A DECISION SUPPORT SYSTEM FOR HARVEST SCHEDULING AND LOG PROCESSING AT THE MALCOLM KNAPP RESEARCH FOREST IN MAPLE RIDGE, BRITISH COLUMBIA

by

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Abstract

This essay develops prototypes of linear programming-based models to project the harvesting level, lumber production, and net revenue of a harvesting plan in order to support forest operation decision-making in the Malcolm Knapp Research Forest (MFRF) in Maple Ridge, British Columbia. Field data were collected from 3 different biogeoclimatic zones within the research forest. Growth and yield of the forest was modeled by Table Interpolation Program for Stand Yields (TIPSY) which is a stand- and forest-level model developed by the British Columbia Ministry of Forest and Range. Then, the growth and yield data were imported into a forest estate linear programming model to forecast the volume of logs harvested from the forest. A sawing pattern model was used to design the sawing pattern and generate Lumber Recovery Factors by log diameter. Subsequently, a log-to-product linear programming model was used to estimate the final lumber production, mill working hours and the net profit for the forest. The results predict that the mill can earn $3,110,141 by producing 141,229 MBF of lumber and 298,818 m^3 of chips over a 60-year planning horizon. Sensitivity analysis included different sawing patterns, price fluctuations and limited mill operating hours. Some potential improvements in model structure, efficiency, availability for big diameter log, and carbon credits are also discussed. Although the forest data and the sawmill configuration used in the models are different from reality, it will not be difficult to modify the model for MKRF.

Key words: linear programming model, forest operations, Malcolm Knapp Research Forest

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List of Acronyms and Abbreviations

BEC: Biogeoclimatic Ecosystem Classification

Cw: Coastal Western redcedar

CWH: Coastal Western Hemlock

CWHdm: Coastal Western Hemlock, Dry Maritime

CWHvm1: Coastal Western Hemlock, Submontane Very Wet maritime

CWHvm2: Coastal Western Hemlock, Montane Very Wet maritime

CRF: Chips Recovery Factor

DBH: Diameter at Breast Height

DWB: Decay, Waste and Breakage

Fd: Coastal Douglas-fir

Hw: Western hemlock

LB: Lower Bound

LP: Linear Program

LRF: Lumber Recovery Factor

MBF: Thousand Board Feet

MKRF: Malcolm Knapp Research Forest

Ha: Hectare

Hr: Hour

OAF: Operational Adjustment Factor

Regen: regenerated

RHS: Right Hand Side

TIPSY: Table Interpolation Program for Stand Yields

UBC: University of British Columbia

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1. Introduction

1.1 Foreword

Forest models are a tool for foresters and ecologists to predict and analyze the state, dynamics and productivity of forests (Clark & Clark, 1999). Models can be applied in forest management, climate change, forest dynamics and the entire biogeochemical cycle (Lischke, 2001). Moreover, forest models can be applied to different aspects of forestry on local, sub-regional, regional and global levels. For instance, forest dynamics models can be utilized in prediction of single trees and forest stands (local level), changes in tree species and age distributions of forests (sub-regional level), stages in biomass redistribution in the regional ecosystem (regional level) and the importance of forests within the global energy cycle (global level) (Vladimirov & Chudnenko, 2009). Therefore, models, which can provide better understanding of forests in the future, can support the decision-making process in long-term forest management and operations (Clark & Clark, 1999).

1.2 Introduction of Malcolm Knapp Research Forest

The 5,157 hectare Malcolm Knapp Research Forest (MKRF), is located in Maple Ridge, British Columbia, approximately 60 km east of Vancouver. Figure 1-1 shows the location of the MKRF. It was established in 1949 as an affiliated facility of the University of British Columbia (UBC) for academic research in forestry and related sciences. Besides its research function, MKRF also provides services in recreation, education and timber production (UBC Malcolm Knapp Research Forest, 2011b). MKRF holds a 250 hectare woodlot license (Woodlot W0037). It also owns a small sawmill, located in the MKRF, so that the MKRF is able to produce wood products within the forest to obtain revenues for the regular operation of the research forest (UBC Malcolm Knapp Research Forest, 2011c). Due to the economic downturn, in 2010 the harvested volume was reduced by 60% compared to 2009 and Woodlot W0037 was not harvested (UBC Malcolm Knapp Research Forest, 2011d). This essay is aimed at developing a decision supports system to predict the harvesting and log processing practices in the MKRF.

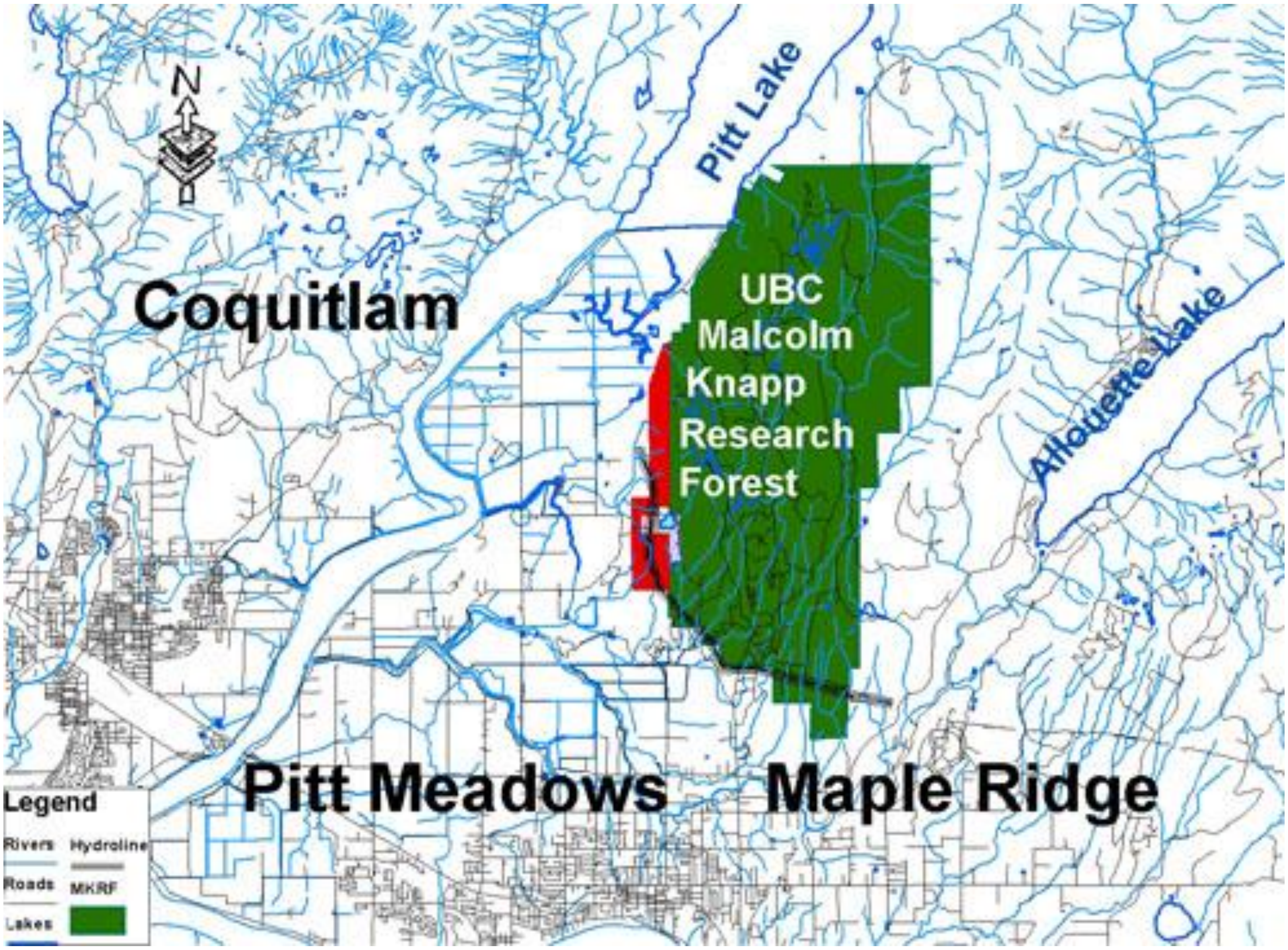

Figure 1-1. Location of UBC Malcolm Knapp Research Forest

(Source: UBC Malcolm Knapp Research Forest, 2011a)

1.3 Goals and Objectives

This essay will use a forest estate linear programming (LP) model, a sawing pattern model, and a log-to-product LP model to project and analyze the forest products production chain for the MKRF and to examine the feasibility of using an LP model in providing optimized solutions for timber harvesting and lumber production. The models will also be used to predict net revenue for the forest operations. The ecological conditions of experiment plots will be introduced and the structure of the model will be described. The optimum result that is obtained through the model will be presented and discussed in terms of the type and volume of harvested tree and lumber to obtain maximum revenue. Then, different scenarios, including sawing pattern, lumber price and limited mill working time, will be discussed. Finally, recommendations will be made for assisting forest management and log processing in MKRF.

2. Method

2.1 Study Site

In this study, three sites were established in the MKRF and the ecological conditions and stand data were collected for the modeling growth and yield with the Table Interpolation Program for Stand Yields program (TIPSY). Table 2-1 summarizes ecological conditions for three study sites.

Table 2-1. Site conditions for three study sites

Sites	Species	Composition	Site Index (m)	Stock Height (cm)
Site One	Fd, Cw, Hm	40% Fd, 30% Cw, 30%Hm	18 for Fd, 18 for Cw, 15.75 for Hw	30 for Fd, 27 for Cw, 22 for Hw
Site Two	Fd, Cw, Hm	30% Fd, 40% Cw, 30%Hm	18 for Fd, 18 for Cw, 15.75 for Hw	30 for Fd, 27 for Cw, 22 for Hw
Site Three	Fd, Cw, Hm	20% Fd, 50% Cw, 30%Hm	18 for Fd, 18 for Cw, 15.75 for Hw	30 for Fd, 27 for Cw, 22 for Hw

There are some general ecological conditions that are common among all three sites:

- Geography: the forest region for all three sites is “coast” and the forest district is

"Chilliwack"; the biogeoclimatic zone (BEC zone) is "Coastal Western Hemlock (CWH)"; and the average slope is 10%;

- Stand establishment: the type of stand regeneration is planted; the density is 1600 stems/ha and there is no delay for regeneration; and
- Coastal Douglas-fir (Fd), Coastal Western Redcedar (Cw) and Coastal Western Hemlock (Hw) are the leading species in the three sites. Site Index for Douglas-fir and Western Redcedar is 18m; Site Index for Western Hemlock is 15.75m

Site One is within the Coastal Western Hemlock, Dry Maritime (CWHdm) zone. The CWHdm is characterized by warm-to-dry summers and mild-to-moist winters with little snow (Pojar& Stewart, 2007a). The site consists of 40% Coastal Douglas-fir, 30% Coastal Western Redcedar and 30% Coastal Western Hemlock.

Site Two is within the Coastal Western Hemlock, Submontane Very Wet Maritime (CWHvm1) zone. This BEC zone has cool summers and mild winters with very little snow (Pojar& Stewart, 2007b). The site is composed of 30% Coastal Douglas-fir, 40% Coastal Western Redcedar and 30% Coastal Western Hemlock.

Site Three is within the Coastal Western Hemlock, Montane Very Wet Maritime (CWHvm2) zone. Different from site 2 (CWHvm1), it has short, cool summers and cool winters with a large amount of snow (Pojar& Stewart, 2007c). Site 3 is 20% Coastal Douglas-fir, 50% Coastal Western Redcedar and 30% Coastal Western Hemlock.

2.2 TIPSY Modeling

The collected data were processed by TIPSY version 4.2. Growth and yield data that are related to volume and wood products were generated by TIPSY.

Since TIPSY does not model multiple species, for each site three TIPSY runs were conducted for three different species, and the volumes of each species were summed up and multiplied by their corresponding composition in order to make adjustments for the correct volume for each site.

In the data entry process, two TIPSY parameters were applied to the ecological data:

- Operational Yield Adjustments: two default TIPSY medium examples of Operational Adjustment Factors (OAF), which are parameters to reflect the yield loss with regards to insects and disease, non-merchantable wood, stocking gaps and other factors, were applied in order to mimic real growth and yield (British Columbia Ministry of Forest and Range, 2005). In example 1, the total age was 0-300, and the factors were 0.85-0.85; in example 2, the total age was 0-300, and the factors were 1-0.95-0.85.
- Decay, Waste and Breakage losses (DWB) factors were applied as the default value in TIPSY.

After data entry and TIPSY analysis, growth and yield curves were created. There are two assumptions that were made in growth and yield tables:

- Only "merchantable volume", which refers to the volume of trees that are greater than 12.5 cm in DBH excluding non-merchantable trees, was considered as available volume.
- Based on the sawmill capacity, logs that are less than 15cm or greater 55 cm in diameter would not be shipped to the sawmill.

Based on the TIPSY projections, Western Redcedar in all three sites would have logs that are greater than 55 cm in diameter after 120 years of age, which exceeded the maximum capacity of the sawmill, so only data from 0 to 120 years old were used. The merchantable volume and composition of different log diameter classes of each age class for the three sites are listed in Table 2-2, Table 2-3 and Table 2-4. The growth and yield curves for the three sites are shown in Figure 2-1.

Table 2-2. Volume and log DBH class by age for site one

Age / yrs	Merchantable volume / m^3	Proportion of Merchantable Volume								
		15	20	25	30	35	40	45	50	55
0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
30	11	0.95	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	52	0.53	0.40	0.07	0.00	0.00	0.00	0.00	0.00	0.00
50	101	0.28	0.47	0.20	0.04	0.01	0.00	0.00	0.00	0.00
60	144	0.16	0.40	0.30	0.10	0.03	0.01	0.00	0.00	0.00
70	181	0.10	0.31	0.34	0.17	0.06	0.02	0.00	0.00	0.00
80	210	0.08	0.24	0.31	0.22	0.09	0.04	0.01	0.00	0.00
90	237	0.06	0.19	0.28	0.25	0.12	0.06	0.03	0.01	0.00
100	264	0.05	0.15	0.25	0.24	0.16	0.08	0.05	0.01	0.00
110	286	0.05	0.13	0.22	0.23	0.18	0.10	0.06	0.03	0.01
120	304	0.04	0.11	0.19	0.22	0.19	0.12	0.07	0.05	0.01

Table 2-3. Volume and log DBH class by age for site two

Age / yrs	Merchantable volume /m^3	Proportion of Merchantable Volume								
		15	20	25	30	35	40	45	50	55
0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
30	11	0.95	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	53	0.51	0.41	0.08	0.00	0.00	0.00	0.00	0.00	0.00
50	104	0.27	0.47	0.21	0.05	0.01	0.00	0.00	0.00	0.00
60	148	0.15	0.38	0.31	0.11	0.04	0.01	0.00	0.00	0.00
70	187	0.09	0.29	0.34	0.18	0.07	0.02	0.00	0.00	0.00
80	217	0.07	0.23	0.30	0.23	0.10	0.05	0.01	0.00	0.00
90	246	0.06	0.18	0.27	0.24	0.13	0.07	0.03	0.01	0.00
100	274	0.05	0.15	0.24	0.23	0.16	0.09	0.06	0.02	0.01
110	296	0.04	0.12	0.21	0.22	0.18	0.11	0.07	0.04	0.01

120	315	0.04	0.11	0.18	0.21	0.19	0.13	0.08	0.06	0.01

Table 2-4. Volume and log DBH class by age for site three

Age / yrs	Merchantable volume /m^3	Proportion of Merchantable Volume								
		15	20	25	30	35	40	45	50	55
0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
30	11	0.95	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	55	0.49	0.41	0.09	0.00	0.00	0.00	0.00	0.00	0.00
50	107	0.25	0.46	0.22	0.06	0.01	0.00	0.00	0.00	0.00
60	153	0.14	0.37	0.31	0.12	0.05	0.01	0.00	0.00	0.00
70	194	0.09	0.28	0.34	0.19	0.08	0.03	0.00	0.00	0.00
80	225	0.07	0.22	0.29	0.23	0.11	0.06	0.01	0.00	0.00
90	254	0.05	0.17	0.26	0.24	0.14	0.08	0.04	0.01	0.00
100	284	0.05	0.14	0.22	0.23	0.17	0.10	0.07	0.02	0.01
110	307	0.04	0.12	0.20	0.21	0.18	0.12	0.08	0.04	0.01
120	326	0.04	0.10	0.17	0.20	0.18	0.14	0.09	0.07	0.02

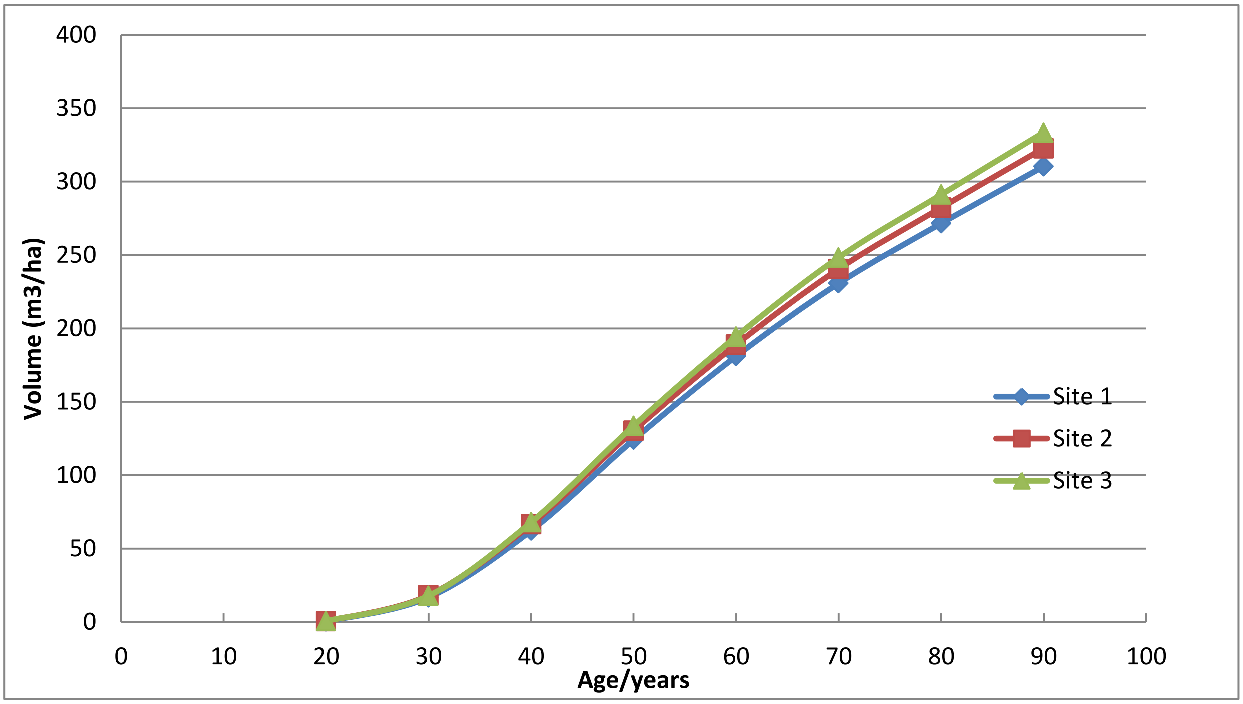

Figure 2-1. Growth and yield curve for three sites

2.3 Linear Programming Models

Linear programming models were built with Microsoft Excel for determining the optimal harvest schedule and the optimal sawmill production. The Solver analysis tool embedded in Excel was used to calculate the optimum solution. A sawing pattern model was used to determine Lumber Recovery Factors for various dimensions of lumber. Figure 2-2 shows the flow of the analysis process.

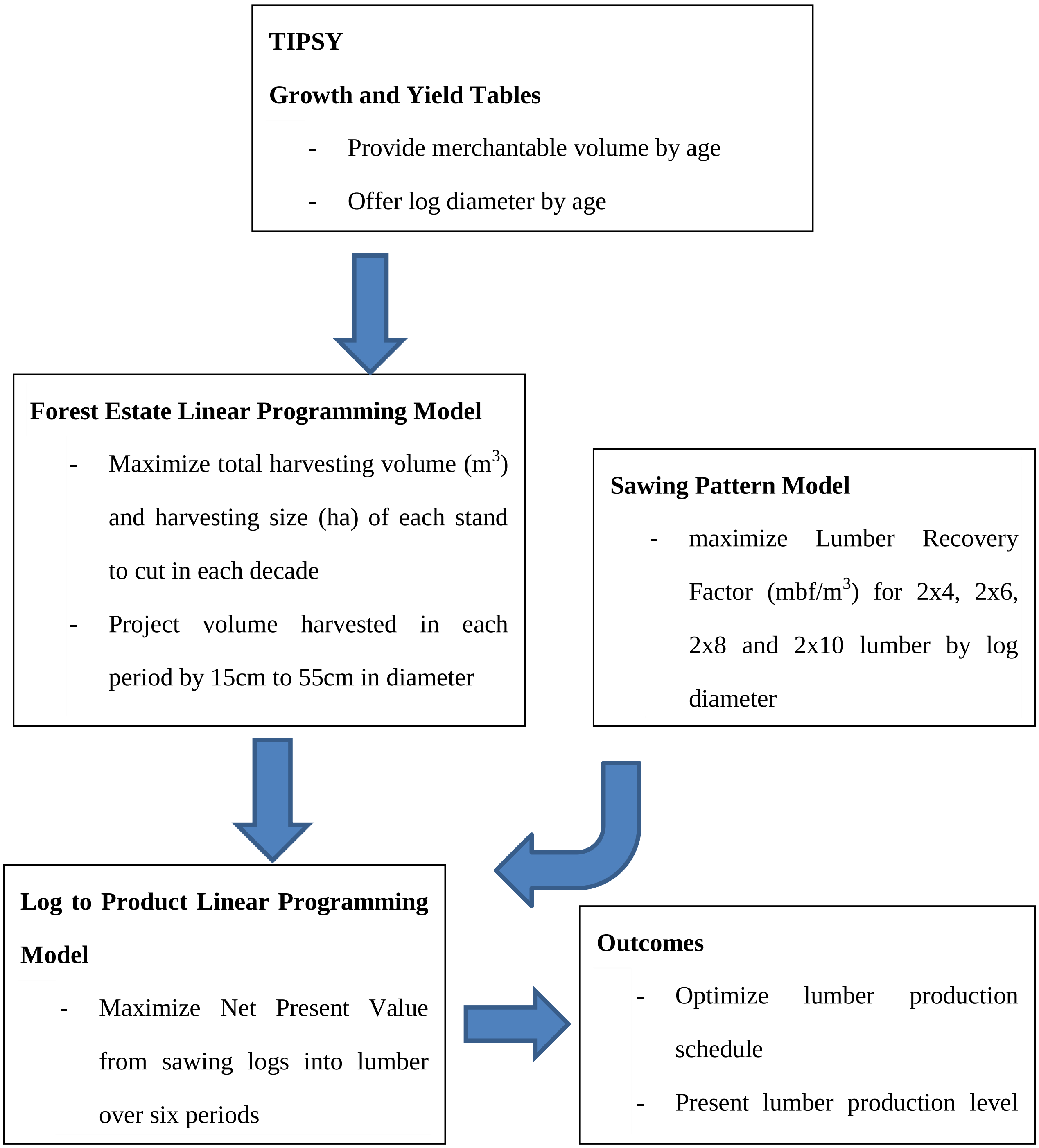

Figure 2-2. Flow of model analysis

2.3.1 Forest Estate Model

The Forest Estate model was used to optimize the harvesting schedule. The model is shown in Appendix A.

2.3.1.1 Model assumptions and data input

Some assumptions and constraints for harvesting were set up for this model:

- Area of site: because the original areas of the study sites were too small to conduct harvesting economically, the size of each site is assumed to be 1000 hectares.
- Period: each period is 10 years; the total planning horizon is 6 periods.
- Period of harvesting: due to the limited merchantable volume of wood and limited capacity of the sawmill, this model only assumes 60 years of stand growth (age 60 to age 110).
- Time of harvesting: trees at age 60 would be harvested in period 1; trees at age 70 would be harvested in period 2 etc.
- Minimum ending inventory: in order to have enough trees left to provide other services, the minimum harvesting inventory is 10,000 m^3.
- Minimum ratio of ending inventory: the ending inventory must be at least equal to one-fourth of the beginning inventory.
- Minimum harvesting per period: in order to ensure harvesting occurs in every period, the minimum harvesting per period is 110,000 m^3.
- Maximum changes of harvesting flow: the maximum change of harvesting level for each period is 20%, which means that the harvesting level for period 2 is between 80% and 120% of the harvesting level for period 1.
- The objective function maximizes to total harvest over the planning horizon.

- Decision variables are the size (ha) of stand $_i$ cut in period $_j$.

Derived from the volume tables (Table 2-2 to Table 2-2) and the growth and yield curve (Figure 2-1), the volume and age classes data for existing stands and future stands were entered, and are shown in Table 2-5 and Table 2-6. Harvested volume of existing and future stands in different periods is shown in Table 2-7. The ending inventory of different periods is shown in Table 2-8.

Table 2-5. Volume and age classes for existing stands

Existing Stands			
	Stand 1	**Stand 2**	**Stand 3**
Age	**Volume**	**Volume**	**Volume**
60	144	148	153
70	181	187	194
80	210	217	225
90	237	246	254
100	264	274	284
110	286	296	307

Table 2-6. Volume and age classes for future stands

Future (Regenerated) Stands							
		Stand 1		**Stand 2**		**Stand 3**	
Periods	Stand Age	volume before harvest	volume cut	volume before harvest	volume cut	volume before harvest	volume cut
0	0	0	0	0	0	0	0
1	10	0	0	0	0	0	0
2	20	0.4	0	0.5	0	0.6	0
3	30	17	0	18	0	18	0
4	40	62	0	67	0	68	0
5	50	124	124	130	130	134	134

Table 2-7. Harvest yield (m^3/ha) at harvesting for different stands

	STAND 1							STAND 2							STAND 3					
PERIOD	1	2	3	4	5	6	Uncut	1	2	3	4	5	6	Uncut	1	2	3	4	5	6
Harvest 1	52							53							55					
Harvest 2		101							104							107				
Harvest 3			144							148							153			
Harvest 4				181							187							194		
Harvest 5					210							217							225	
Harvest 6	124					237		130					246		134					254
SUM	176	101	144	181	210	237	0	183	104	148	187	217	246	0	189	107	153	194	225	254

Note: X_{ij} refers to number of hectares of stand I first cut in period j

Table 2-8. Ending inventory (m^3/ha) of different stands

Period	1	2	3	4	5	6	Uncut	1	2	3	4	5	6	Uncut	1	2	3	4	5	6	Uncut
End-Inven1	0	52	52	52	52	52	52	0	53	53	53	53	53	53	0	55	55	55	55	55	55
End-Inven2	0	0	101	101	101	101	101	0	0	104	104	104	104	104	0	0	107	107	107	107	107
End-Inven3	0.4	0	0	144	144	144	144	0.5	0	0	148	148	148	148	0.6	0	0	153	153	153	153
End-Inven4	17	0.4	0	0	181	181	181	18	0.5	0	0	187	187	187	18	0.6	0	0	194	194	194
End-Inven5	62	17	0.4	0	0	210	210	67	18	0.5	0	0	217	217	68	18	0.6	0	0	225	225
End-Inven6	0	62	17	0.4	0	0	237	0	67	18	0.5	0	0	246	0	68	18	0.6	0	0	254

2.3.1.2 Model Structure

The forest estate model follows the typical structure of an LP model. There are five series of columns (decision variables) and seven series of rows (constraints) in the model. As for columns, the model has six periods for each of the three stands, harvest of each period and beginning and ending inventory. In terms of rows, the model has yields at harvesting, ending inventory, existing volume, regenerated volume, minimum harvesting level, harvesting flow and size of each stand. The names of each variable are shown in the "Variable name" row; total harvested volume per ha for each period of each stand is shown in the "Objective" row; the areas that would be harvested are calculated by Solver and put into the "Answer" row; "Sign" and "Right Hand Side (RHS)" columns are designated for constraints; the final result, total volume of harvesting, is shown at top of the "Result" column. Other rows of the "Result" column are used to check if the answer that was obtained fits with constraints (“Sign” and “RHS” columns) by the “sumproduct” function and the Solver.

Yields (m3/ha) at harvesting for different stands (Table 2-7) are shown in the “harvest 1” to “harvest 6” rows. Harvested volumes in each period are summed into a total volume variable. Taking period 1 as an example, the total harvested volume of period 1 consists of harvesting in 3 stands. Therefore, the total volume of wood can be calculated by Equation 1:

$$V_{ij}=\sum_{i=1}^{3}(V_{ij} \times A_i) \quad [1]$$

Where i represents the harvesting period; V_{ij} represents the available volume stand I in period j (m^3/ha), and A_i represents the area of the stand i.

Subsequently, Solver automatically fills the harvest volume into the “harv 1” column of the “Answer” row. This method is applied to the entire LP model.

The inventory section of the model shows the beginning inventory and ending inventory for each period of each stand and the minimum ratio of ending inventory. Beginning inventory was calculated by the sum of the products of the initial volume (volume at age 60) of each stand and its corresponding harvesting area. Ending inventory of each period is the same as Table 2-8.

The “existing-ha” and “regen-ha” rows are the constraints for Solver which state that all values in the harvesting area are positive. The “Absolute-LB-Harvest” rows are used to set constraints for the minimum harvesting level per period, which is 110,000 m^3 in the model. The “LB Harvest flow” rows are used to constrain the change of harvesting level for each period. The mechanism of limiting changes is also linked to Solver by applying a limit factor. Specifically, it is assumed that the allowable change of harvesting from period 1 to period 2 is ±X%, so the limiting factor in the model is - (1-|X|). Therefore, if the change of harvesting level is within ±10%, the harvesting level for the first period, multiplied by the limiting factor plus harvesting level for the second period, will be equal to or greater than 0. For example, assuming the harvesting level for the first period is 10,000 m^3 and the harvesting level for the second period is 9,500 m^3, the change in harvesting level is $\frac{9{,}500\ m^3 - 10{,}000 m^3}{10{,}000 m^3}$ = - 5%, and the limiting factor is - (1- |-0.05|) = -0.95. The harvesting level for the first period is multiplied by the limiting factor is 10,000× (-0.95) = -9500. Finally, the "ha available stand" rows limit the sum of harvested area and uncut area for each stand to the total area of the stand, which is 1000 hectares.

2.3.2 Sawing Pattern Model

The Sawing Pattern Model is used for computing the Lumber Recovery Factor (LRF), which is an important component of the Log-to-product model. The sawing pattern model used in this essay is a Microsoft Excel-based model provided by Dr. Thomas Maness from Oregon State University at Corvallis, Oregon. This sawing pattern model can calculate the LRF based on diameters of logs and dimensions of lumber produced. For the detailed sawing patterns for each diameter of log, refer to Appendix B.

2.3.2.1 Model assumptions and data input

The strategy of this model is to maximize the usage of the log, producing lumber of as large dimensions as possible. Some assumptions of the input log and the designated products are applied in this study:

- Small end diameter: logs accepted range from 15 cm to 55 cm in the log small end diameter with an interval of 5cm (e.g. 15cm, 20cm, 25cm etc.);
- Length: due to the balance of log diameter and economic value, all the lumber it produces

is 8 feet in length;

- Taper: the value of taper is 1%, which means that for every 100 inches of log length, the large end diameter will be 1 inch more than the small end diameter;
- Large end diameter: it is assumed that for an 8-foot-long log, the larger end is 1 inch greater than the small end;
- Trim Allowance: 0.25 foot is set for trim allowance for the loss from end injuries or uneven cuts in processing;
- Log sweep: there is no log sweep assumed;
- Side shift and horns angle: side shift and horns angle will not be applied in the model
- Saw kerf, wane allowance, infeed mechanism, log class size and other parameters are set at default values;
- Volume of log: the volume of log is calculated by Equation 2:

$$Volume\ (foot^3) = 0.001818 \times log\ length\ (D_s^2 + D_s D_l + D_l^2) \quad [2]$$

where 0.001818 is a constant, D_s is the log small end diameter, D_l is the log large end diameter and log length is in feet (Grosenbaugh, 1963).

- Volume of lumber: The volume of a board can be calculated by Equation 3:

$$Volume\ of\ lumber\ (MBF) = \frac{(\ length \times width \times thickness)}{144000\ inch^3/mbf} \quad [3]$$

where the units for length, width and thickness are inches and the thickness and width of lumber used in the calculation are the finished value. The corresponding finished value of different dimensional lumber is shown in Table 2-9.

Table 2-9. Finished thickness and width value of corresponding nominal lumber

Nominal		Finished	
Thickness	Width	Thickness	Width
2	4	1.5	3.5
2	6	1.5	5.5
2	8	1.5	7.5
2	10	1.5	9.5

- LRF: the LRF can be computed by Equation 4 and the summary of LRF is demonstrated in Table 2-10:

$$LRF\ (MBF/M^3) = \frac{lumber\ volume\ in\ board\ feet}{log\ volume\ in\ m^3} \qquad [4]$$

Table 2-10. Lumber and Chips Recovery Factor

Lumber Recovery (MBF/m3)									
Lumber	**15 cm**	**20 cm**	**25 cm**	**30 cm**	**35 cm**	**40 cm**	**45 cm**	**50 cm**	**55cm**
2x4 - 8'	0.1305	0.1526	0.0500	0.0176	0.0262	NA	NA	NA	NA
2x6 - 8'	NA	NA	0.1570	0.1938	0.1440	0.0476	0.0379	NA	NA
2x8 - 8'	NA	NA	NA	NA	NA	0.1466	NA	NA	NA
2x10 - 8'	NA	NA	NA	NA	0.1153	0.0890	0.3541	0.3782	0.3614
sum LRF	0.1305	0.1526	0.2070	0.2114	0.2855	0.2832	0.3920	0.3782	0.3614
Chips	0.6421	0.5899	0.4615	0.4512	0.2763	0.2817	0.0250	0.0575	0.0972

- Chip Recovery Factor (CRF): chip recovery factors are shown in Table 2-10. An assumption is made that there is 5% sawdust loss in this sawmill, and anything besides lumber and sawdust loss can be converted into wood chips. The CRF can be calculated by Equation 5:

$$Chip\ Recovery\ Factor = 1 - sawdust\ loss - sum\ LRF \times 2.360\ m^3 / MBF \qquad [5]$$

Where the sawdust loss is 5%.

The 2.360 m^3 / MBF is the conversion factor for LRF. 1 board foot has 12 inches in length, 12 inches in width and 1 inch in thickness. To convert cubic meters into MBF, use the formula $\frac{(12\ inches \times 12 inches \times 1\ inch) \times 2.54}{100} \times\ 1000$ = 2.360m^3/MBF. The sum of LRF includes the LRF for 2x4x8, 2x6x8, 2x8x8 and 2x10x8.

2.3.2.2 Model Structure

Figure 2-3 and Figure 2-4 show the structure of the sawing pattern model. Figure 2-3 shows the display portion of the model, including log parameters mentioned above, log volume and LRF for different dimensions of lumber. Figure 2-4 shows the summary portion of the model, including the number of different dimensions of lumber produced from this log and the corresponding volume of each product.

The volumes of different dimensional lumber are already built into the model. When the log small end diameter is entered, a graph showing the cross-sectional area of the log will be generated, as can be seen in the Figure 2-3. The blue line represents the small end of the log, the red line represents the large end of the log. The dotted line is the average of the small end and the large end. Lumber of various dimensions are arranged in the circle by manually entering the type of products (e.g. 2x4, 2x6) and the length, which is all 8 feet in this case. In order to have a sufficient amount of wood to produce lumber, the dimensions of the lumber must fit the small end of the log (the blue circle). When the number of lumber boards that can be produced is maximized, the volume of lumber (board foot) will be computed by summing up all the volumes of lumber in different dimensions.

In this study, the strategy for lumber production optimization is to produce as much larger dimension lumber as possible in order to get higher profits.

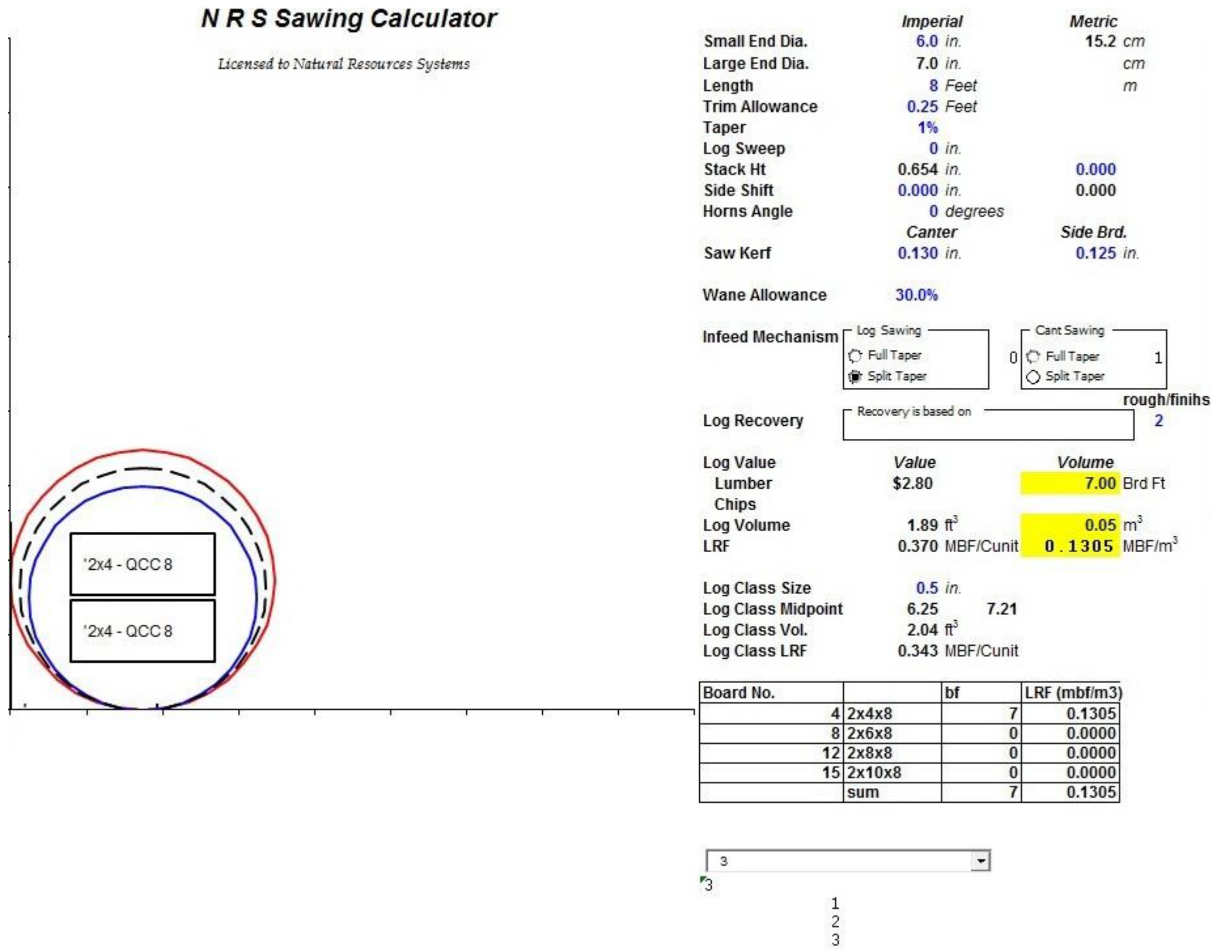

Figure 2-3. Display portion of sawing calculator

Sawing Calculator Pattern

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB													
Outside Right SB													
Inside Left SB													
Outside Left SB													
Bottom Board	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Centre Cant 1	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Centre Cant 2													
Centre Cant 3													
Centre Cant 4													
Centre Cant 5													
Centre Cant 6													
Centre Cant 7													
Centre Cant 8													
Centre Cant 9													
Centre Cant 10													
Centre Cant 11													
Centre Cant 12													
Centre Cant 13													
Centre Cant 14													
Centre Cant 15													
	2		2						3.765			7.00	2.80

	Height	
Outside Left SB	5.000	FALSE
Inside Left SB	5.000	FALSE
Bottom Board	1.300	FALSE
Inside Right SB	5.000	FALSE
Outside Right SB	5.000	FALSE

Move the stack of boards around with these numbers

Figure 2-4. Summary portion of sawing calculator

However, this model is not fully capable of handling larger logs, such as 50cm and 55cm logs, because the graph representing the cross-sectional area of the log cannot be shown appropriately. In order to adjust this situation, the half of the log that can be seen in the graph is filled in by cant lumber, and then the volume of cant lumber is doubled to calculate the total volume of lumber.

2.3.3 Log-to-product model

The log-to-product model optimizes the sawing of logs (by small end diameter) into various dimensions of lumber products. Chips are a by-product of the sawing process. The model has six time periods and the log distributions for each period were provided by the forest estate model. The model is shown in the Appendix C.

2.3.2.1 Model assumptions and data input

Assumptions that were applied to this model are:

- Cost: the stumpage cost for MKRF is $50/ m^3; haul cost is $10 / m^3. Therefore, the total cost is $60/ m^3 (data provided by Dr. John Nelson, UBC Faculty of Forestry).
- Headsaw productivity: a headsaw is a machine used to cut the log into a narrower canted log to adjust for other sawing equipment. (Jadeja, 2007). The headsaw productivity for this mill is shown in Table 2-11. Based on the capacity, the headsaw can process 1125 8-foot logs in 1 hour. The volume of log can be calculated by the Average End Method. Therefore, the productivity of headsaw (hours/m^3) can be calculated by Equation 6:

$$\textit{Productivity of headsaw } (hour/m^3) = \frac{1\ hour}{logs\ processed\ in\ 1\ hour \times volume\ per\ log} \qquad [6]$$

Table 2-11. Headsaw productivity

Headsaw Productivity Table				
Log dia (cm)	**Logs/hr**	**Volume /log**	**Volume /hr**	**hrs/m^3**
15	1125	0.0525	59.08	0.0169
20	1125	0.0896	100.79	0.0099
25	1125	0.1365	153.61	0.0065
30	1125	0.1934	217.55	0.0046
35	1125	0.2601	292.61	0.0034
40	1125	0.3367	378.80	0.0026
45	1125	0.4232	476.11	0.0021
50	1125	0.5196	584.53	0.0017
55	1125	0.6259	704.08	0.0014

- Trimmer productivity: A trimmer is the machine that cuts the lumber to form square ends (Mardikar, 2007). The trimmer productivity can be seen in Table 2-12. The trimmer can process 4617 boards per hour. Therefore, the productivity of the trimmer (hour/MBF) can be calculated by Equation 7:

$$Productivity\ of\ trimmer\ (hour/MBF) = \frac{1\ hour}{boards\ processed\ in\ 1\ hour \times volume\ per\ board} \quad [7]$$

However, the ratio of headsaw productivity to trimmer productivity is 1.69. In order to balance the productivity of both machines, adjustments are made such that all the trimmer productivities are divided by 1.32. The trimmer productivities after adjustment are used in the model.

Table 2-12. Trimmer productivity

Trimmer Productivity					
Size	**Boards / Hr**	**MBF/Board**	**MBF / Hr**	**Hr / MBF(before adjustments)**	**Hr / MBF(after adjustments)**
2x4-8'	4617	0.0035	16.1595	0.06190	0.0469
2x6-8'	4617	0.0055	25.3935	0.0394	0.0298
2x8-8'	4617	0.0075	34.6275	0.0289	0.0219
2x10-8'	4617	0.0154	71.1788	0.0140	0.0106

- Cost and Revenue: The price of lumber in different dimensions, the cost of shipping, finishing, hourly headsaw and trimmer operations, and maximum hours for the headsaw and the trimmer are shown in Table 2-13. The 8-foot lumber price is based on the 2001-2011 average lumber prices for random length (TradingCharts, 2011). This price, which is $273 / MBF, is used for the price of 2x4 lumber. Values for the 10-year averages for 2x6, 2x8 and 2x10 were determined using the current value relative to the price of 2x4 lumber. Based on the patterns of current lumber price (Madison's Canadian Lumber Reporter, 2011), The prices for 2x6, 2x8 and 2x10 are all higher than 2x4, 15%, 14%, and 17% respectively. For instance, the price for 2x6 is 15% higher than the price of 2x4, so the price for 2x6 can be calculated by:

$$Price_{2\times6} = Price_{2\times4} \times 1.15 = \$273 \times 1.15 = \$314/MBF$$

The price of chips is the courtesy of Tony Peiffer, the general manager of fibre supply for Interfor Ltd. Other cost information is assumed based on the previous data provided by Dr. John Nelson. The sawmill is scheduled to run 4600 hours to finish the processing of these logs. When the headsaw is running, $500 per hour will be charged for operation. If the headsaw is in the "down" status, it also incurs costs of $250 per hour. The trimmer costs are $422 and $211 per hour, respectively.

Table 2-13. Price of Lumber and Cost of Sawmill Operation

Revenue			Costs				
Product	**Price**	**Units**	**Shipping**	-$10	**/ MBF Headsaw Run**	$500	**/hr**
2x4 - 8'	$273	**/ MBF**			**/ MBF Headsaw Down**	$250	**/hr**
2x6 - 8'	$314	**/ MBF**					
2x8 - 8'	$311	**/ MBF**	**Finishing**	-$35	**/ MBF Trimmer Run**	$422	**/hr**
2x10 - 8'	$319	**/ MBF**			**Trimmer Down**	$211	**/hr**
CHIPS	$36	**/ m^3**					
					Maximum hours/week for Head saw & Trimmer	4600	

- Minimum production level for each period: in order to have a relatively even production flow, the minimum of production is set at 100,000 m^3 for each diameter of log.

2.3.2.2 Model Structure

Similar to the tree-to-log model, the log-to-product model is an LP model in Microsoft Excel. It has 5 series of columns: stand & period, logs sorted by diameter (m^3), produced lumber (MBF) &

chips (m^3), headsaw hours and trimmer hours, and 5 corresponding rows plus a series of maximum production levels. Specifically, since there are 6 harvesting periods, there are 18 columns and rows for the "stand & period" series (6 harvesting periods for 3 stands), 54 columns and rows for the "log sorted by diameter" series (9 categories of log diameter for 6 periods), 30 columns and rows for the "lumber & chips" series (1 chip and 4 types of lumber for 6 periods), 2 columns and rows for "headsaw" series, 2 columns and rows for "trimmer" series and 6 rows for "maximum production level" series. As in the forest estate model, the "variable name" row contains the name for each variable; the "answer" row shows the value for each variable; the "objective" row shows the cost and revenue for each variable. Constraints are checked by the "sumproduct" function and the Solver in the "result", "sign" and "RHS" columns. The result of each series of variables will be shown in the "answer" row in corresponding columns and the final result (net revenue) will be shown in the "net revenue" cell.

3. Results

3.1 Forest Estate Model

The results of the forest estate model are shown in Table 3-1 and Table 3-2. All hectares in stand 1 and stand 2 are harvested and 206 hectares of stand 3 are not harvested. In terms of harvesting periods, 110,000 m^3 of wood, which is the minimum level of harvesting, are harvested during each period, from period 1 to 5. For the final period, besides the minimum harvesting level, an additional 16,752 m^3 of wood are harvested. In total, 676,752 m^3 of wood are harvested out of the forest. In terms of ending inventory, from period 1 to period 6, the ending inventory decreases, reaching the lowest point in period 6, which is 111,353 m^3. Figure 3-1 graphically shows the harvesting and inventory volumes for each period. The graph shows that as the time goes by, the ending inventory is decreasing. Figure 3-2 shows harvest by existing and regenerated stands. The regenerated stand is only harvested in period 6.

Table 3-1. Harvesting area in each period for each stand

	Harvesting in each period (ha)						
	1	2	3	4	5	6	Uncut
Stand 1	339	0	524	28	0	109	0
Stand 2	412	588	0	0	0	0	0
Stand 3	0	0	0	406	388	0	206

Table 3-2. Harvesting volume in each period

period	Harvesting			Inventory/m^3
	Total (m^3)	Existing (ha)	Regen (ha)	
1	110000	751	0	335410
2	110000	588	0	313051
3	110000	524	0	253529
4	110000	434	0	190251
5	110000	388	0	146396
6	126752	109	751	111353
summary	676752	2794	751	1349990

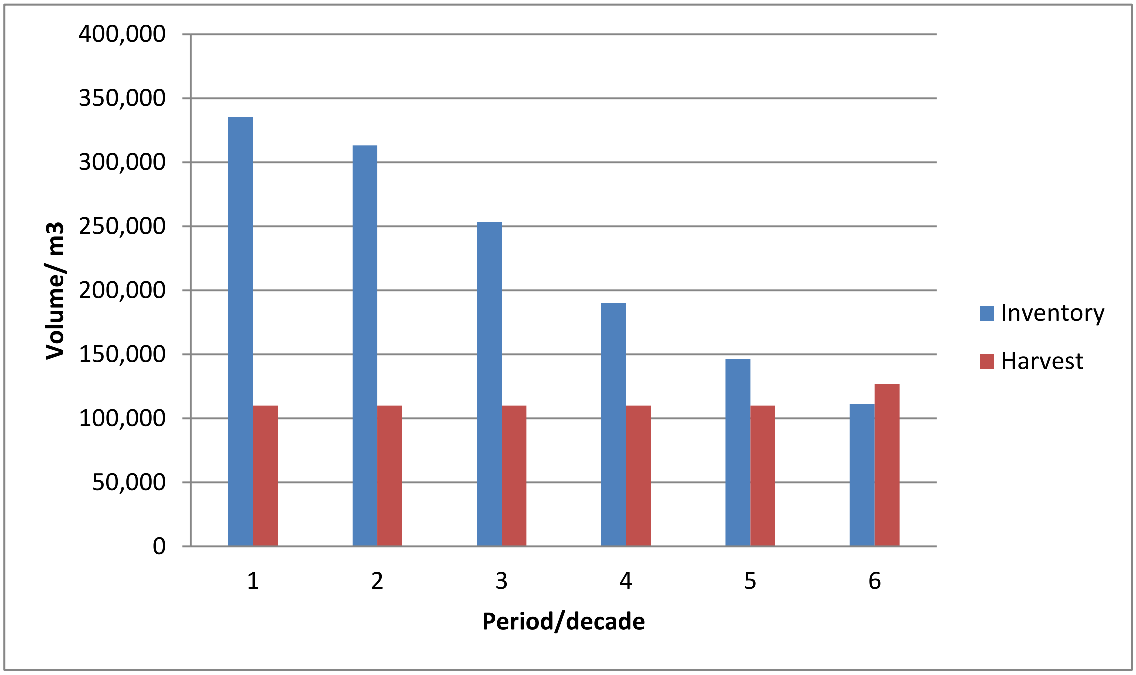

Figure 3-1. Inventory and harvest in each period

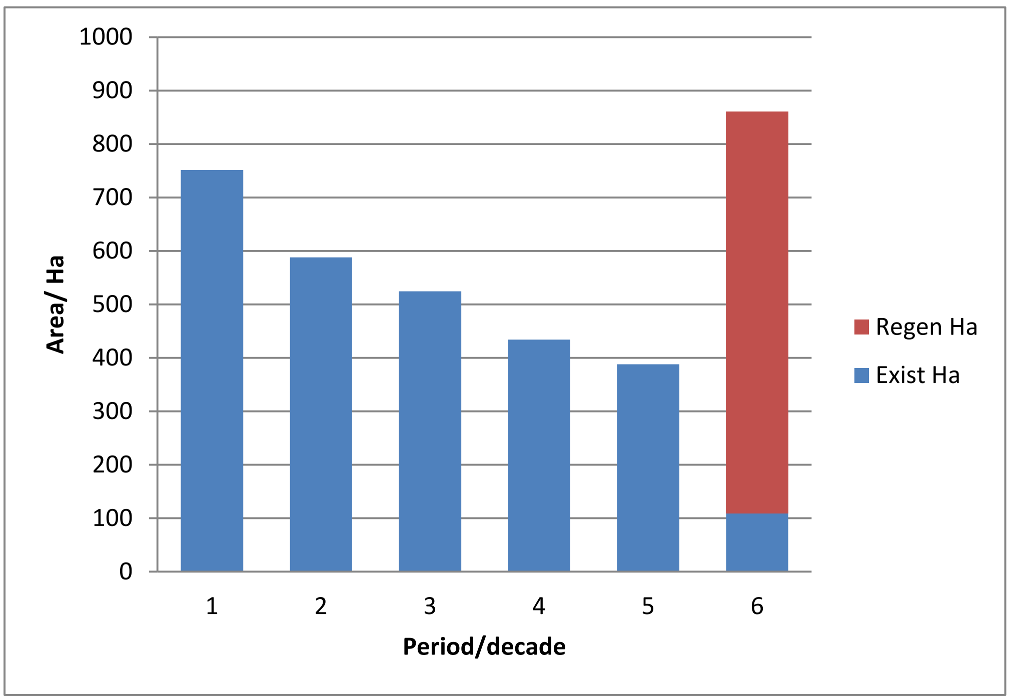

Figure 3-2. Stand composition of harvesting stands

3.2 Log-to-product model

The final result of the tree-to-log model is shown in Table 3-5. The optimal solution is for the sawmill to produce 141,229 MBF of lumber and 298,818 m^3 of chips with a net revenue of $3,110,141. The final result is derived from the data shown in Table 3-3 and Table 3-4. Table 3-3 illustrates the log volume available and used for processing. The upper part is the available log volume in each period for each stand, as derived from the forest estate model; the lower part is the log used for processing, as calculated by MS Excel Solver. Comparing the two parts, it can be seen that all the logs are processed except for 10,000 m^3 of log in stand 1 for period 1. This is due to the optimization process by Solver. The logs that are subject to processing are sorted by diameter, which is shown in Table 3-4. The table indicates that logs ranging from 25cm to 30cm in diameter comprise the biggest portion of the log volume, comprising 45% of the total. From period 1 to period 6, the number of small logs declines steadily, whereas the number of bigger logs increases (Figure 3-3). Table 3-5 shows the 4 different dimensions of lumber and chips produced from the logs in each period, and it illustrates that the lumber production increases from period 1 to period 6. Moreover, it can be seen that 2x6 and 2x4 are produced in the largest volume. 2x8 is the least in production because only 40cm logs are used to produce 2x8 lumber. Figure 3-4 illustrates the lumber composition and volume and indicates that as the log diameter increases, a greater amount of larger-dimension lumber is produced.

Table 3-3. Logs available and used in each period for each stand

	Logs available in each period for each stand (m^3)					
	1	**2**	**3**	**4**	**5**	**6**
Stand 1	48,786	0	110,000	6,587	0	73,153
Stand 2	61,214	110,000	0	0	0	53,599
Stand 3	0	0	0	103,413	110,000	0
	Logs used in each period for each stand (m^3)					
	1	**2**	**3**	**4**	**5**	**6**
Stand 1	38,786	0	110,000	6,587	0	73,153
Stand 2	61,214	110,000	0	0	0	53,599
Stand 3	0	0	0	103,413	110,000	0

Table 3-4. Logs sorted by diameter in each period (m³)

Period	SED-15	SED-20	SED-25	SED-30	SED-35	SED-40	SED-45	SED-50	SED-55	sum
1	15,388	38,776	30,612	10,612	3,612	1,000	0	0	0	100,000
2	9,900	31,900	37,400	19,800	7,700	2,200	0	0	0	108,900
3	8,800	26,400	34,100	24,200	9,900	4,400	1,100	0	0	108,900
4	5,566	18,832	28,732	26,466	15,268	8,668	4,334	1,100	0	108,966
5	5,500	15,400	24,200	25,300	18,700	11,000	7,700	2,200	1,100	111,100
6	5,802	15,942	27,349	28,617	22,815	13,211	8,141	4,339	1,268	127,483
sum	50,955	147,249	182,393	134,995	77,996	40,479	21,275	7,639	2,368	665,349

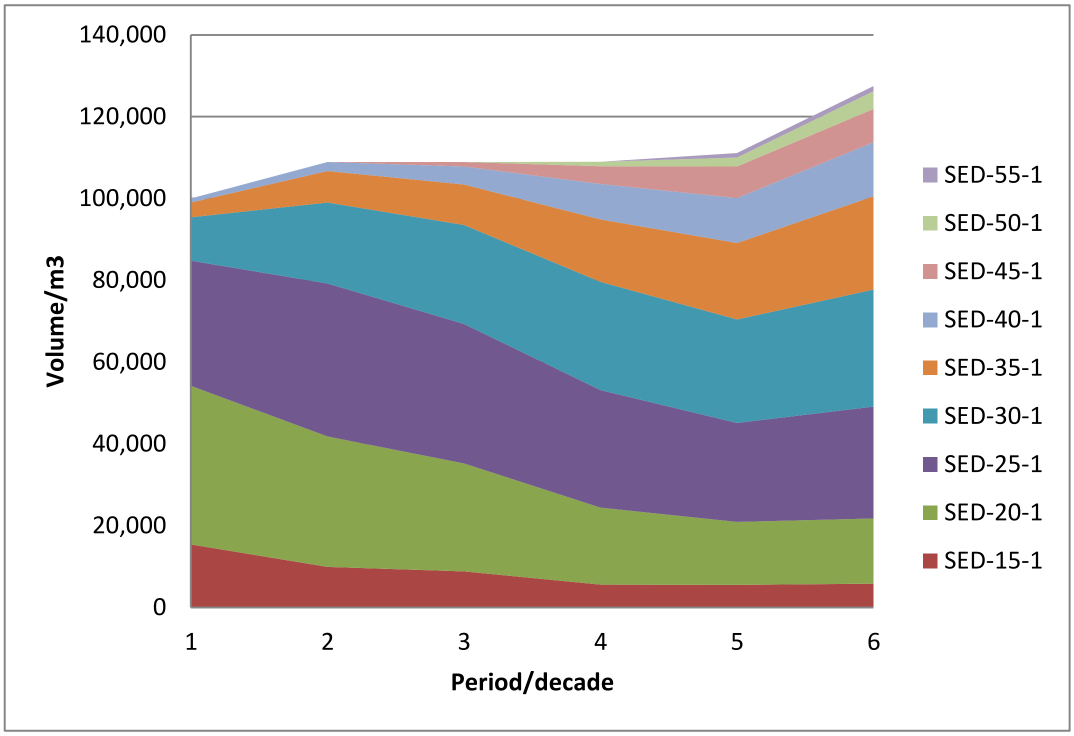

Figure 3-3. Log composition and volume for each period sorted by diameter

Table 3-5. Lumber (MBF) and chips (m^3) produced in each period

Period	2x4_8	2x6_8	2x8_8	2x10_8	chips	Sum lumber
1	9,737	7,430	147	505	52,950	17,820
2	8,580	10,923	323	1,084	54,116	20,909
3	7,567	11,720	645	1,923	51,882	21,855
4	5,902	12,415	1,271	4,483	46,715	24,071
5	5,213	12,211	1,613	7,091	43,891	26,128
6	5,659	14,063	1,937	8,788	49,264	30,446
Sum	42,659	68,762	5,934	23,874	298,818	141,229

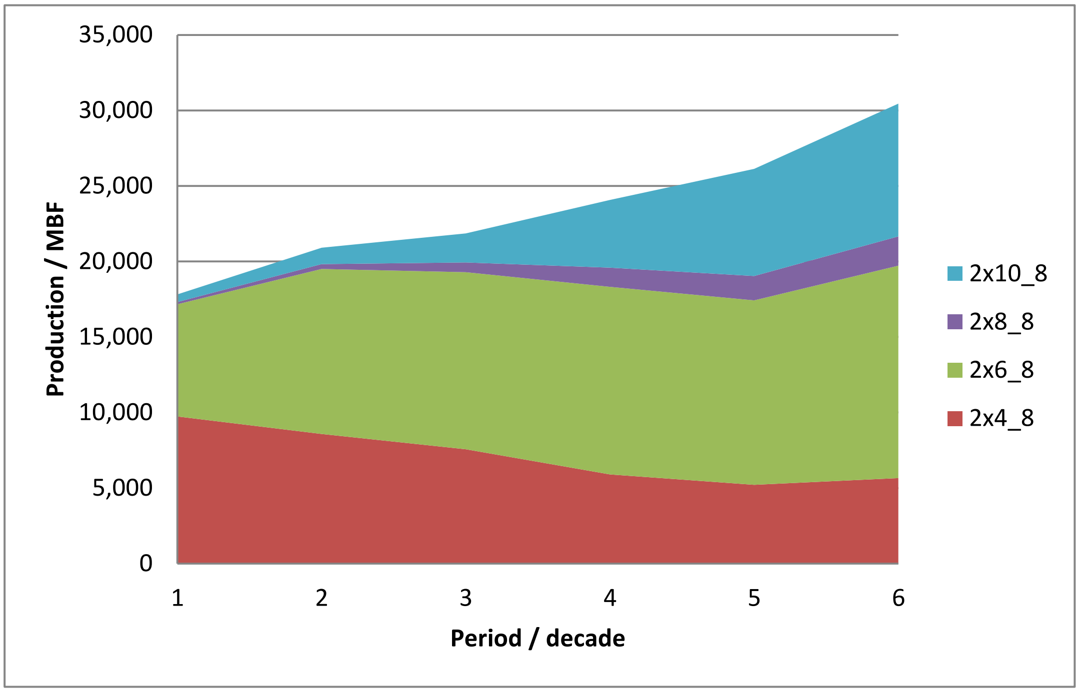

Figure 3-4. Final lumber production and composition

4. Discussion

The preceding models are appropriate tools for predicting production and net revenue of forest operations. In order to have a better understanding of the system, three scenarios, 2x8-oriented sawing pattern, lumber price fluctuation and limited mill working time, were applied to the model to evaluate its performance and assess these assumptions.

4.1 2×8-oriented sawing pattern

In the previous Sawing Pattern Model application, the strategy was to produce as much larger-dimension lumber as possible (2x10-oriented). However, if the 2x8 lumber markets improve, increasing 20% over the current price, the mill would like to use another sawing pattern (2x8-oriented) to increase its customer share in the 2x8 market. In order to begin 2x8 lumber production, the sawing pattern has to be changed to 2x8-oriented.

Since logs less than 35cm in diameter are not big enough to produce 2x8 lumber, and logs greater than 50cm are more valuable in producing 2x10 lumber, logs ranging from 35cm to 45cm are applicable for the LRF change. Table 4-1 shows the difference between the 2 LRF types in production, price and net revenue. Based on the table, in 2x10-oriented sawing type, 35cm, 40cm and 45cm logs would all be used to produce 2x10 whereas only 40cm logs would be used to produce 2x8. As the result, the final volume of lumber is different. According to the production distribution of 2x8-oriented and 2x10-oriented sawing patterns (Figure 4-1), the 2x8-oriented sawing pattern results in 4.5 times larger volume of 2x8 lumber; however, except for 2x8 lumber, the volume of other dimensions of lumber produced under the 2x8-oriented sawing pattern is less, especially 2x10 lumber; it is about 3 times less than the level of the 2x10-oriented sawing pattern. However, since the price of 2x8 lumber has increased 20%, the net revenues of the two sawing patterns are similar.

Table 4-1. Difference between 2x8 and 2x10 production, price and net revenue

	2x8-oriented			2x10-oriented		
	35 cm	40 cm	45 cm	35 cm	40 cm	45 cm
2x4 - 8'	NA	NA	NA	0.0262	NA	NA
2x6 - 8'	NA	0.0476	NA	0.144	0.0476	0.0379
2x8 - 8'	0.2169	0.1466	0.2165	NA	0.1466	NA
2x10 - 8'	NA	0.089	NA	0.1153	0.089	0.3541
sum LRF	0.2169	0.2832	0.2165	0.2855	0.2832	0.392
Chips	0.4382	0.2817	0.4391	0.2763	0.2817	0.025
2X8 price	$373			$311		
Net revenue	$3,108,753			$3,110,141		

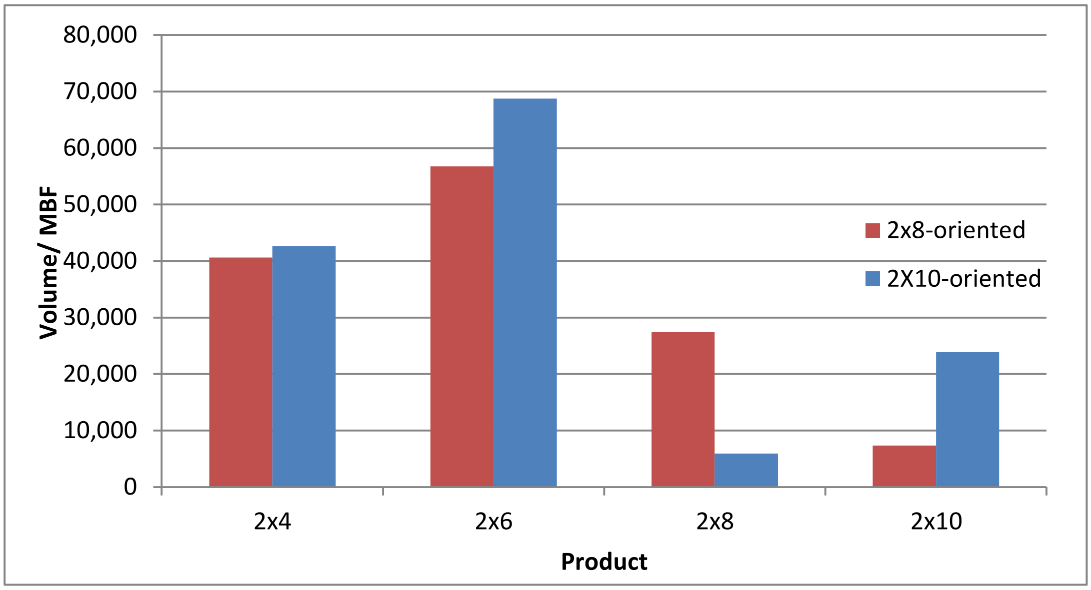

Figure 4-1. Production distribution of 2x8-oriented and 2x10-oritented sawing patterns

Based on the previous analysis, it is clear that the sawing pattern is a key factor in the mill operation and it is directly related to profitability. Mill managers should clearly identify the market direction beforehand, and then implement the corresponding sawing pattern.

4.2 Lumber price fluctuation

Price has important effects in terms of production and marketing. It is directly linked to supply and demand of commodity products (Rewoldt et al., 1973). Since lumber is a type of commodity product, price plays a pivotal role in the sawmill operational decisions. Figure 4-2 shows the lumber price from the 4th quarter of 2006 to the 2nd quarter of 2011 (Council of Forest Industries, 2012). It illustrates that, with the US housing crash in 2008, the price experienced a significant decrease. The price dropped 30%-40% in the second half of the 2008. However, the industry has shown a trend of rebounding (Cross, 2011). Ebner and Grant (2011) claimed that the recovery of the forest sector could even contribute to Canadian exports hitting the pre-recession level in 2012.

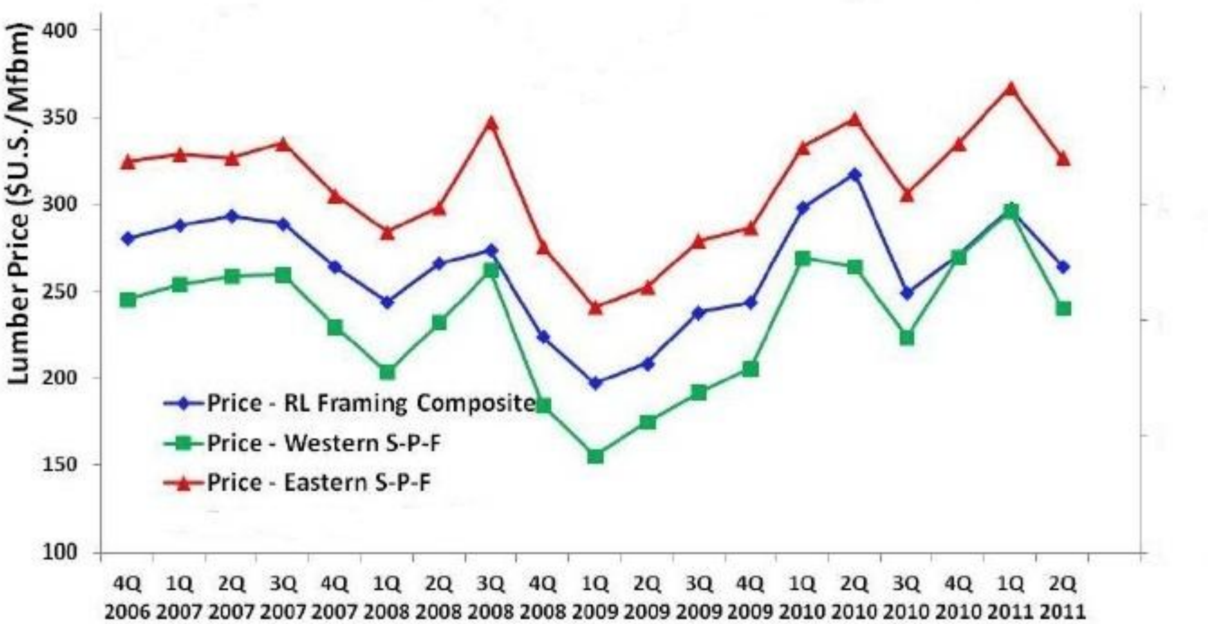

Figure 4-2. Quarterly lumber prices from 2007 to 2011

(Source: Council of Forest Industries, 2012)

Therefore, two price fluctuation scenarios were applied to the model, assuming there is a ±20% change of price without any change in other parameters. -20% change represents the lumber price during the recession period; +20% change represents the price before recession and the price that can be reached in the future. Table 4-2 shows the lumber price, production and net revenue under three scenarios. Lumber production did not undergo significant change as the prices changed, but the net revenue underwent dramatic changes. In the 20% increase scenario, the sawmill can obtain an additional $8,576,137 in net revenue by only increasing lumber production by 651 MBF. A similar situation occurs with the 20% decrease scenario. After running the model, the production only decreased approximately 10% from the original production level, but net revenue decreased dramatically, falling 268% from the baseline.

Table 4-2. Lumber price, production and net revenue for three scenarios

	Baseline	20% increase	20% decrease
2x4 / MBF	$273	$328	$218
2x6 / MBF	$314	$377	$251
2x8 / MBF	$311	$373	$249
2x10 / MBF	$319	$383	$256
Net revenue	$3,110,141	$11,686,278	-$5,238,221
Total lumber production /MBF	141,229	141,880	126,689

As these results show, price is very sensitive for commodity products, so knowing the critical point of the lumber price in terms of earning or losing money is essential for the sawmill. A sensitivity analysis was conducted to examine this critical point for lumber price in the model. The sensitivity report shows that 92.6% to 92.7% of the original price is the critical point. Table 4-3 shows the price and net revenue at 92.6% of the original price and 92.7% of the original price. The table shows that if the price drops 0.1 %, from 92.7% to the 92.6% of the original price, the mill will suffer a $42,197.97 loss in net revenue.

Considering the importance of price and the downturn in the lumber market, the decision of the MKRF to reduced harvesting by 60% in 2010 helped the sawmill operation avoid potential loss in the lumber market (UBC Malcolm Knapp Research Forest, 2011d). However, since the US market is recovering and the Chinese market is rising, it is more likely that there is future opportunity for the mill to gain profit (British Columbia Ministry of Jobs, Tourism and Innovation, 2011). Therefore, mill managers have to be aware of the current price and its trends to adjust the mill operation.

Moreover, knowing the critical point of the lumber price is also essential for mill operation. Since the price and cost information keeps changing, the critical point of price also changes consequently. Hence, the current critical point of lumber price is important information.

Table 4-3. Net revenue comparison of 92.6% of the original price and 92.7% of the original price

92.6% of original price		92.7% of original price	
2x4 - 8'	$252.80	**2x4 - 8'**	$253.07
2x6 - 8'	$290.72	**2x6 - 8'**	$291.03
2x8 - 8'	$288.19	**2x8 - 8'**	$288.50
2x10 - 8'	$295.77	**2x10 - 8'**	$296.09
Net revenue	-$36174	**Net revenue**	$6024

4.3 Limited mill working time

Mill working time is directly linked to the labour cost, which constrains lumber production and therefore is a vital factor in the profit optimization process. Canada has one of the highest labour costs in the world, which poses challenges for many Canadian companies, especially small companies (Van Liemt, 1992). The sawmill in MKRF has a small capacity, so working time has to be taken into consideration in terms of general operation and cost-saving.

In the previous analysis, the sawmill was scheduled running 4,600 hours in order to process as many logs as possible. In this limited mill working time scenario, the mill has 1 year to process those harvested logs. Generally the mill will shut down for 4 weeks within 1 year, so the mill operates about 48 weeks per year and 2 shifts per week. For 1 shift, a mill worker works 8 hours per day and 5 days per week. Therefore, the total mill working time is 8 hours $\times$ 5 days $\times$ 2 shifts $\times$ 48 weeks = 3840 hours. The ratio of headsaw and trimmer productivity was re-adjusted to 1.3 because the available time for both of the machines changed.

After running the model, no feasible answer could be obtained with a mill working time of 3840 hours. In order to explore the reason, 2 sensitivity analyses were conducted. One examined the critical point for the working time that is feasible for the LP model; the other one removed the constraint on minimum production level of each period and kept the mill working hour as 3840 hours to explore the feasible minimum production level for each period.

As for feasible mill working time, the sensitivity analysis showed that the mill can have positive net revenue only if the mill working time is greater than 4156 hours. The main reason for the model generating this number is the minimum production level constraint. In the original analysis, in order to have an even production flow, the assumption was made to produce 100,000 MBF lumber per period for the mill. Therefore, if the mill working time is less than 4156 hours, the mill will not be able to meet this requirement, so the LP model cannot provide a feasible result for the processing.

Another sensitivity analysis was conducted to test the critical point for the minimum production level. It was necessary to assume that the mill working time is 3840 hours, and there is a change in the minimum reduction level. The sensitivity analysis indicates that if the minimum production level is less than 92000 MBF per period, the mill is able to maintain its production.

The previous analyses for the mill working time illustrate that mill working time and minimum production level are linked closely. The mill manager has to determine the minimum production level carefully based on the projected mill working time, or vice versa.

4.4 Possible Improvements of Models

Throughout this research, the series of models projected the volume of harvested trees, lumber production, mill working time and net revenue. However, the model has room for improvement. These possible improvements include combining the tree-to-log and forest estate models together; increasing the upper limit of log diameter of sawing pattern model and introducing a section for carbon credit consideration into the model.

4.4.1 Combine 2 LP Models

In this study, two linear programming models, forest estate model and log-to-product model, were built separately. However, the two models have similar structures and they both need Microsoft Excel Solver to run, so there may be a way to appropriately design an LP model that combines the two models together. There are two main reasons for this improvement. Primarily, one Excel spreadsheet is more efficient and more manageable for mill managers. Currently, the forest estate model must be run first, then the data output (available log volume for each period) has to be copied and pasted manually into the log-to-product model. There is more probability of error in this "copy-and-paste" process. If the model can incorporate the two parts together, it is more user-friendly for a mill manager. Additionally, what the Solver does now is optimize the value for each separate model. However, an optimized answer for one part is not necessarily the best answer overall. If this situation happens, the mill manager may be misled by model outcomes and therefore the mill will suffer some unnecessary losses. Hence, if models can be consolidated, it will be more beneficial for the model users.

4.4.2 Improve Available Log Diameter Range of Sawing Pattern Model

In the sawing pattern model, logs that are greater than 50cm in diameter encounter some design problems due to the inappropriate graphing of the log cross-section. The reason for this problem is the insufficient coordinates of the graph. Based on the size of the log and the product selected, some default coordinates are already embedded in the Excel spreadsheet so that the cross-section of a log and the products can be shown when the information is entered. Although an adjustment was used to generate the LRF for the study, it is expected to have some error compared to a full view design for sawing patterns. Therefore, more default coordinates are needed to be built into the model; however, currently there is a technical deficiency in this study so coordinates are not able to be set up. However, if the sawing pattern model is intended to be used by mill managers in reality, this problem should be fixed.

4.4.3 Introduce a Carbon Credit Section

With the increasing awareness of climate change issues and the establishment of formal carbon credit legislations, carbon credits are considered another important "product" from forests additional to traditional lumber production. British Columbia is leading in greenhouse gas reduction in Canada as it is the first province in Canada to establish carbon tax (Greig & Bull, 2009). Therefore, conserving forest to obtain carbon credits is a serious option for forest managers. As for the MKRF, some projects examining carbon credits for the forest are ongoing in the UBC Faculty of Forestry. Therefore, it is worth exploring some methods to incorporate a carbon section into the LP model, which will give the forest manager more choice. For example, constraints can be added to lower harvesting level, resulting in high growing stock and therefore revenue from carbon credits. However, more research is needed to be done in this field.

5. Conclusion

This study provides a prototype decision support system to project forest operations and log processing in the Malcolm Knapp Research Forest. Actual forest area and sawmill specific parameters were not used for MKRF, but the system could be modified to make it suitable for the research forest. Growth and yield data were simulated by TIPSY, based on information collected in the field. Cost and revenue data were either derived from the market or defined by reasonable assumptions. Models were developed by Microsoft Excel and model simulations were conducted by the Microsoft Excel Solver add-in. The result shows that the mill can obtain $3,110,141 by producing 141,229 MBF of lumber and 298,818 m^3 of chips. Additionally, three scenarios, 2x8-oriented sawing pattern, lumber price fluctuation and limited mill working time, were tested by changing data inputs to the model. The results indicated that market-preferred type of lumber, price trend and mill operation time are three important things of which mill managers need to know. Therefore, the mill manager must continually update and optimize the model.

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7. Appendices

7.1 Appendix A: Forest Estate Model

Appendix A (Figure 7-1 to Figure 7-4) show the structure of the forest estate model. The forest estate model is a linear-programming based model, which is used to project the volume of logs that need to be harvested for the processing in this study. The assumptions and structure of the model were described in the 2.3.1 section of this article. The numbers in the matrix are the optimized solutions for operation.

7.1.1 Stand One

stand 1						
1	2	3	4	5	6	Uncut
S1-P1	S1-P2	S1-P3	S1-P4	S1-P5	S1-P6	S1-uncut
339.2	0.0	524.2	27.8	0.0	108.8	0.0
267.83	180.69	209.83	237.16	263.71	285.78	0
144	0	0	0	0	0	0
0	181	0	0	0	0	0
0	0	210	0	0	0	0
0	0	0	237	0	0	0
0	0	0	0	264	0	0
124	0	0	0	0	286	0
144	144	144	144	144	144	144
0	144	144	144	144	144	144
0	0	181	181	181	181	181
0.4	0	0	210	210	210	210
17	0.4	0	0	237	237	237
62	17	0.4	0	0	264	264
0	62	17	0.4	0	0	286
0	62	17	0.4	0	0	286
1						
	1					
		1				
			1			
				1		
					1	

7.1.2 Stand Two

stand 2						
1	2	3	4	5	6	Uncut
S2-P1	S2-P2	S2-P3	S2-P4	S2-P5	S2-P6	S2-uncut
412.3	587.7	0.0	0.0	0.0	0.0	0.0
278.47	187.17	217.18	245.8	273.66	296.27	0
148	0	0	0	0	0	0
0	187	0	0	0	0	0
0	0	217	0	0	0	0
0	0	0	246	0	0	0
0	0	0	0	274	0	0
130	0	0	0	0	296	0
148	148	148	148	148	148	148
0.0	148	148	148	148	148	148
0.0	0	187	187	187	187	187
0.5	0	0	217	217	217	217
18	1	0	0	246	246	246
67	18	1	0	0	274	274
0	67	18	0.5	0	0	296
0	67	18	0.5	0	0	296
1						
	1					
		1				
			1			
				1		
					1	

7.1.3 Stand Three

stand 3						
1	2	3	4	5	6	Uncut
S3-P1	S3-P2	S3-P3	S3-P4	S3-P5	S3-P6	S3-uncut
0.0	0.0	0.0	406.4	387.9	0.0	205.7
287.11	193.65	224.53	254.44	283.61	306.76	0
153	0	0	0	0	0	0
0	194	0	0	0	0	0
0	0	225	0	0	0	0
0	0	0	254	0	0	0
0	0	0	0	284	0	0
134	0	0	0	0	307	0
153	153	153	153	153	153	153
0	153	153	153	153	153	153
0	0	194	194	194	194	194
0.6	0	0	225	225	225	225
18	0.6	0	0	254	254	254
68	18	0.6	0	0	284	284
0	68	18	0.6	0	0	307
0	68	18	0.6	0	0	307
1						
	1					
		1				
			1			
				1		
					1	

7.1.4 Harvesting, Inventory and Result

Harvesting						Inventory				
Harv1	Harv2	Harv3	Harv4	Harv5	Harv6	Begin_Inven	Ending_Inven			
110,000	110,000	110,000	110,000	110,000	126,752	445,410	111,353	Result		
								676,752	Sign	RHS
-1								0	=	0
	-1							0	=	0
		-1						0	=	0
			-1					0	=	0
				-1				0	=	0
					-1			0	=	0
						-1		0	=	0
								335,410	>=	10000
								313,051	>=	10000
								253,529	>=	10000
								190,251	>=	10000
								146,396	>=	10000
								111,353	>=	10000
							-1	0	=	0
						-0.25	1	0	>=	0
								751	>=	0
								588	>=	0
								524	>=	0
								434	>=	0
								388	>=	0

7.2 Appendix B: Sawing Patterns for Each Type of Log

Appendix B (Figure 7-5 to Figure 7-15) illustrates the different sawing patterns used in the Sawing Pattern Model, referred to in 2.3.2 section of this essay. Appendix B also contains the Lumber Recovery Factor for logs ranging from 15cm to 55cm in the 2x10-oriented pattern and different sawing patterns for 35cm log and 45cm log in the 2x8-oriented pattern. However, due to the design limitation of the sawing pattern model, logs greater than 50cm could not be shown in the cross-section appropriately. Therefore, an adjustment was used, so that only half of the cross-section was filled, in the centre cant, then the volume of that lumber was doubled and the LRF was calculated.

7.2.1 2x10-oriented Lumber Recovery Factor

7.2.1.1 15cm log

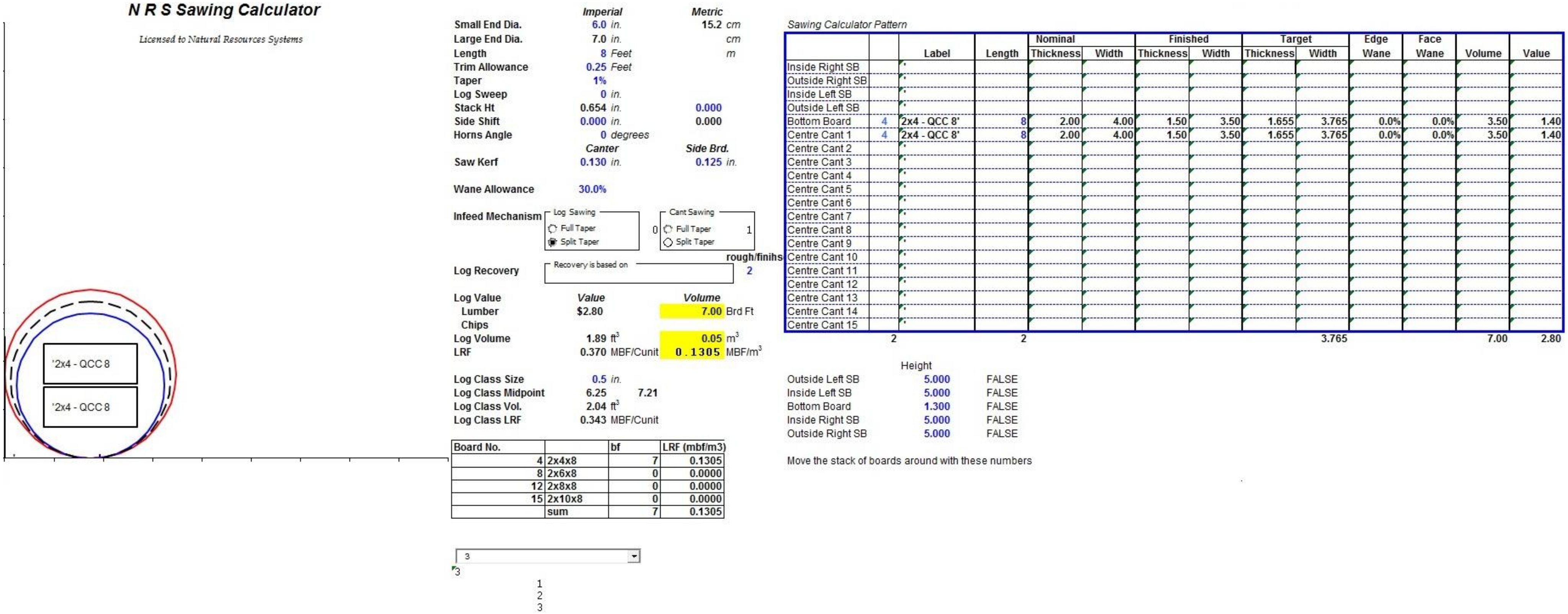
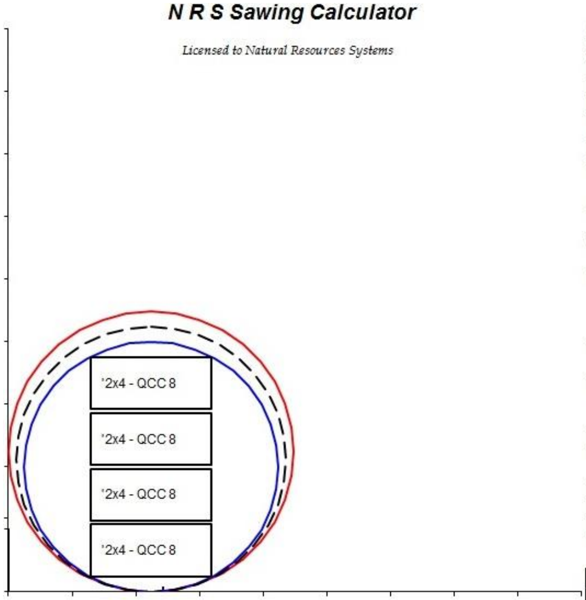


Figure 7-5. 2x10-oriented sawing pattern and LRF for 15cm log

7.2.1.2 20cm log

N R S Sawing Calculator

Licensed to Natural Resources Systems



	Imperial		Metric	
Small End Dia.	8.0	in.	20.3	cm
Large End Dia.	9.0	in.		cm
Length	8	Feet		m
Trim Allowance	0.25	Feet		
Taper	1%			
Log Sweep	0	in.		
Stack Ht	0.305	in.	0.000	
Side Shift	0.000	in.	0.000	
Horns Angle	0	degrees		
	Canter		Side Brd.	
Saw Kerf	0.130	in.	0.125	in.
Wane Allowance	30.0%			

Infeed Mechanism

Log Sawing: Full Taper / Split Taper — 0

Cant Sawing: Full Taper / Split Taper — 1

Log Recovery — Recovery is based on — rough/finihs 2

	Value		Volume	
Log Value				
Lumber	$5.60		14.00	Brd Ft
Chips				
Log Volume	3.24	ft^3	0.09	m^3
LRF	0.432	MBF/Cunit	0.1526	MBF/m^3
Log Class Size	0.5	in.		
Log Class Midpoint	8.25	9.21		
Log Class Vol.	3.43	ft^3		
Log Class LRF	0.408	MBF/Cunit		

Board No.		bf	LRF (mbf/m3)
4	2x4x8	14	0.1526
8	2x6x8	0	0.0000
12	2x8x8	0	0.0000
15	2x10x8	0	0.0000
	sum	14	0.1526

3

3

1
2
3

Sawing Calculator Pattern

		Label	Length	Nominal Thickness	Nominal Width	Finished Thickness	Finished Width	Target Thickness	Target Width	Edge Wane	Face Wane	Volume	Value
Inside Right SB													
Outside Right SB													
Inside Left SB													
Outside Left SB													
Bottom Board	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Centre Cant 1	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765			3.50	1.40
Centre Cant 2	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765			3.50	1.40
Centre Cant 3	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Centre Cant 4													
Centre Cant 5													
Centre Cant 6													
Centre Cant 7													
Centre Cant 8													
Centre Cant 9													
Centre Cant 10													
Centre Cant 11													
Centre Cant 12													
Centre Cant 13													
Centre Cant 14													
Centre Cant 15													
	4		4						3.765			14.00	5.60

	Height	
Outside Left SB	2.000	FALSE
Inside Left SB	2.000	FALSE
Bottom Board	0.500	FALSE
Inside Right SB	2.000	FALSE
Outside Right SB	2.000	FALSE

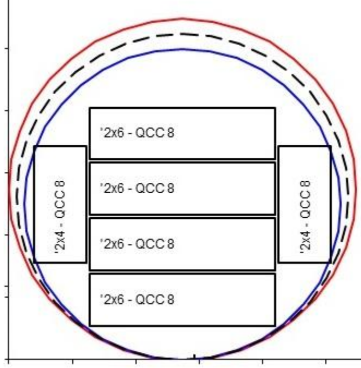
Move the stack of boards around with these numbers

Figure 7-6. 2x10-oriented sawing pattern and LRF for 20cm log

7.2.1.3 25cm log

N R S Sawing Calculator

Licensed to Natural Resources Systems



	Imperial		Metric	
Small End Dia.	10.0	in.	25.4	cm
Large End Dia.	11.0	in.		cm
Length	8	Feet		m
Trim Allowance	0.25	Feet		
Taper	1%			
Log Sweep	0	in.		
Stack Ht	0.830	in.	0.000	
Side Shift	0.000	in.	0.000	
Horns Angle	0	degrees		
	Canter		Side Brd.	
Saw Kerf	0.130	in.	0.125	in.
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: Full Taper / Split Taper (selected) 0 — Cant Sawing: Full Taper / Split Taper 1

rough/finihs

Log Recovery — Recovery is based on 2

	Value		Volume	
Log Value				
Lumber	$12.15		29.00	Brd Ft
Chips				
Log Volume	4.95	ft^3	0.14	m^3
LRF	0.586	MBF/Cunit	0.2070	MBF/m^3

Log Class Size	0.5	in.
Log Class Midpoint	10.25	11.21
Log Class Vol.	5.18	ft^3
Log Class LRF	0.559	MBF/Cunit

Board No.		bf	LRF (mbf/m3)
4	2x4x8	7	0.0500
8	2x6x8	22	0.1570
12	2x8x8	0	0.0000
15	2x10x8	0	0.0000
	sum	29	0.2070

3

3

Sawing Calculator Pattern

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	4.1%	8.3%	3.50	1.40
Outside Right SB		'											
Inside Left SB	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	4.1%	8.3%	3.50	1.40
Outside Left SB		'											
Bottom Board	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 1	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 2	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 3	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 4		'											
Centre Cant 5		'											
Centre Cant 6		'											
Centre Cant 7		'											
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	4		4						5.825			29.00	12.15

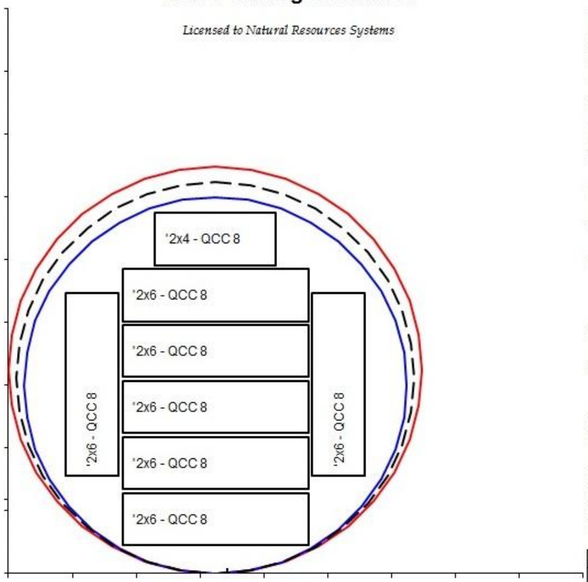
	Height	
Outside Left SB	2.000	FALSE
Inside Left SB	3.100	FALSE
Bottom Board	1.100	FALSE
Inside Right SB	3.100	FALSE
Outside Right SB	2.000	FALSE

Move the stack of boards around with these numbers

Figure 7-7. 2x10-oriented sawing pattern and LRF for 25cm log

7.2.1.4 30cm log

N R S Sawing Calculator



	Imperial		Metric	
Small End Dia.	12.0	*in.*	30.5	*cm*
Large End Dia.	13.0	*in.*		*cm*
Length	8	*Feet*		*m*
Trim Allowance	0.25	*Feet*		
Taper	1%			
Log Sweep	0	*in.*		
Stack Ht	0.555	*in.*	0.000	
Side Shift	0.000	*in.*	0.000	
Horns Angle	0	*degrees*		
	Canter		*Side Brd.*	
Saw Kerf	0.130	*in.*	0.125	*in.*
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: ○ Full Taper ● Split Taper 0 — Cant Sawing: ○ Full Taper ○ Split Taper 1

rough/finihs 2

Log Recovery — Recovery is based on

Log Value	Value		Volume	
Lumber	$17.76		42.00	Brd Ft
Chips				
Log Volume	7.01	ft^3	0.20	m^3
LRF	0.599	MBF/Cunit	0.2115	MBF/m^3

Log Class Size	0.5	*in.*	
Log Class Midpoint	12.25		13.21
Log Class Vol.	7.30	ft^3	
Log Class LRF	0.576	MBF/Cunit	

Board No.		bf	LRF (mbf/m3)
4	2x4x8	3.5	0.0176
8	2x6x8	38.5	0.1938
12	2x8x8	0	0.0000
15	2x10x8	0	0.0000
	sum	42	0.2115

3

3

Sawing Calculator Pattern

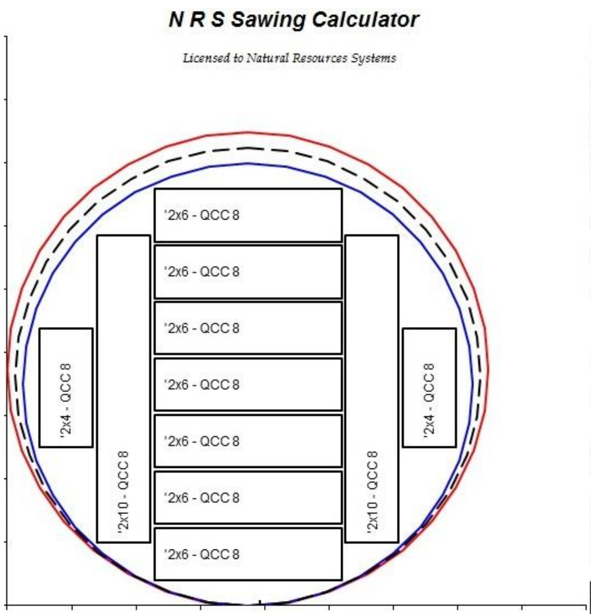
				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Outside Right SB		'											
Inside Left SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Outside Left SB		'											
Bottom Board	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 1	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 2	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 3	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 4	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 5	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Centre Cant 6		'											
Centre Cant 7		'											
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	6		6						5.825			42.00	17.76

	Height	
Outside Left SB	2.000	FALSE
Inside Left SB	3.100	FALSE
Bottom Board	0.900	FALSE
Inside Right SB	3.100	FALSE
Outside Right SB	2.000	FALSE

Move the stack of boards around with these numbers

Figure 7-8. 2x10-oriented sawing pattern and LRF for 30cm log

7.2.1.5 35cm log



	Imperial		Metric	
Small End Dia.	14.0	*in.*	35.6	*cm*
Large End Dia.	15.0	*in.*		*cm*
Length	8	*Feet*		*m*
Trim Allowance	0.25	*Feet*		
Taper	1%			
Log Sweep	0	*in.*		
Stack Ht	0.380	*in.*	0.000	
Side Shift	0.000	*in.*	0.000	
Horns Angle	0	*degrees*		
	Canter		**Side Brd.**	
Saw Kerf	0.130	*in.*	0.125	*in.*
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: ○ Full Taper ● Split Taper 0 — Cant Sawing: ○ Full Taper ○ Split Taper 1

rough/finihs 2

Log Recovery — Recovery is based on

	Value		Volume	
Log Value				
Lumber	$33.04		76.33	Brd Ft
Chips				
Log Volume	9.44	ft^3	0.27	m^3
LRF	0.809	MBF/Cunit	0.2855	MBF/m^3

Log Class Size	0.5	*in.*	
Log Class Midpoint	14.25		15.21
Log Class Vol.	9.77	ft^3	
Log Class LRF	0.782	MBF/Cunit	

Board No.		bf	LRF (mbf/m3)
4	2x4x8	7	0.0262
8	2x6x8	38.5	0.1440
12	2x8x8	0	0.0000
15	2x10x8	30.83333	0.1153
	sum	76.33333	0.2855

3

3

Sawing Calculator Pattern

		Label	Length	Nominal		Finished		Target		Edge	Face	Volume	Value
				Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane		
Inside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Right SB	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Inside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Left SB	4	2x4 - QCC 8'	8	2.00	4.00	1.50	3.50	1.655	3.765	0.0%	0.0%	3.50	1.40
Bottom Board	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 1	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 2	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 3	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 4	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 5	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825			5.50	2.34
Centre Cant 6	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 7		'											
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	7		7						5.825			76.33	33.04

	Height	
Outside Left SB	5.000	FALSE
Inside Left SB	2.000	FALSE
Bottom Board	0.800	FALSE
Inside Right SB	2.000	FALSE
Outside Right SB	5.000	FALSE

Move the stack of boards around with these numbers

Figure 7-9. 2x10-oriented sawing pattern and LRF for 35cm log

7.2.1.6 40cm log

N R S Sawing Calculator

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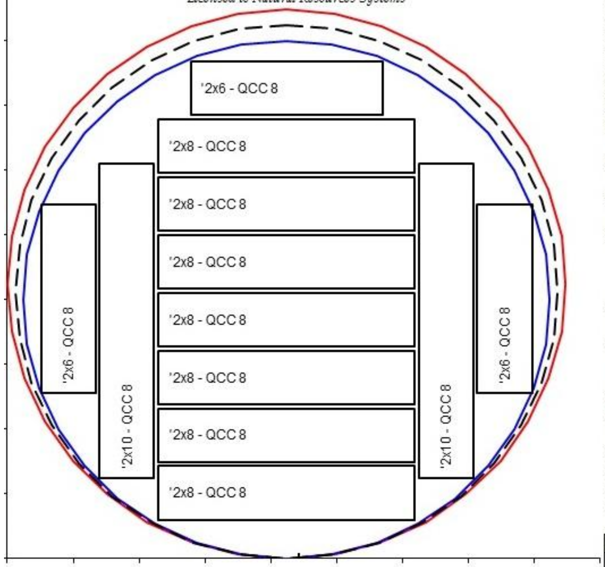


	Imperial		Metric	
Small End Dia.	16.0	in.	40.6	cm
Large End Dia.	17.0	in.		cm
Length	8	Feet		m
Trim Allowance	0.25	Feet		
Taper	1%			
Log Sweep	0	in.		
Stack Ht	0.806	in.	0.000	
Side Shift	0.000	in.	0.000	
Horns Angle	0	degrees		
	Canter		Side Brd.	
Saw Kerf	0.130	in.	0.125	in.
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: Full Taper / Split Taper (selected) 0 — Cant Sawing: Full Taper / Split Taper 1

rough/finihs 2

Log Recovery — Recovery is based on

Log Value	Value		Volume	
Lumber	$40.93		98.08	Brd Ft
Chips				
Log Volume	12.22	ft^3	0.35	m^3
LRF	0.802	MBF/Cunit	0.2832	MBF/m^3

Log Class Size	0.5	in.	
Log Class Midpoint	16.25		17.21
Log Class Vol.	12.60	ft^3	
Log Class LRF	0.779	MBF/Cunit	

Board No.		bf	LRF (mbf/m3)
4	2x4x8	0	0.0000
8	2x6x8	16.5	0.0476
12	2x8x8	50.75	0.1466
15	2x10x8	30.83333	0.0890
	sum	98.08333	0.2832

3

3

1

Sawing Calculator Pattern

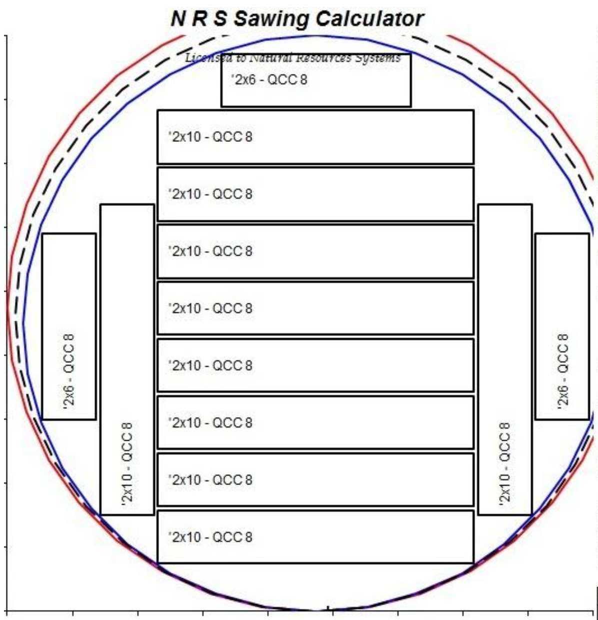
		Label	Length	Nominal Thickness	Nominal Width	Finished Thickness	Finished Width	Target Thickness	Target Width	Edge Wane	Face Wane	Volume	Value
Inside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Right SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.5%	0.4%	5.50	2.34
Inside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Left SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.5%	0.4%	5.50	2.34
Bottom Board	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Centre Cant 1	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 2	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 3	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 4	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 5	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 6	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 7	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	8		8						7.790			98.08	40.93

	Height	
Outside Left SB	5.100	FALSE
Inside Left SB	2.500	FALSE
Bottom Board	1.200	FALSE
Inside Right SB	2.500	FALSE
Outside Right SB	5.100	FALSE

Move the stack of boards around with these numbers

Figure 7-10. 2x10-oriented sawing pattern and LRF for 40cm log

7.2.1.7 45cm log



	Imperial		Metric	
Small End Dia.	18.0	*in.*	45.7	*cm*
Large End Dia.	19.0	*in.*		*cm*
Length	8	*Feet*		*m*
Trim Allowance	0.25	*Feet*		
Taper	1%			
Log Sweep	0	*in.*		
Stack Ht	1.255	*in.*	0.000	
Side Shift	0.000	*in.*	0.000	
Horns Angle	0	*degrees*		
	Canter		**Side Brd.**	
Saw Kerf	0.130	*in.*	0.125	*in.*
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: ○ Full Taper ● Split Taper 0 — Cant Sawing: ○ Full Taper ○ Split Taper 1

rough/finihs 2

Log Recovery — Recovery is based on

Log Value	Value		Volume	
Lumber	$76.39		170.67	Brd Ft
Chips				
Log Volume	15.37	ft^3	0.44	m^3
LRF	1.110	MBF/Cunit	0.3920	MBF/m^3

Log Class Size	0.5	*in.*	
Log Class Midpoint	18.25		19.21
Log Class Vol.	15.79	ft^3	
Log Class LRF	1.081	MBF/Cunit	

Board No.		bf	LRF (mbf/m3)
4	2x4x8	0	0.0000
8	2x6x8	16.5	0.0379
12	2x8x8	0	0.0000
15	2x10x8	154.1667	0.3541
	sum	170.6667	0.3920

Sawing Calculator Pattern

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Right SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Inside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Left SB	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Bottom Board	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Centre Cant 1	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 2	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 3	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 4	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 5	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 6	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 7	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 8	8	2x6 - QCC 8'	8	2.00	6.00	1.50	5.50	1.655	5.825	0.0%	0.0%	5.50	2.34
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	9		9						9.710			170.67	76.39

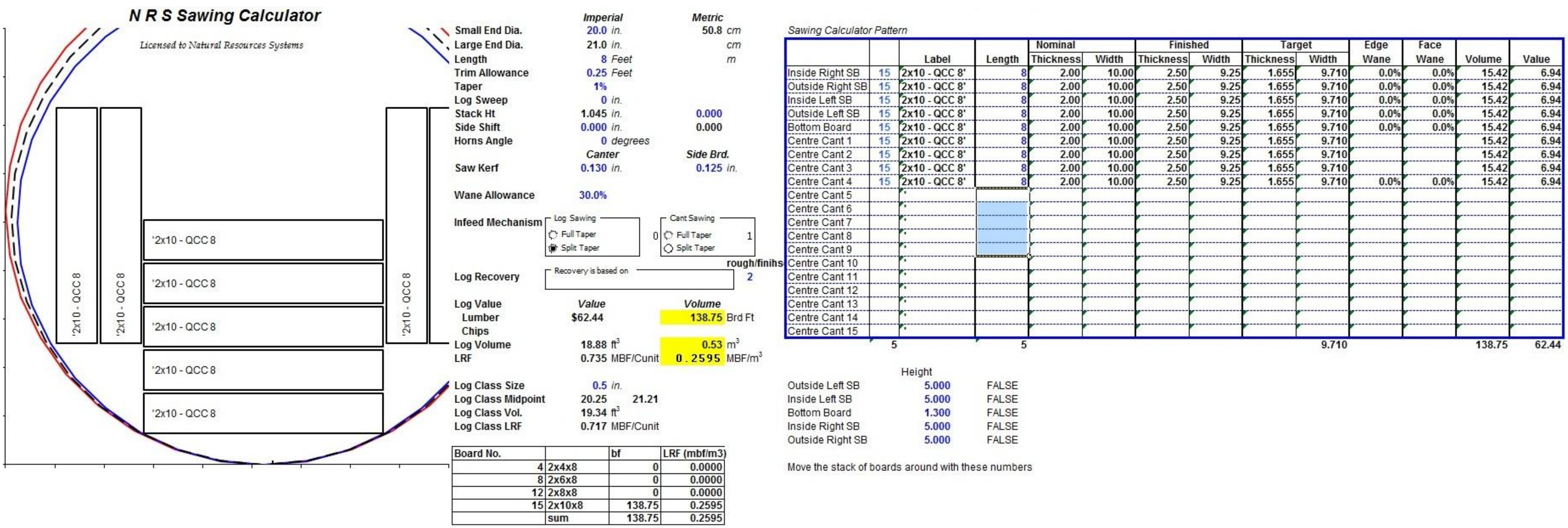
	Height	
Outside Left SB	6.000	FALSE
Inside Left SB	3.000	FALSE
Bottom Board	1.500	FALSE
Inside Right SB	3.000	FALSE
Outside Right SB	6.000	FALSE

Move the stack of boards around with these numbers

Figure 7-11. 2x10-oriented sawing pattern and LRF for 45cm log

7.2.1.8 50cm log

Adjustment: there are 5 2x10 lumber in the centre cant and 4 2x10 lumber in the side board, which is 138.75 board feet. It was tested that 4 more 2x10 can be filled into the upper part of the centre cant. Therefore, the volume of lumber from this log is 138.75+ 4× 15.42 = 200.43 board feet. LRF (MBF/m³) $= \frac{value\ of\ lumber\ in\ board\ feet}{value\ of\ log\ in\ m^3} = \frac{\frac{200.43\ board\ feet}{1000}}{0.53\ m^3}$ = 0.3782



Board No.		bf	LRF (mbf/m3)
4	2x4x8	0	0.0000
8	2x6x8	0	0.0000
12	2x8x8	0	0.0000
15	2x10x8	138.75	0.2595
	sum	138.75	0.2595

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Inside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Bottom Board	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Centre Cant 1	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 2	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 3	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 4	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Centre Cant 5		'											
Centre Cant 6		'											
Centre Cant 7		'											
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	5		5						9.710			138.75	62.44

Figure 7-12. 2x10-oriented sawing pattern and LRF for 50cm log

7.2.1.9 55cm log

Adjustment: there are 6 2x10 lumber in the centre cant and 4 2x10 lumber in the side board, which is 154.17 board feet. It was tested that 5 more 2x10 can be filled into the upper part of the centre cant. Therefore, the volume of lumber from this log is 138.75+ 5× 15.42 = 231.27 board feet. LRF (MBF/m³) $= \frac{value\ of\ lumber\ in\ board\ feet}{value\ of\ log\ in\ m^3} = \frac{\frac{231.27\ board\ feet}{1000}}{0.64\ m^3}$ = 0.3614

N R S Sawing Calculator

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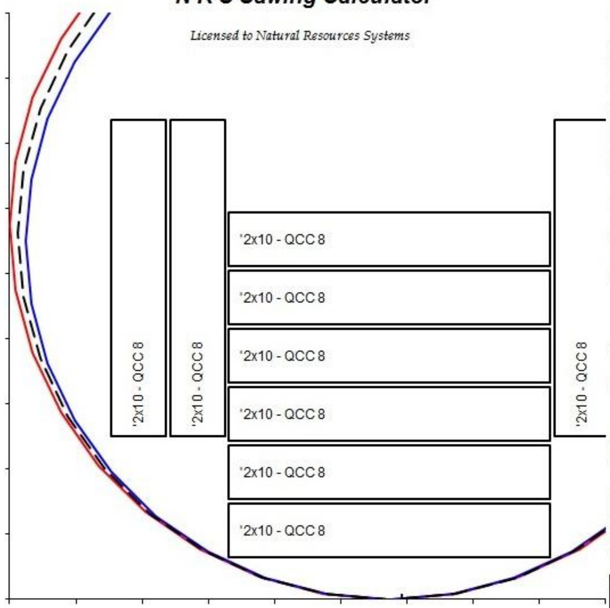


	Imperial		Metric	
Small End Dia.	22.0	in.	55.9	cm
Large End Dia.	23.0	in.		cm
Length	8	Feet		m
Trim Allowance	0.25	Feet		
Taper	1%			
Log Sweep	0	in.		
Stack Ht	0.884	in.	0.000	
Side Shift	0.000	in.	0.000	
Horns Angle	0	degrees		
	Canter		Side Brd.	
Saw Kerf	0.130	in.	0.125	in.
Wane Allowance	30.0%			

Infeed Mechanism: Log Sawing (Full Taper / Split Taper [selected]) 0; Cant Sawing (Full Taper / Split Taper) 1

rough/finihs 2

Log Recovery: Recovery is based on

	Value		Volume	
Log Value				
Lumber	$69.38		154.17	Brd Ft
Chips				
Log Volume	22.74	ft³	0.64	m³
LRF	0.678	MBF/Cunit	0.2393	MBF/m³

Log Class Size	0.5	in.	
Log Class Midpoint	22.25		23.21
Log Class Vol.	23.25	ft³	
Log Class LRF	0.663	MBF/Cunit	

Board No.		bf	LRF (mbf/m3)
4	2x4x8	0	0.0000
8	2x6x8	0	0.0000
12	2x8x8	0	0.0000
15	2x10x8	154.1667	0.2393
	sum	154.1667	0.2393

Sawing Calculator Pattern

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Right SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Inside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Outside Left SB	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Bottom Board	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Centre Cant 1	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 2	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 3	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 4	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710			15.42	6.94
Centre Cant 5	15	2x10 - QCC 8'	8	2.00	10.00	2.50	9.25	1.655	9.710	0.0%	0.0%	15.42	6.94
Centre Cant 6		'											
Centre Cant 7		'											
Centre Cant 8		'											
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	6		6						9.710			154.17	69.38

	Height	
Outside Left SB	5.000	FALSE
Inside Left SB	5.000	FALSE
Bottom Board	1.300	FALSE
Inside Right SB	5.000	FALSE
Outside Right SB	5.000	FALSE

Move the stack of boards around with these numbers

Figure 7-13. 2x10-oriented sawing pattern and LRF for 55cm log

7.2.2 2x8-oriented Lumber Recovery Factor

Since logs less than 35cm in diameter are too small to produce 2x8 lumber; logs greater than 50cm are more suitable in producing 2x10 lumber and the sawing pattern for 40cm log is well-designed; only 35cm log and 45cm log are subject to change.

7.2.2.1 35cm log

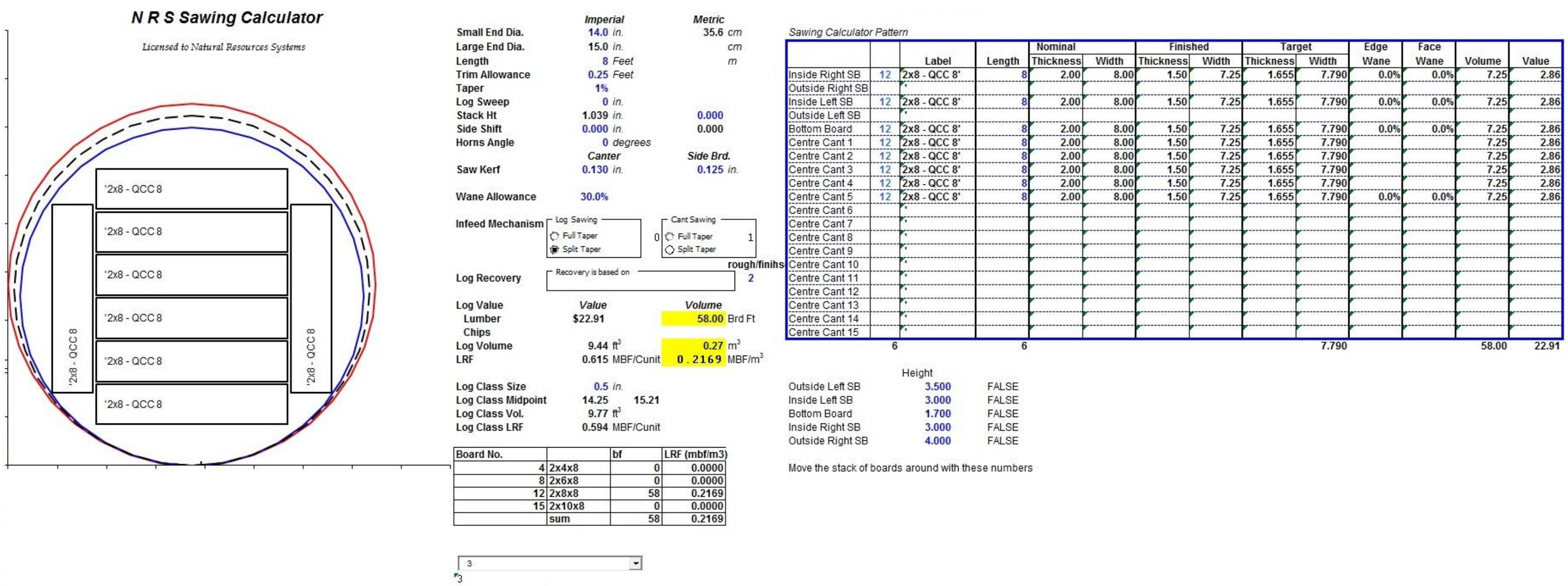
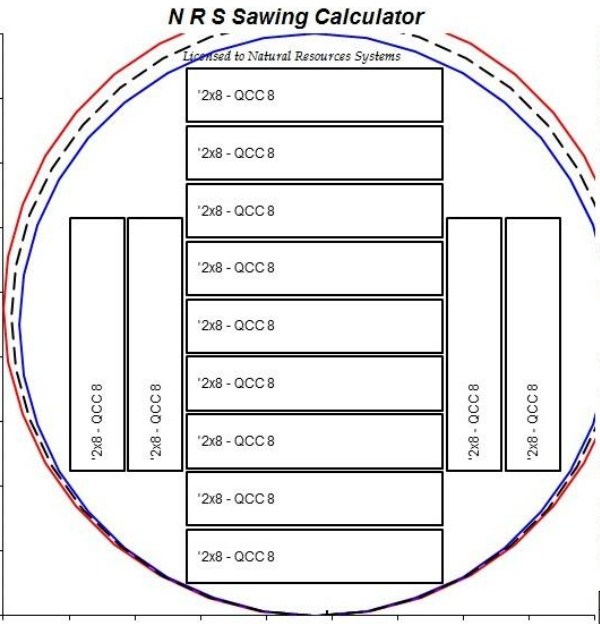


Figure 7-14. 2x8-oriented sawing pattern and LRF for 35cm log

7.2.2.2 45cm log



	Imperial		Metric	
Small End Dia.	18.0	in.	45.7	cm
Large End Dia.	19.0	in.		cm
Length	8	Feet		m
Trim Allowance	0.25	Feet		
Taper	1%			
Log Sweep	0	in.		
Stack Ht	0.638	in.	0.000	
Side Shift	0.000	in.	0.000	
Horns Angle	0	degrees		
	Canter		Side Brd.	
Saw Kerf	0.130	in.	0.125	in.
Wane Allowance	30.0%			

Infeed Mechanism — Log Sawing: Full Taper / Split Taper (0); Cant Sawing: Full Taper / Split Taper (1)

Log Recovery — Recovery is based on — rough/finihs 2

	Value		Volume	
Log Value				
Lumber	$37.23		94.25	Brd Ft
Chips				
Log Volume	15.37	ft^3	0.44	m^3
LRF	0.613	MBF/Cunit	0.2165	MBF/m^3
Log Class Size	0.5	in.		
Log Class Midpoint	18.25	19.21		
Log Class Vol.	15.79	ft^3		
Log Class LRF	0.597	MBF/Cunit		

Board No.		bf	LRF (mbf/m3)
4	2x4x8	0	0.0000
8	2x6x8	0	0.0000
12	2x8x8	94.25	0.2165
15	2x10x8	0	0.0000
	sum	94.25	0.2165

Sawing Calculator Pattern

				Nominal		Finished		Target		Edge	Face		
		Label	Length	Thickness	Width	Thickness	Width	Thickness	Width	Wane	Wane	Volume	Value
Inside Right SB	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Outside Right SB	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Inside Left SB	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Outside Left SB	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Bottom Board	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Centre Cant 1	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 2	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 3	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 4	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 5	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 6	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 7	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790			7.25	2.86
Centre Cant 8	12	2x8 - QCC 8'	8	2.00	8.00	1.50	7.25	1.655	7.790	0.0%	0.0%	7.25	2.86
Centre Cant 9		'											
Centre Cant 10		'											
Centre Cant 11		'											
Centre Cant 12		'											
Centre Cant 13		'											
Centre Cant 14		'											
Centre Cant 15		'											
	9		9						7.790			94.25	37.23

	Height	
Outside Left SB	4.500	FALSE
Inside Left SB	4.500	FALSE
Bottom Board	1.000	FALSE
Inside Right SB	4.500	FALSE
Outside Right SB	4.500	FALSE

Move the stack of boards around with these numbers

Figure 7-15. 2x8-oriented sawing pattern and LRF for 55cm log

7.3 Appendix C: Log-to-product Model

Appendix C shows the structure of the log-to-product LP model. This model is also a linear-programming based model, and is used to simulate the volume of logs that need to be used for processing, lumber production, machine working time and net revenue in this study. The assumptions and structure of the model were described in section 2.3.3 of this essay. The numbers in the ANSWER row are the optimized solution.