Francis et al. (in press) defined forest types relevant to industry. In this paper, only spotted gum and Queensland blue gum forests are considered for analysis. The distribution of these two forest types on private land around Gympie (mill location 1) and Esk (mill location 2) in southern Queensland is illustrated in Figure 1. In the absence of better information, it has been assumed that landholders of only 50 % of the PNF resource harvest their timber (MBAC Consulting Pty Ltd, 2003a; Bureau of Rural Sciences, 2004). This resulted in a total areas of harvestable spotted gum and Queensland blue gum in the case study area available under the code and due to landholder management intentions are 102,284 ha and 43,048 ha, respectively.

Figure 1. Distribution of (a) spotted gum; and (b) Queensland blue gum resources

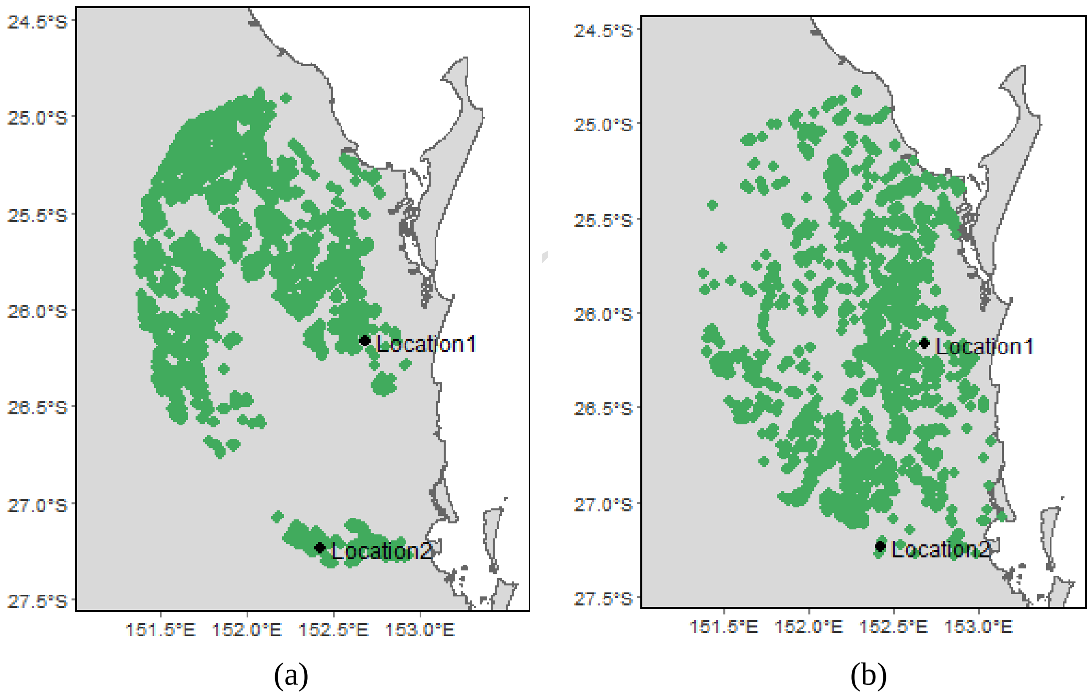


Table 3 reports log specifications and other model parameters by log type. The small-end diameter under bark (SEDUB) specifications are expected means for the four natural forest hardwood log types, with small peeler and top logs having the same specifications. For the purposes of this case study, values of sweep and taper for logs have been set at 0.005 m m^{-1} and 0.0075 m m^{-1}, respectively, which are average levels for small-diameter *Eucalyptus* and *Corymbia* natural forest and plantation logs processed in multiple recent veneering studies (McGavin *et al.*, 2014; McGavin and Leggate, 2019). The harvestable volume per hectare estimates ($SLVil$) are the average harvestable volumes reported in the most recent inventory of private natural forests in the southern Queensland part of the study area (MBAC Consulting Pty Ltd, 2003a, b). The harvestable volume for top logs has been taken from empirical work by Leggate et al. (2019). No data is available to facilitate differentiation of harvestable log volumes by forest type. Log volume and log volume loss due to rounding has been estimated with equations reported in Venn et al. (2020).

Table 3. Case study log specifications and vector parameters

Log specification or model parameter	Log type		
	A-grade sawlog	B-grade sawlog	Small peeler and top logs
Billet length (m)	2.6	2.6	2.6
Small-end diameter under bark, SEDUB (cm)	45	35	25
Mean billet volume before rounding (m^3 log^{-1})	0.432	0.264	0.138
Log volume loss due to rounding (%)	4.4	5.6	8.0
SLV_{il} (m^3 ha^{-1})	1.1	3.5	3.4, 0.6
S_{ils} (\$ m^{-3})	110	55	40
CSL_{lf} (\$ m^{-3})	43.5	43.5	66, 48
$LVPH_l$ (m^3 h^{-1})	18.3	16.3	13.3
RF_{lsmp} (%)	52	49	43
MP_{sp} (\$ m^{-3}; one-stage EWP; spotted gum and Queensland blue gum)	1000; 900	1000; 900	1000; 900

Stumpage and harvest costs

Industry partners in QLD provided mean stumpage prices paid to landholders (S_l), as well as mean cut, snig and load costs for A-grade and B-grade sawlogs reported in Table 3. There is capacity for the model to assign alternative stumpage values for different forest polygons on the landscape, *i*, different log types, *l*, and different species, *s*. Cut, snig and load costs may vary by forest type, *f*, as well as log type, *l*. Presently, there is a limited market for small peeler logs and top logs in the study area, and parameter levels adopted for these log types are derived in (Venn and McGavin, 2018).

Haul costs

Haul distances from each harvestable forest polygon to both mill locations were calculated as follows. Shapefiles containing the private native forest data were imported into R statistical software, along with the 'Baseline roads and tracks – Queensland' roads layer available from Qspatial. The "st_length" function within the R package "sf" was used to estimate the length of each road in the network from the road's start and end coordinates. The function "knn (K nearest neighbours)" function within the package "nabor" uses the coordinates of each forest polygon to identify the closest point on the road network, and attaches the forest polygon to that closest point. The "distances" function in the "gdistances" package was then used to perform a network analysis to select and calculate the shortest road distance between each forest polygon and the mill, $Dist_i$. The model user can define a maximum haul distance from the mill to limit the forest area available to supply the mill. Haul costs from each forest polygon to both mill locations was then calculated using the haul costs in Table 4.

Table 4. Haul costs in southern Queensland

Haul zone	Haul distance (km)	HFC_i (\$ m^{-3})	HVC_i (\$ m^{-3})
1	0-30	10.33	0.3856
2	31-50	21.90	0.3153
3	51-80	28.21	0.2355
4	81-100	35.28	0.2007
5	101 +	39.29	0.1731

Notes: These costs are 2018 rates paid to several haul contractors by a major hardwood processor in the study area. These costs are not representative of a particular truck configuration, as configurations do vary between contractors. Fixed costs (*HFC*) are total haul costs for the minimum haul distance from a particular haul zone to the mill, and variable costs (*HVC*) are the costs per cubic metre per kilometre thereafter.

Processing and product recovery rates, and market price

The processing efficiency (PR_{ml}), utilisation rate of equipment and machinery (UR_m), recovery of final product from log volume (RF_{lsmp}), and final product market price (MP_{sp}) reported in Tables 3 and 5 have been adopted from Venn et al. (2020a) and Venn et al. (2020), Venn and McGavin (2021) and Venn et al. (2021). The engineered wood product (EWP) selected for analysis was one-stage laminated veneer lumber. The one-stage LVL product examined here is assumed to substitute for sawn timber in applications where high mechanical performance is required (e.g., in multistorey construction). The model can also accommodate different EWP prices between forest types; to demonstrate this, the model has adopted a spotted gum EWP market price of \$1000 m^{-3} based off data collected from Venn et al. (2021) and a Queensland blue gum EWP price of \$900 m^{-3}.

Table 5. Processing and product recovery rates

Parameter	Processing stage (m)		
	Green veneer	Dry veneer	One-stage EWP
UR_m (%)	65 (lathe)	85 (dryer)	50 (hot press)
PR_{ml} (m^3 h^{-1})	13.85 m^3 h^{-1} of 25 cm SEDUB logs, 15.80 m^3 h^{-1} of 35 cm SEDUB logs, or 18.37 m^3 h^{-1} of 45 cm SEDUB logs per lathe	4.8 m^3 h^{-1} of green veneer per small dryer or 7.0 m^3 h^{-1} of green veneer per large dryer	5 m^3 h^{-1} of dry veneer per hot press
RF_{lsmp} (% of log volume)			
Small peeler and top logs	69	52	43
B-grade sawlogs	79	59	49
A-grade sawlogs	84	63	52

Product manufacturing costs

Non-labour operating costs and freight to market

This milestone focusses on the forest to mill module. However, in order to optimally select logs for processing, accounting for some product manufacturing costs is necessary. Table 6 outlines preliminary non-labour operating costs accommodated in this version of the model. Fixed land, building, plant and equipment costs are not accounted for in this milestone report. Future versions of the model will accommodate a comprehensive set of manufacturing costs.

Table 6. Non-labour operating costs

Item	Variable name	Costs ($ m^{-3} of final product)
Freight to market	F_p	55.00
Packaging	NLC_p	0.24
Adhesive	NLC_p	52.40
Total		113.60

Labour costs

Table 7 reports the salaries, hourly labour costs and the number of full-time equivalent (FTE) workers required per shift at each stage of production, as estimated by Venn et al. (2021). A shift is eight hours per day, five days per week, 48 weeks per year, for a total of 1920 hours per year. Processing rates at each stage of production are used by the financial model to estimate the annual number of hours of labour required for each processing stage by log procurement scenario. Labour costs in Table 7 are cumulative, such that total labour costs for one-stage EWP manufacture are the summation of labour costs of administration, green veneer production, dry veneer production and one-stage EWP manufacture.

Table 7. Labour costs by stage of production

Position	Annual salary ($)	Hourly Cost ($/FTE/h)	Number of employees at processing stage			
			Admin	Green veneer	Dry veneer	One-stage EWP
Manager	150,000	114	1	0	0	0
Senior administration	80,000	61	1	0	0	0
Supervisor/Maintenance	80,000	61	0	0.25	0.25	1.25
Loader/ machine operators	55,000	42	0	3	0	8
Machine assistants	45,000	34	0	2	3	0
Administration support	45,000	34	1	0	0	0
Quality control supervisor	80,000	61	1	0	0	0
Packaging	45,000	34	0	0	0	0.25
Total number of employees			*4*	*5.25*	*3.25*	*9.5*

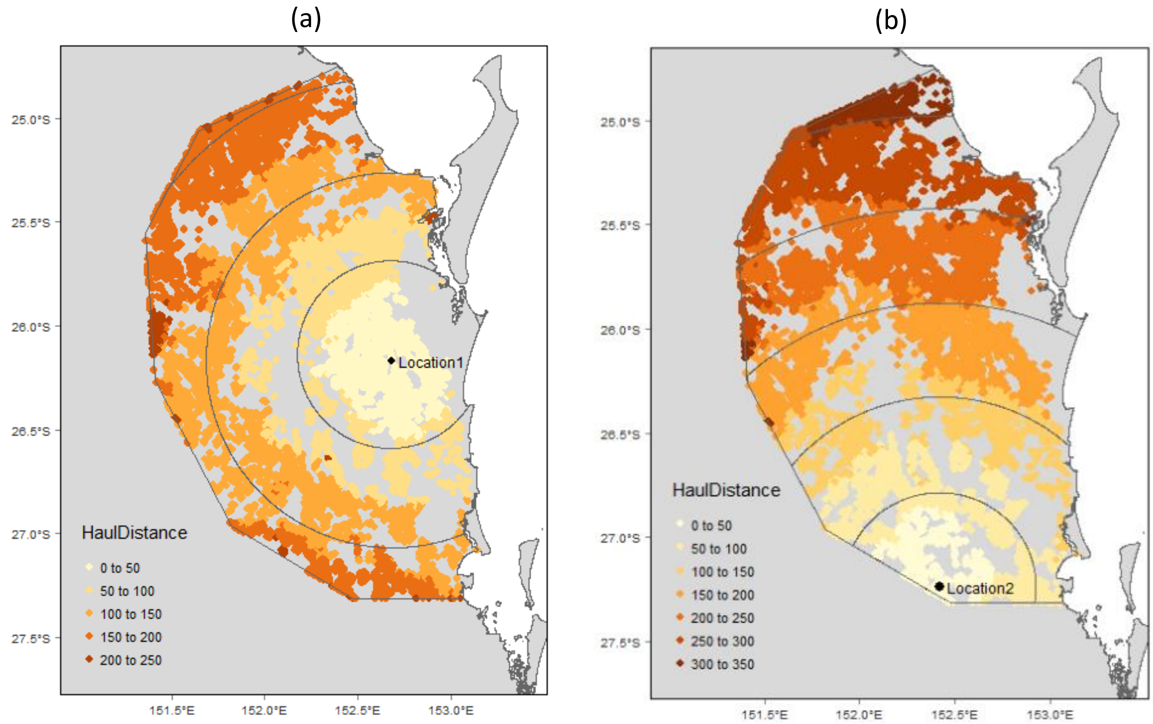
3. Results from the Case Study

These preliminary results are focussed on showing progress in development of the mathematical programming model.

3.1 Haul distances

In the Excel version of the model, haul distances were calculated as Euclidean distance from the processing facility, and haul zones were perfect concentric rings radiating out from the mill. The network analysis performed by the model has calculated haul distances based on the actual road network. Figure 2 highlights how this has improved the model's representation of reality relative to concentric circles.

Figure 2. Haul distances from forest polygons to mill location 1 (a) and 2 (b). Concentric black rings radiate in 50 km Euclidean intervals from each mill location. Note that haul distances calculated via the road network are inside their respective concentric ring, indicating the potential for underestimating haul costs.



3.2 Mill-delivered log costs

Figures 3 and 4 illustrate average mill-delivered log cost for log procurement scenario 4 for processing locations 1 and 2, respectively. The difference in costs between the facility locations reflects *a priori* expectations given the long haul distances from the north of the study area to location 2.

3.3 Harvested forest polygons by forest type over time

Figure 5 illustrates the harvested polygons by forest type for mill locations 1 and 2 for log procurement scenario 4 throughout the 30-year simulation. Table 8 summarises the total area of forest available (TA) within each mill-delivered log cost category and the area harvested (HA) over the 30-year simulation for log procurement scenario 4 for each mill location. Figure 5 and Table 8 reveal that it is optimal to: (a) harvest forests closer to the mill; (b) harvest more spotted gum forest than Queensland blue gum forest; and (c) haul spotted gum logs further than Queensland blue gum logs. These three observations suggest the model is working as expected, given the final market price for spotted gum products was assumed to be \$100 m^{-3} higher than Queensland blue gum product.

Figure 3. Average mill-delivered log cost for log procurement scenario 4 for processing location 1 for spotted gum forest (a) and Queensland blue gum forest (b)

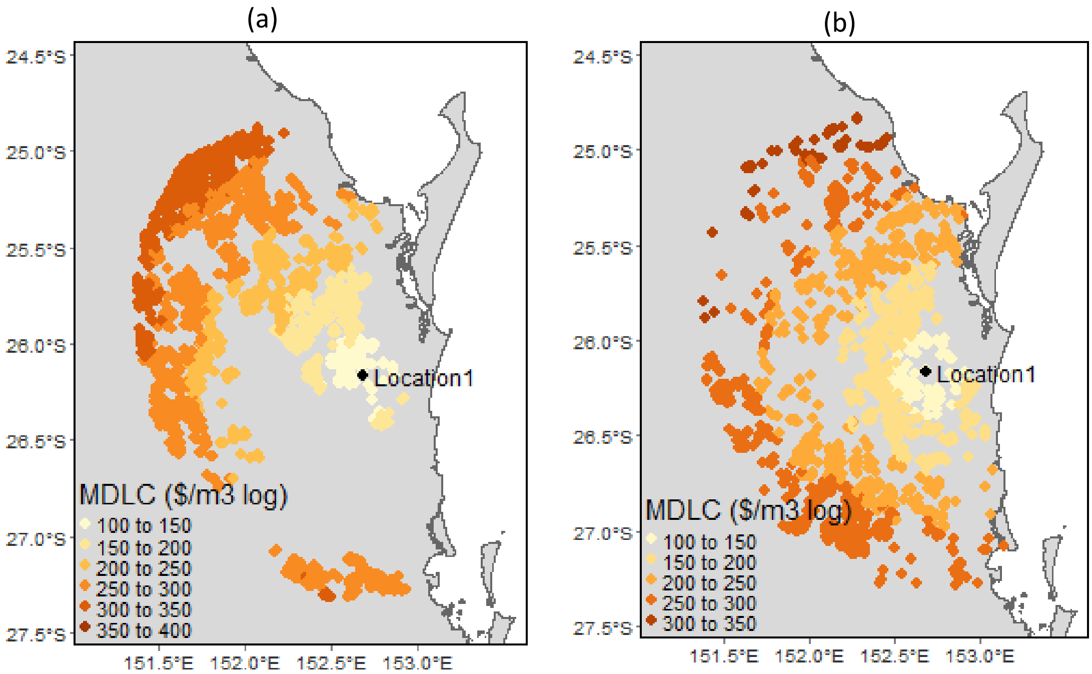


Figure 4. Average mill-delivered log cost for log procurement scenario 4 for processing location 2 for spotted gum forest (a) and Queensland blue gum forest (b)

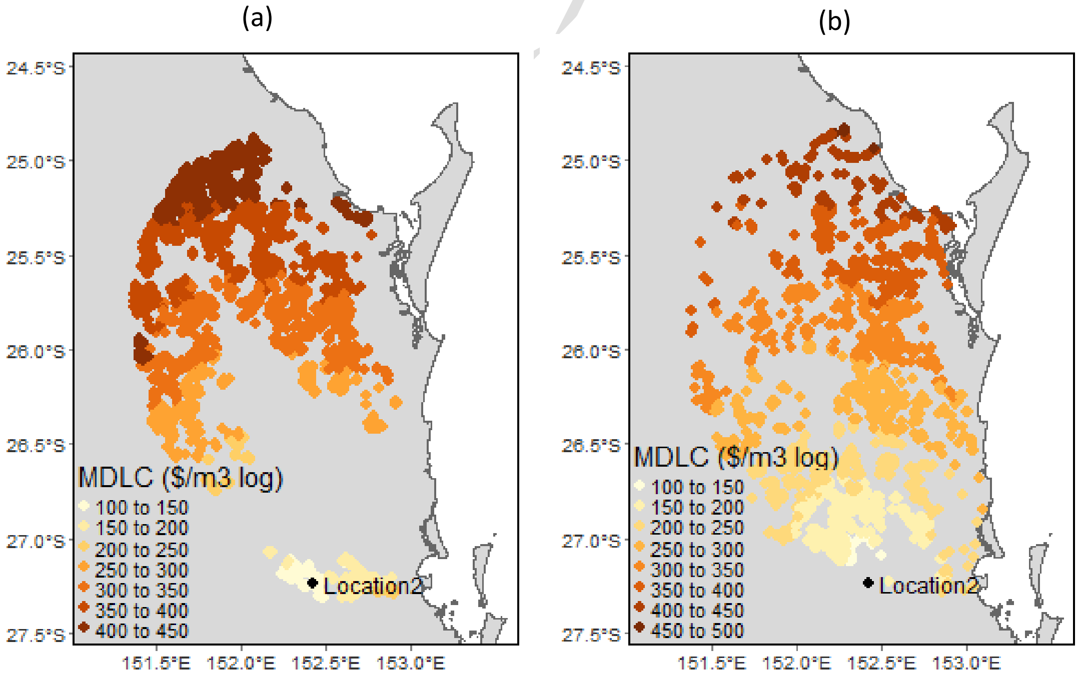


Figure 5. Harvested polygons by forest type for log procurement scenario 4 over the 30-year simulation period for mill locations 1 (a) and 2 (b)

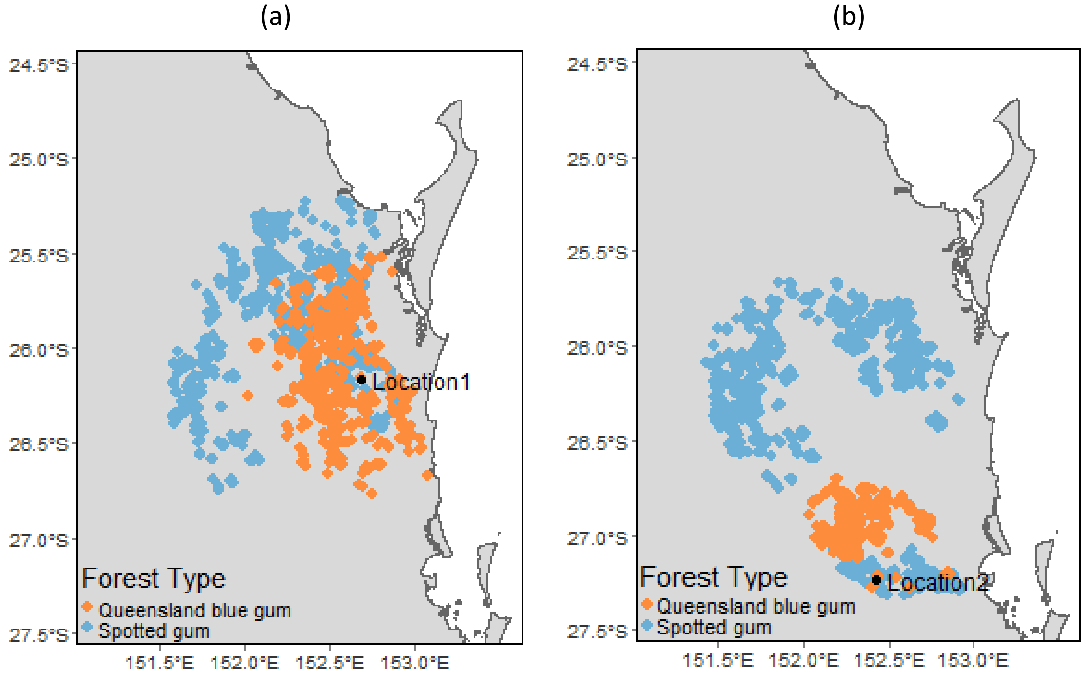


Table 8. Area of forest harvested by mill-delivered log cost category for log procurement scenario 4

MDLC ($\$m^{-3}$ of log)	Mill location 1						Mill location 2					
	Spotted gum forest area (ha)			Queensland blue gum forest area (ha)			Spotted gum forest area (100s ha)			Queensland blue gum forest area (100s ha)		
	TA	HA	%	TA	HA	%	TA	HA	%	TA	HA	%
100 to 149	2973	2973	100	1421	1421	100	1838	1838	100	496	496	100
150 to 199	10,998	10,998	100	7820	7425	95	3206	3206	100	11,404	7955	70
200 to 249	17,294	16,245	94	15,025	816	5	1411	1411	100	7101	0	0
250 to 299	38,145	6632	17	17,847	0	0	10,095	10,095	100	7252	0	0
300 to 349	32,591	0	0	935	0	0	24,204	17,517	0	7776	0	0
350 to 399	2.83	0	0	0	0	0	28,537	0	0	4925	0	0
400 to 449	0	0	0	0	0	0	21,888	0	0	1717	0	0
450 to 499	0	0	0	0	0	0	0	0	0	62	0	0
Total	102,284	36,848	36	43,048	9662	22	91,179	34,067	37	40,733	8451	21

3.4 Estimated gross margins by log procurement scenario

Figures 6 and 7 report the average costs per cubic metre of final product for EWP manufacturing at mill locations 1 and 2, respectively. The average gross margins reported assume the spotted gum final product value. All log processing costs, freight to market costs and the final product market price were assumed to be identical at the two mill locations, so the differences in GM between locations for the same forest type is entirely due to the distribution of forest resources (spotted gum and Queensland blue gum) around each mill. Mill location 2 had higher mill-delivered log costs, which resulted in GM at mill location 2 being considerably lower than mill location 1.

At mill location 1, GM was maximised with log procurement scenarios 3 and 4. At mill location 2, log procurement scenario 4 was optimal. Interestingly, Venn and McGavin (2021) found scenario 4 – utilise all harvestable logs per hectare – never maximised GM, which was consistent with Dobner et al. (2013) for veneer production from *Pinus taeda* L. logs in Brazil. When low volumes are being processed relative to the available resource, Venn and McGavin (2021) found scenario 5 generated the greatest returns. This is because of the processing efficiencies with larger logs and relatively short haul distances when forest resources are abundant. The abundance of forest resources in the simulation reported in this milestone report is low relative to some of the scenarios reported in Venn and McGavin (2021). In Venn and McGavin (2021), when processing scale increased or harvestable forest area proximate to the facility decreased, log procurement scenario 3 tended to maximised GM. This is because considerably more volume can be procured per hectare under this scenario than scenario 5, which reduced the harvest area and haul distances (and costs). When scenario 3 maximised GM, the haul cost saving outweighed the log processing efficiency gains from utilising A-grade sawlogs in scenario 5.

4. Conclusions

The forest to mill module is appropriately accommodating spatially-explicit resource and cost variables. The network analysis performed within the module is correctly estimating road distances. These distances are being reflected in mill-delivered log cost estimates. Hypothetical differences in the market value of final products where it was assumed Queensland blue gum forests produced products of lower value than products made from logs harvested from spotted gum forests, resulted in less Queensland blue gum forest being harvested than would be expected if final product values were identical and the only difference was MDLC.

The last necessary work on the forest to mill module is to develop the optimal log procurement scenario, which will optimise the harvest of alternative log types from different parts of the landscape. This work is being completed in early 2022.

Figure 6. Gross margins from processing spotted gum by log procurement scenario at mill location 1

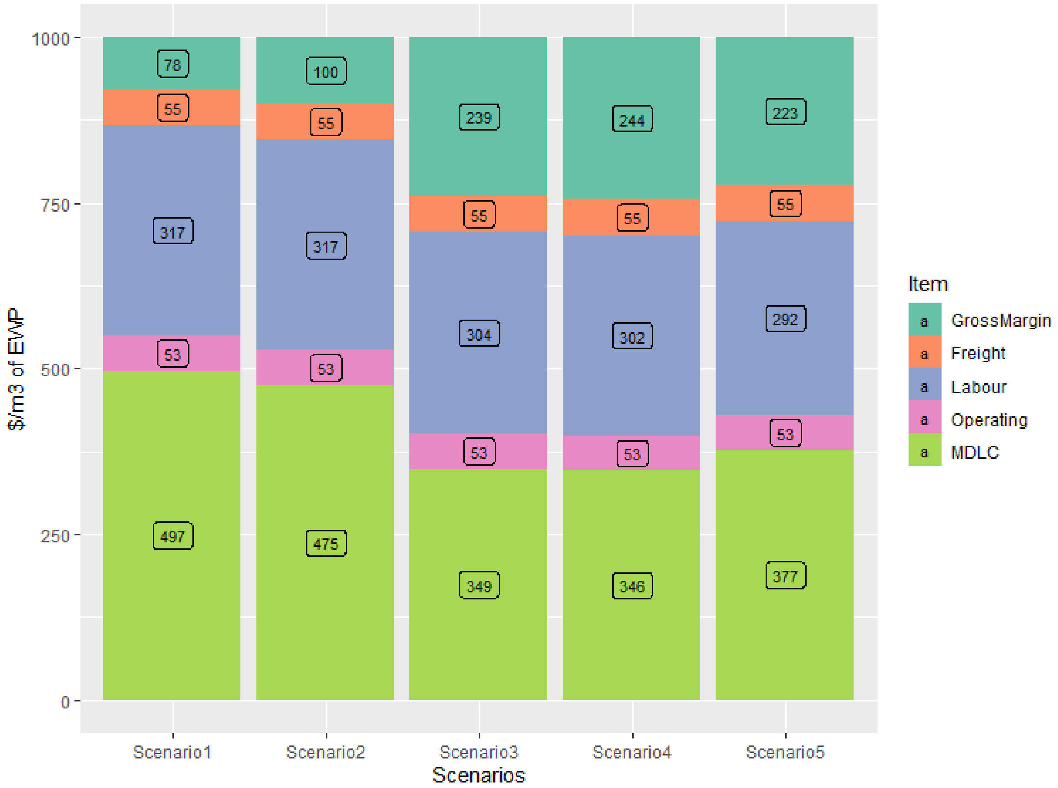
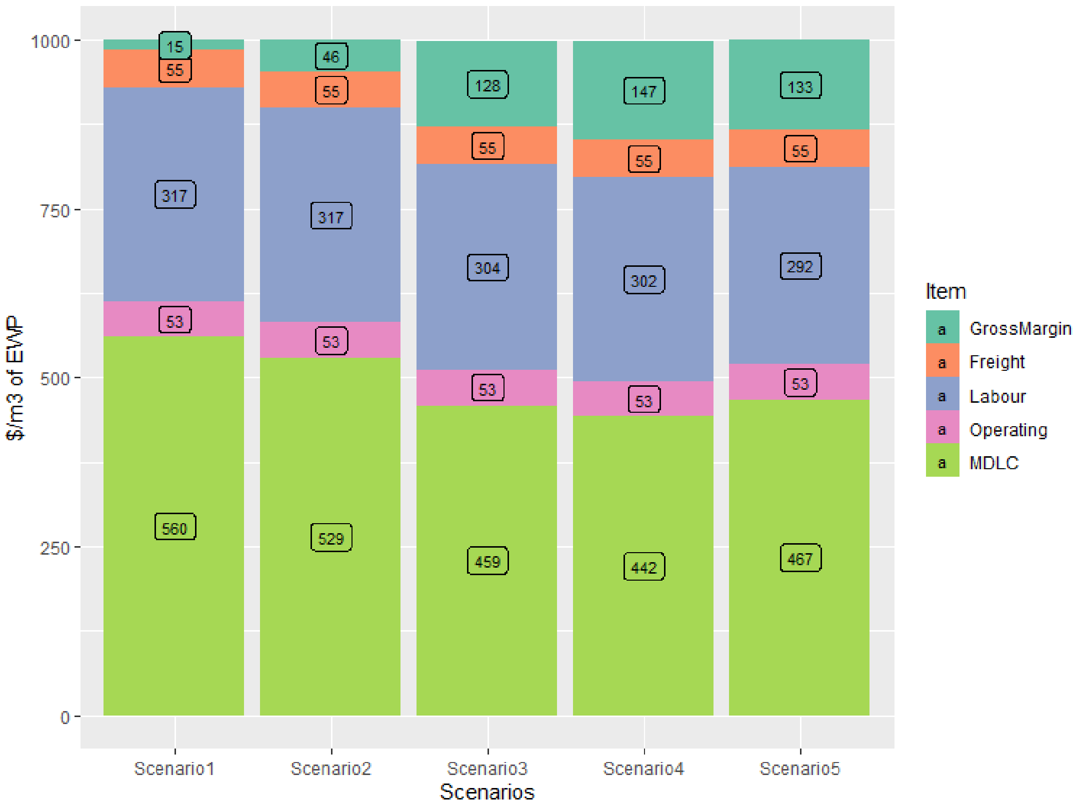


Figure 7. Gross margins from processing spotted gum by log procurement scenario at mill location 2



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