2015

Estimation of Energy Intensity in Wood Processing Sawmills based on Analysis of Product, Process and System parameters

Dayakar Devaru

Estimation of Energy Intensity in Wood Processing Sawmills based on Analysis of Product, Process and System parameters

Dayakar Devaru

Dissertation

Submitted to the
Benjamin M. Statler
College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Industrial Engineering

Bhaskaran Gopalakrishnan, Ph.D., P.E., Chair
Robert C. Creese, Ph.D., P.E.
Feng Yang, Ph.D.
Shawn T Grushecky, Ph.D.
Jingxin Wang, Ph.D.

Department of Industrial and Management Systems Engineering
Morgantown, West Virginia
2015

Keywords: Sawmills Energy Profiling, Lumber Sawing, Energy Consumption Estimation, Wood Processing, Multiple Linear Regression, Lumber Surface Area, Sawmill Motors

ABSTRACT

Estimation of Energy Intensity in Wood Processing Sawmills based on Analysis of Product, Process and System parameters

Dayakar Devaru

Energy costs have risen immensely in the recent past and have strained US industrial sectors. The forest products sector is considered as an energy intensive industry group and energy use has an important impact on sawmill's financial integrity. Energy intensity or specific energy consumption (SEC) is an important aspect to wood products producing sawmills since it also represents production efficiency to some extent. This research focuses on developing SEC profiles for the manufacture of hardwood lumber in sawmills and estimating energy intensity based on product, process and system parameters. Energy benchmarking will help the sawmill industry to know their level of performance and opportunities to improve their energy efficiency and productivity. Process, production and energy data were gathered by visiting three sawmills with single sawing lines and two sawmills with double sawing lines in West Virginia.

Initially SEC was calculated in the traditional way as total energy consumption by total board feet sawn and the average SEC for all the sawmills was around 100 kWh per thousand board feet of lumber sawn. Effect of lumber sizes sawn on energy consumption was analyzed and a method to calculate SEC based on surface area sawn was developed. Sawmills' SEC developed based on surface area sawn yielded better results than traditionally calculated SEC since it exposed production bottle necks.

Data from four sawmills was used to develop three estimation models to estimate SEC of the fifth sawmill based on product, process and system parameters. The parameters that were included in the model were: species and lumber sizes for product, sawing time and maintenance schedule for process, and motor horse power, availability of resaw and production line configuration for system. The model which had 'motor horse power x minutes' as one of the estimator variables was better than the other two models in terms of both R^2 and ability to estimate SEC of the fifth sawmill. One estimation model was developed to predict total energy consumption and although this model had the highest R^2, it didn't estimate the fifth sawmill that well. Sensitivity analysis was conducted to find the effect of different widths of lumber sawn on energy consumption and also the parameters used in the estimation model were analyzed for their sensitivity towards the energy consumption. Energy consumption of Sawmill 3 was highly sensitive to estimator variables 'motor horse power' and 'grade lumber sizes'. Energy consumption of sawmill motors were compared and the highest energy consumer of sawmill 2 and 4 motors was main saw and carriage feed, since there was no resaw or a gang saw in them. The energy consumption of sawmill 1 motors was similar to sawmill 3 and energy consumption of sawmill 2 motors was similar to sawmill 4.

The 'Sawmill Energy Estimation Program' that takes the inputs from the user and estimates sawmill's energy intensity based on sawmill parameters and analyzes sawmill's efficiency and gives recommendations with estimated savings to improve sawmill's energy efficiency and productivity was also developed to help sawmill owners to analyze their sawmill.

Dedication

This research work is dedicated to the universal consciousness also called as God with different names by different religions and is the thing which is responsible for the creation of this Universe and also manifests itself in every living being. Without that consciousness this work wouldn't have occurred since I am just a channel through which it is operating.

Acknowledgement

I would like to wholeheartedly thank my advisor, Dr. B. Gopalakrishnan, for his continued support, guidance, and encouragement during my graduate studies at WVU and during this research work. I would also like to thank my research committee members, Dr. Shawn Grushecky, Dr. Robert Creese, Dr. Feng Yang, and Dr. Jingxin Wang for their constant advice and support and for providing me a scientific perspective to the analytical approach used in this research.

I would like to extend my special thanks to Mr. Bill Glasscock, Mr. Ed Dallison, Mr. John DiLorenzo, Mr. Mark Caroll, Mr. Mark Wilson, Mr. Mark Jones, Mr. David Shields and Mr. Tyler King, and the staff at sawmill facilities who made it possible to collect the invaluable data required for this research. I would like to extend my special thanks to Mr. Ramakrishna Maddula , Mr. Amir Abolhassani and my brother-in-law Mr. Vinod Kumar for their invaluable help and support for the success of this project.

Above all, I would like to thank my loving parents Mr. Gurupada Devaru and Mrs. Sundaramma for their moral support and blessings and my wife Shwetha for her constant support and my daughter Tanya for her inspiration and enabling my success and happiness in all my pursuits and endeavors in life.

Table of Contents

Nomenclature

BF	Board Feet
MBF	1000 Board Feet
kWh	Kilowatt Hour (Energy Usage)
kW	Kilowatt (Power)
MMBtu	Million British Thermal Units = 293 kWh
SEC	Specific Energy Consumption (kWh/MBF)
SMEEP	Sawmill Energy Estimation Program
SCFM	Standard Cubic Feet per Minute (Volumetric Air Flow Rate)
hp	Horsepower of the motor
MJ	Mega Joule
PF	Power Factor
HVAC	Heating, Ventilation, and Air Conditioning
ITTO	International Tropical Timber Organization
Tim	Timber
Mins	Minutes
Temp	Temperature
GDP	Gross Domestic Product
FPI	Forest Products Industry
AFPA	American Forest and Paper Association
IMF	International Monetary Fund
USDA	U.S. Department of Agriculture
FPIP	Forest Products Industry Profile
EERE	Energy Efficiency & Renewable Energy
EPA	Environmental Protection Agency
FSP	Fiber Saturation Point

List of Figures

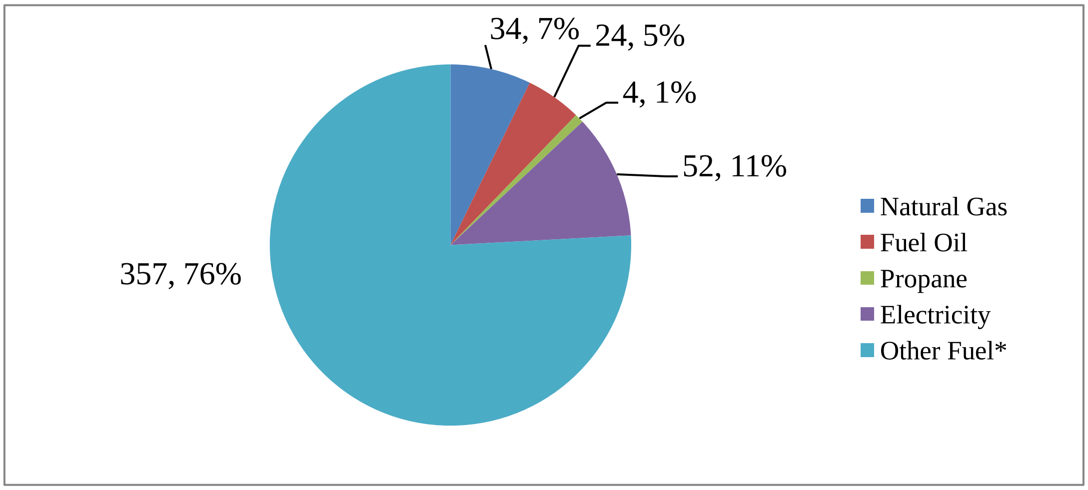
List of Tables

1. Introduction

The global forest-based industry is an important component of society in many nations. Its total economic value was US $468 billion in 2006, employing 13.7 million people, according to the United Nations (FPI roadmap 2010). The world's forest-based industry covers six continents, with North America, Europe, and Asia having the largest portions.

The United States forest products industry accounted for approximately 4.5 percent of the total U.S. manufacturing gross domestic product (GDP) in 2012, placing it on par with the automotive and plastics industries (AFPA 2012). The industry generated $240 billion in 2012 in sales and employs approximately 900,000 people earning $50 billion in annual payroll and $4.6 billion in state and local taxes. The industry is among the top 10 manufacturing employers in 47 states. This geographic diversity results in a widespread employment base that is concentrated in the nation's rural communities.

In 2012, the total value of shipments for sawmills and the engineered wood and panel products combined was $67.4 billion, which is approximately 28 percent of the total shipment of $238.8 billion for the forest products industry (AFPA 2012). In 2010, the U.S. forest products industry consumed 2.6 quadrillion Btu (quad), accounting for 13 percent of total manufacturing energy demand. Pulp and paper manufacturing industry used 2.1 quads, wood products industry used 0.27 quads and sawmills used 0.23 quads of energy (US EIA 2010). Figure 1.1 shows the energy consumption by wood products industry in 2010. In 2010, the sawmill industry consumed 4.5 billion kWh (15.4 million MMBtu) in electricity or $390 million in electricity costs, 5 billion cubic feet (5 million MMBtu) of natural gas or $27.5 million in gas costs and 195 million MMBtu of other fuels (US EIA 2010).

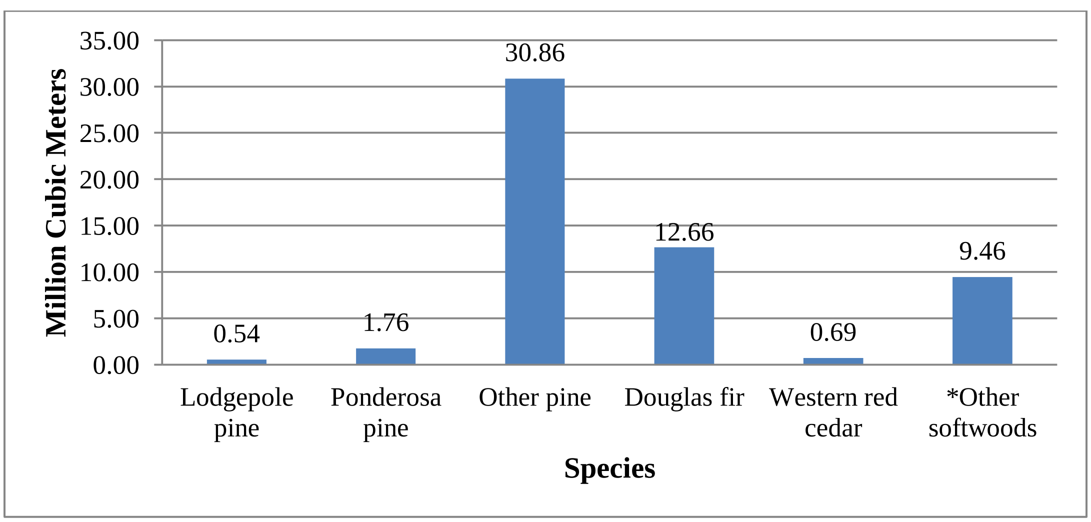


*Asphalt and road oil, lubricants, naphtha, waxes, and miscellaneous nonfuel products like biomass etc.,

Figure 1.1: Energy Consumption by Wood Products Industry in 2010 in Million MMBtu

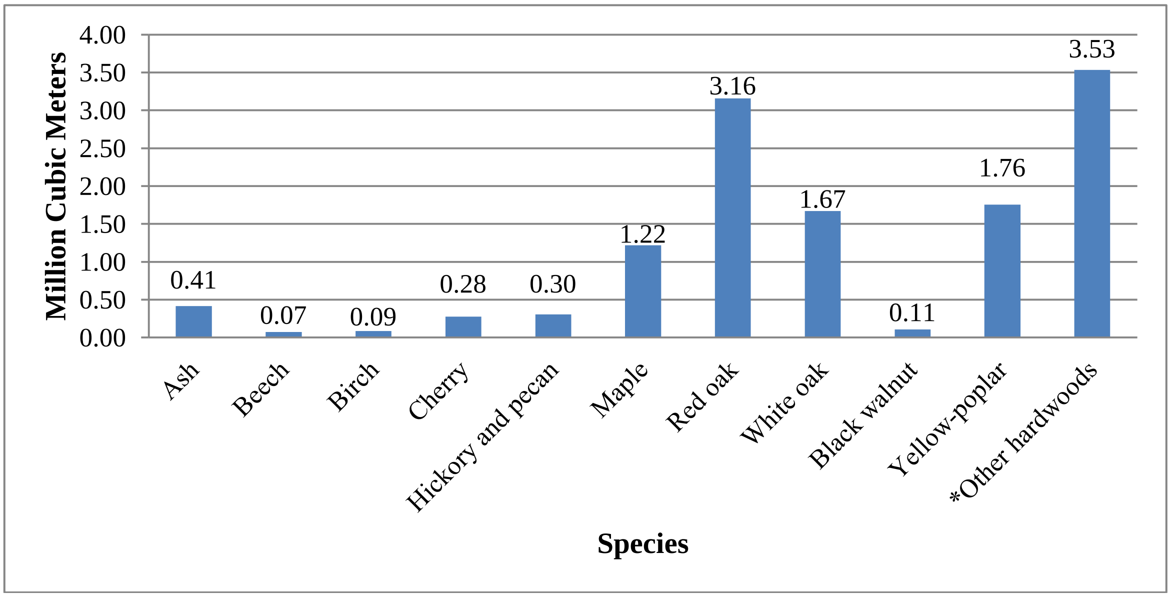
1.1 Lumber Production in US and Global Market

The total lumber production in United States in 2010 was 68.5 million cubic meters (29,057 Million Board Feet). The total lumber exports was 5.6 million cubic meters and imports was 22.3 million cubic meters. The softwoods production was 56 million cubic meters (23,718 Million Board Feet) and hardwoods production was 12.5 million cubic meters (5,339 Million Board Feet) (USCB 2010). Figure 1.2 and 1.3 shows the volume of different species of softwood and hardwood lumber produced in United States during 2010.



*Other softwoods: hemlock, spruce, fir, cedar, and mixed softwoods

Figure 1.2: US Softwood Lumber Production in 2010 (USCB 2010)



*Other hardwoods: cottonwood, aspen, gum, and mixed hardwoods

Figure 1.3: US Hardwood Lumber Production in 2010 (USCB 2010)

The total world lumber production in 2011 was 346.2 million cubic meters as per ITTO (International Tropical Timber Organization) annual review of 2012 (ITTO 2012). The total world exports of sawnwood was 101.4 million cubic meters worth of US $27 billion and imports was 104.7 million cubic meters worth of US $28 billion in 2011. Figure 1.4 shows the trends in GDP growth for ITTO producers and consumers over the last 12 years and International Monetary Fund (IMF) forecasts for 2013 to 2017. The GDP growth profile clearly shows the economic downturn of the years 2008 and 2009.

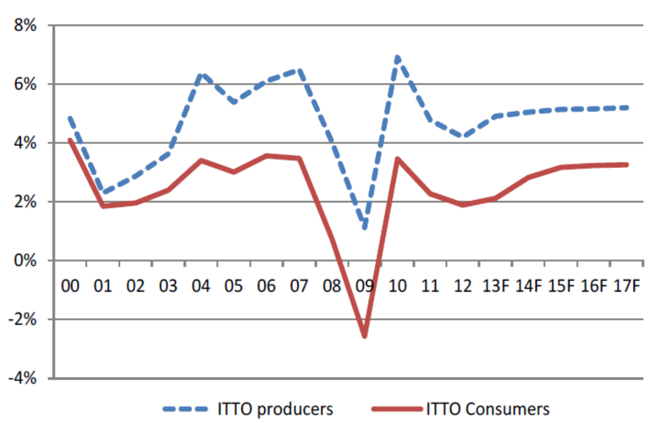
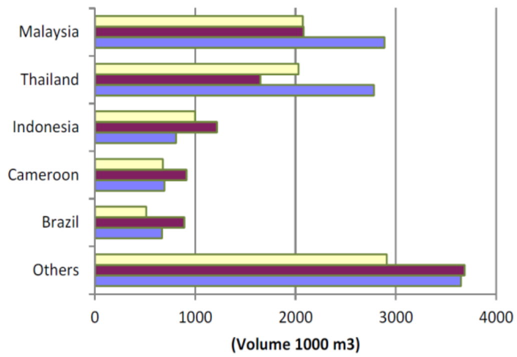
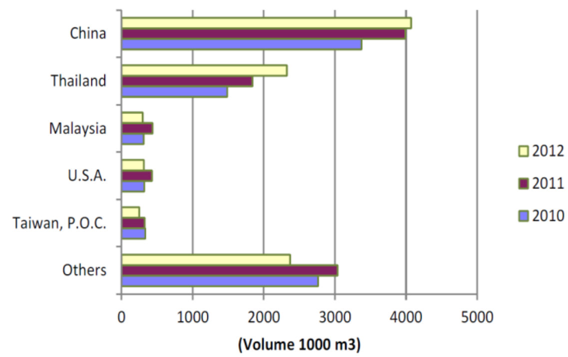


Figure 1.4: ITTO Producers and Consumers Real GDP Growth, 2000-2017 (ITTO 2012)

Figure 1.5 shows the major trade flows of tropical sawnwood from 2010 to 2012. China and Thailand are the major importers of the sawnwood and Malaysia and Thailand are the major exporters. Increase in sawnwood imports by China and Thailand can be seen from 2010 to 2012.



(ITTO 2012)



(ITTO 2012)

Figure 1.5: Major Tropical Sawnwood Exporters (left) and Importers (right)

1.2 Wood Industry Situation in United States

The United States wood industry was severely affected in the last economic downturn of 2008. The total number of wood products manufacturing establishments closed between 2006 and 2012 was 2,716 (BLS 2013). In 2006 the total number of wood products manufacturing establishments was 17,431 where as in 2012 it was 14,715 a reduction of 15.6 % in last 6 years. The number of jobs lost was an alarming reduction rate of 38.9%. In 2006 the total number of employees in wood products manufacturing sector was 555,237 where as in 2012 it was 338,977. Sawmills sector was also affected similarly from the economic downturn. The number of sawmills in 2006 was 3,870 and in 2012 was 3,228 a reduction of 16.6%. The number of employees in sawmill sector in 2006 was 105,608 and in 2012 was 75,361 a reduction of 28.6%. Figure 1.6 shows the number of employees and establishments in wood industry and sawmills from year 2006 to 2012 (BLS 2013). The operators that have remained in business over the last economic downturn have been investigating ways to lower the costs associated with the production of hardwood lumber. One potential way to lower costs is to focus on reducing their energy consumption.

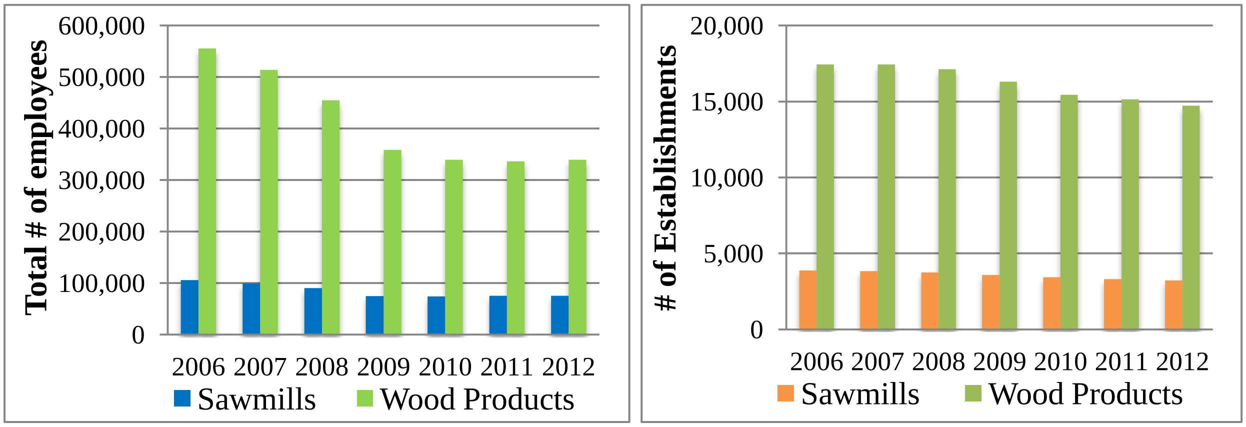


Figure 1.6: Total Number of Employees and Establishments in Wood Products Sector (BLS 2013).

In West Virginia, sawmills represent the largest component of the primary processing sector in both number of establishments and employees. West Virginia currently has approximately 85 sawmills that produce lumber of various grades from different hardwood species. The wood industry of West Virginia generates $3.2 billion annually to the state's economy and employs more than 30,000 workers (WVDOF 2013).

1.3 Energy Usage in a Sawmill

If a sawmill produces only rough green lumber and has no kiln-drying facility, electricity will be the primary energy form consumed, otherwise the fuel used to produce heat for lumber drying will be the most important component of energy usage. Energy costs can be a significant component of operating costs in a lumber manufacturing industry (Gopalakrishnan et al. 2003) and can vary between 1 and 10 percent of the total operating costs (Mardikar 2007). With the addition of kilns at primary-processing facilities, energy use can be much higher, potentially using 6 to 9 times more energy than the sawmilling operation itself (Wengert and Meyer 1992).

Figure 1.7 shows the breakdown of sawmill operating costs. Raw materials account for 60 percent of the total operating costs, whereas labor and overhead costs are 15 percent each, and the energy costs are 10 percent of the total sawmills operating costs (FPIP 1979).

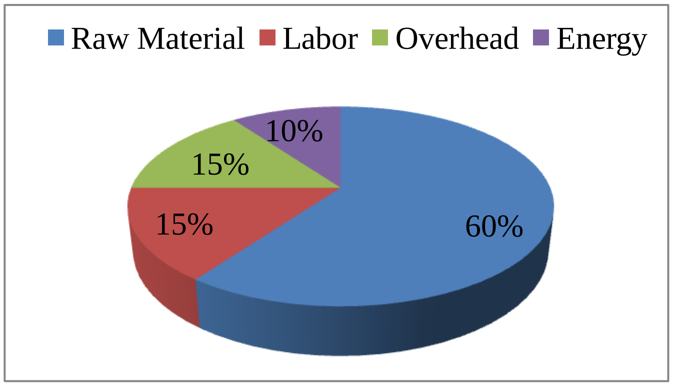


Figure 1.7: Breakdown of Sawmill Operating Costs (FPIP 1979)

The amount of energy required by each process in a sawmill varies widely but, as per the United Nations study the energy consumption in a typical Sawmill with kiln drying is shown in Figure 1.8 (UN 1983). Electrical energy usage is divided mainly among six processing categories, as shown in the Figure 1.8. For a sawmill with kiln-drying operations, thermal energy is by far the largest part of the energy consumption. However, 63%-80% of the thermal BTU's will be generated from wood residues (Bond 2008).

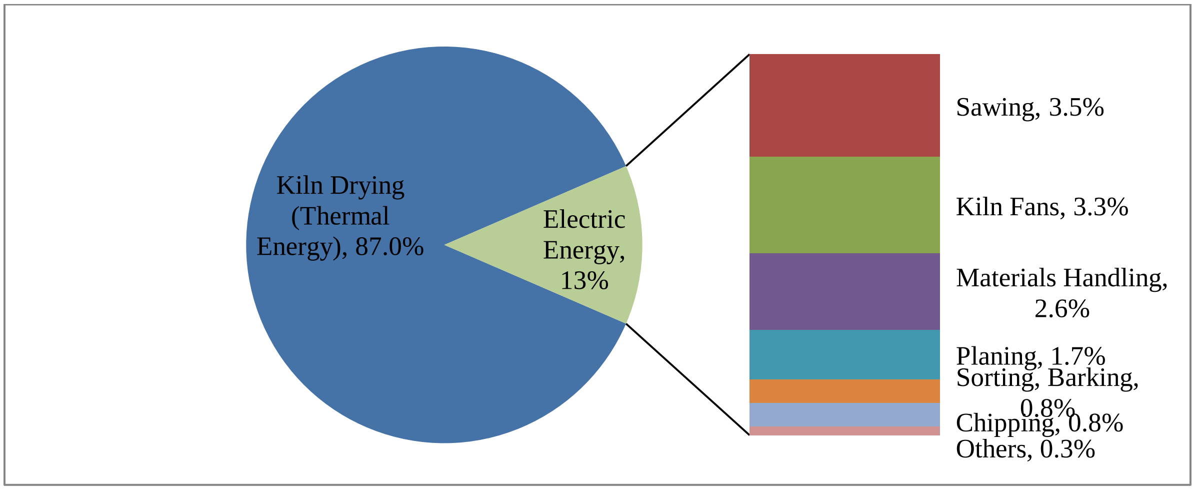


Figure 1.8: Breakdown of Sawmill's Energy Use (UN 1983)

Increasing energy costs has a significant impact on the profit margin of lumber production, especially since it can represent a large percentage of the total costs of production. Although it has recently stabilized, the price of electricity for industrial sector has risen by more than 40 percent from 2000 to 2012, and natural gas prices increased and again decreased during the same period as shown in Figure 1.9 (US EIA 2013). Therefore, more attention is being given to energy consumption due to increasing energy prices (Mate 2002). The hardwood lumber prices have gone down from 2004 as shown in Figure 1.9 (USDA 2011). Hence, the sawmills must become more productive to compensate for the reduction in lumber prices and increase in energy costs.

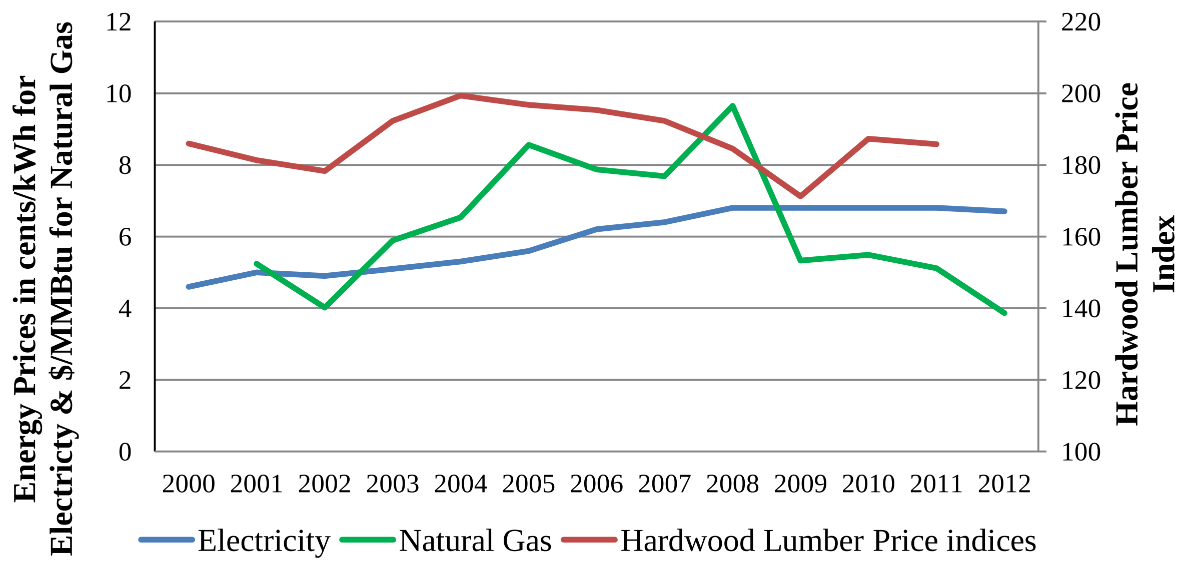


Figure 1.9: Comparison between Prices of Electricity, Natural Gas and Lumber (EIA2013)

1.4 Emissions from Forest Products Industry

The total carbon-dioxide emissions from the forest products industry was 68 million metric tons for year 2006 (AMO 2012). Air pollutants emitted to the environment from Wood

Products industry in year 2002 is shown in Figure 1.10 (EPA 2007). The total energy related ‘Criteria Air Pollutants’ emission was 408,000 tons out of total emissions of 515,000 tons.

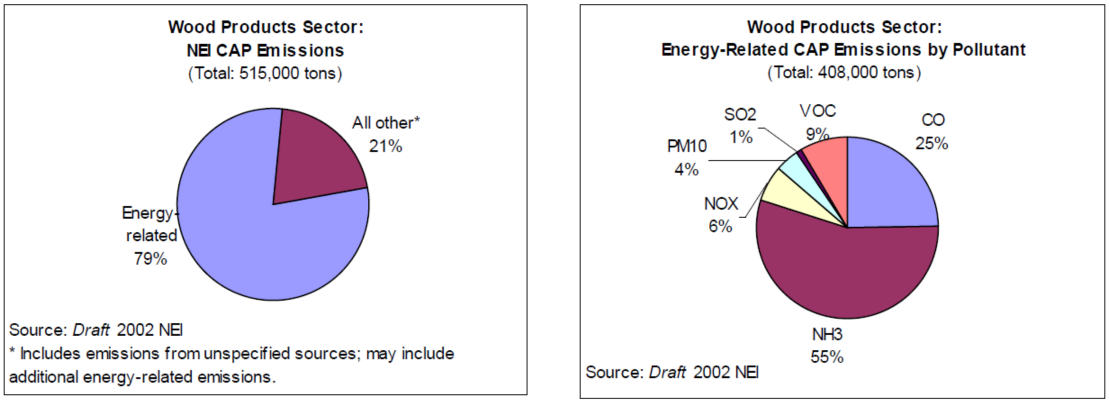


Figure 1.10: ‘Criteria Air Pollutants’ Emissions from Wood Industry for Year 2002 (EPA 2007)

1.5 Need for Research

Energy Intensity also can be called as specific energy consumption (SEC) is measured by the quantity of energy required per unit output or activity, so that using less energy to produce a product reduces the intensity (EERE 2012). In case of lumber manufacturing, SEC will be kilowatt hour consumed to produce one thousand board feet of lumber. One board feet of lumber is defined as a board of size 1 feet wide by 1 feet long by 1 inch thick (Figure 1.11).

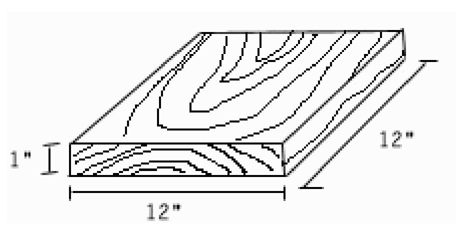


Figure 1.11: Board Feet Measurement

SEC for a particular type of manufacturing industry helps the industry to benchmark itself against standard energy consumption or industry bests and know its level of performance and the opportunities available to improve. Benchmarking is the process of comparing one's manufacturing processes and performance metrics to industry bests or best practices from other companies. The industry best practices can keep on improving due to inventions and continuous improvements happening every day. Research done has calculated the SEC of a sawmill by dividing total energy consumption by total board feet sawn (Gopalakrishnan et al. 2005, Lin et al. 2012). This overall SEC gives a rough estimate of the energy efficiency of a sawmill. Overall SEC calculated from data of 10 West Virginia hardwood sawmills collected during energy audits conducted by Industrial Assessment Center at West Virginia University between 2001 and 2010 are shown in Figure 1.12.

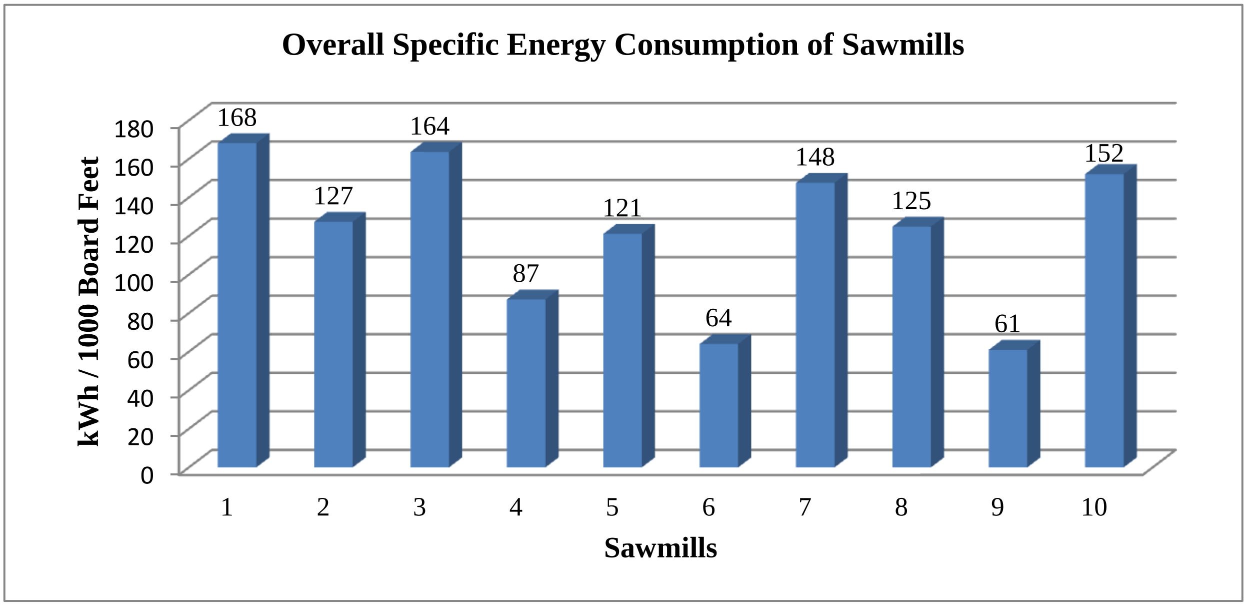


Figure 1.12: Overall Specific Energy Consumption of Sawmills

From the Figure 1.12, it can be seen that overall SEC of sawmills vary considerably. Comparing overall SEC is not an accurate method since each sawmill produces different species and sizes of lumber in varying quantities. If one sawmill is sawing more denser species compared to another sawmill, then it will consume more energy for sawing same volume of lumber since specific cutting energy for denser wood species is higher than less denser species as shown in Table 1.1 (Williston 1988 Chapter 25). Specific cutting energy is defined as the horsepower required to remove one cubic foot of wood per minute.

Table 1.1: Specific Cutting Energy for Hardwoods and Softwoods (Williston 1988 Chap. 25)

Wood Type	Species Name	Specific Cutting Energy*	Specific Gravity (no units)
Hardwoods	Hickory or Pecan	32.6	0.61
	White Oak	29.1	0.59
	Cottonwood	14.6	0.33
Softwoods	Southern Pine	24.7	0.43
	Hemlock	18.3	0.41

***C = Specific cutting energy (hp / ft3 / min)**

Lumber is sawn in different sizes based on its end use. Typically lumber is sawn in three different size ranges; board, dimension or cant and timbers. Lumber in board size are less than 2 inches thick, dimension size are between 2 and 5 inches thick and timbers size are greater than 5 inches thick. As the size indicates, less board feet will be present in a board size lumber than a dimension lumber or a timber for a piece of same width and length, but the amount of work involved to saw a board lumber is almost equal to the work for sawing a dimension lumber or timber. Hence if a sawmill is producing more of board size lumber, then it will consume more energy for sawing same volume of lumber than a sawmill producing more of dimension lumber or timbers. Hence, a method is required to calculate the SEC for sawing a particular size lumber of a particular species since more than one lumber size is sawn in the same shift. Once the method is developed, best achievable SEC can be calculated for different species and sizes sawn.

Also, it is important to know why the SEC of one sawmill is higher than the best achievable SEC since knowing this will help the sawmill to improve its energy efficiency. This can be known by studying a sawmill from the view point of productivity since energy efficiency also represents production efficiency to some extent. Also, SEC of a particular species and size sawn will help the sawmill industry to price its product based on the energy costs associated with sawing that particular type of product.

Production and energy consumption data must be collected to develop SEC for sawing of different species and sizes of lumber and calculating best achievable energy consumption from it. Data cannot be collected from every sawmill to calculate SEC and hence there should be a way to estimate the SEC for the sawmills where data cannot be collected. An estimation model based on product, process and system parameters of the sawmill must be developed to estimate SEC using the knowledge obtained from collected data.

Product, Process and System Parameters

The main product parameters will be the type of wood species sawn and the board feet of different size lumber sawn. There were 10 different species that were sawn during the study and the density of these species can be considered as one of the variable to estimate the energy consumption. There are around 7 lumber sizes that were sawn in the sawmills during this study and the board feet sawn of each size can be considered as a variable.

The main process parameter will be the sawing time since it drives the production rate and hence it affects the sawing energy consumption. Other process parameters that can be considered are temperature and moisture content of the wooden logs and literature must be studied to find out the effect of these parameters on the sawing energy consumption and also collected data must be analyzed to find out the effect of these parameters.

The main system parameter will be the motor horsepower of the equipment used for sawing process. Each sawmill has different total motor horsepower and produce different production quantities and hence there is a direct relationship between the energy consumed for sawing and motor horsepower used for it. Also, type of equipment used for sawing and the line configuration employed can affect the energy consumption. The effect of type of equipment must be studied from the literature and also from the collected data. Other relevant product, process and system parameters must be considered after analyzing the data of the five sawmills.

Sawmill Energy Estimation Program (SMEEP) that can estimate the SEC, total energy consumption and SEC of individual sizes of the species sawn based on the product, process and system parameters must be developed. The developed SEC must be compared and analyzed with the best achievable SEC. Reasons for the higher or lower value of SEC of particular sawmill must be found using the knowledge learnt from the data collected sawmills. Methods that can be used to improve productivity and efficiency of the new sawmill with estimated savings must be suggested to make more sense for the analysis. The SMEEP will help the sawmill owners to know their level of performance and the opportunities to improve.

1.6 Research Objectives and Scope

The objectives of this research are:

1. Develop a method to allocate energy consumption based on effect of lumber sizes sawn on energy consumption and calculate SEC for sawing different species and sizes of 5 sawmills and compare them.
2. Develop and validate a model that can estimate sawing energy consumption based on product, process and system parameters and conduct sensitivity analysis.
3. Develop SMEEP that takes sawmill’s product, process and system parameters and calculates the sawing energy consumption and SEC of individual sizes, compares the calculated SEC with the best achievable SEC and analyzes the results.

Various steps of the research (Figure 1.13) are to collect data from the sawmills, analyze it to find the relation between lumber sizes sawn and energy consumption, develop a method to allocate energy based on lumber sizes sawn, calculate SEC for different sizes and species of lumber sawn and find the best achievable SEC, develop and validate a model to estimate energy consumption based on product, process and system parameters, and develop SMEEP (Figure 1.14) to calculate energy consumption and SEC for different sizes sawn and analyze the results.

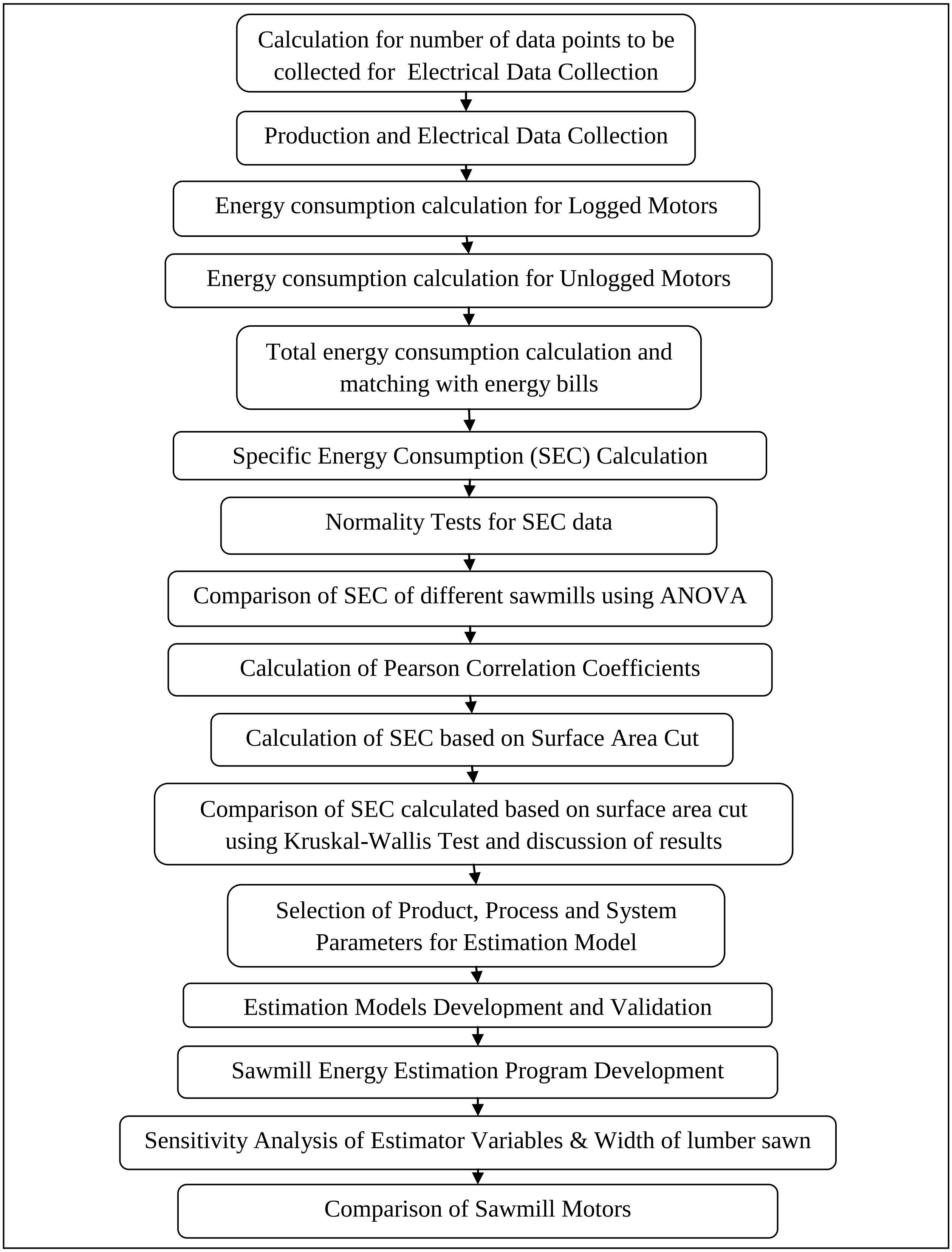


Figure 1.13.: Various Steps of the Research

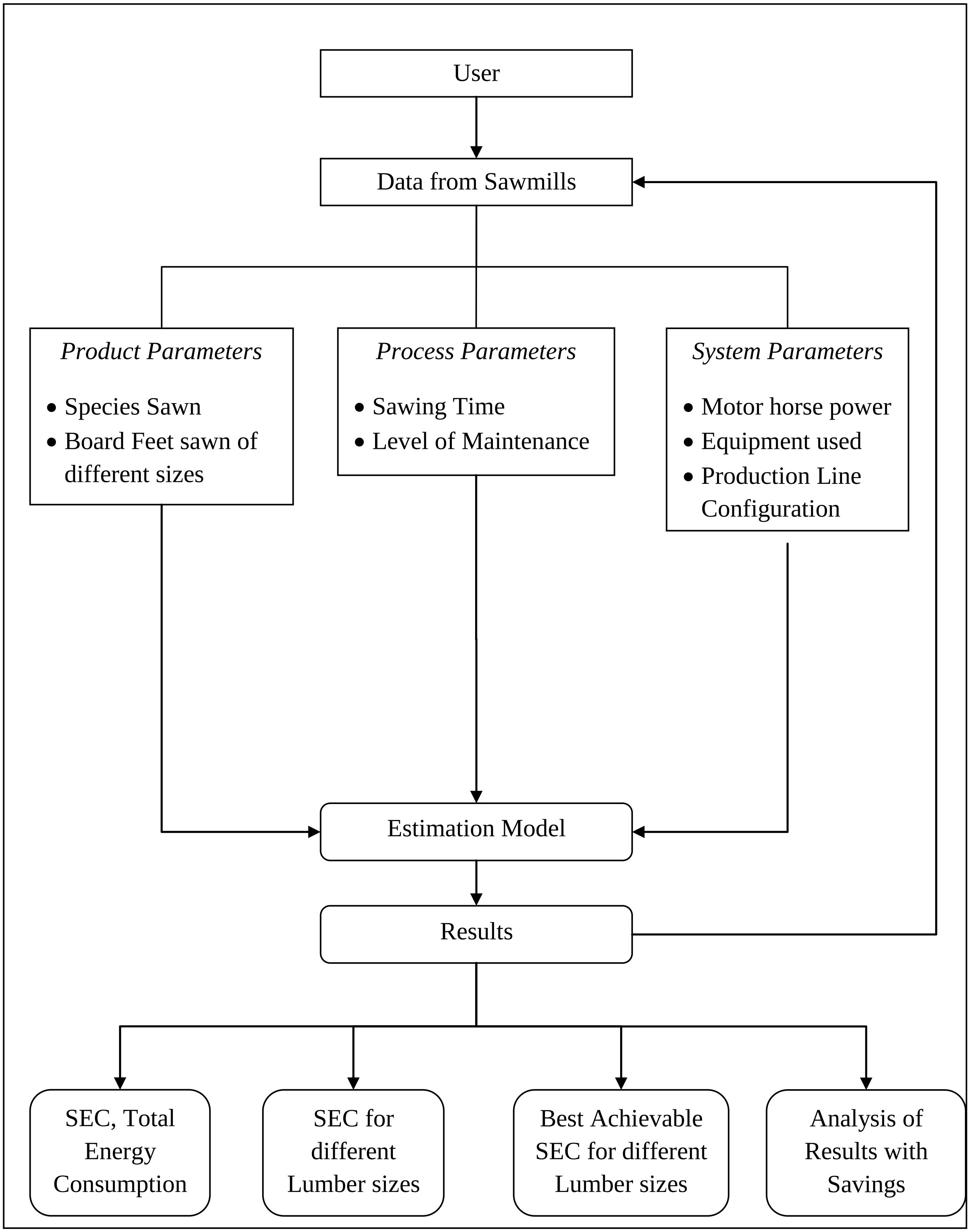


Figure 1.14: System Diagram of Sawmill Energy Estimation Program (SMEEP)

1.7 Introduction to Sawmills

A typical hardwood sawmill combines five main operations including log debarking, log sawing, flitch edging and trimming, and waste chipping (Figure 1.15). Most hardwood sawmills have similar designs in that they have multiple pieces of equipment that are being run by several large electric motors. The motor size of the de-barker, head saw, head saw carriage, re-saw, edger, trimmer, and chipper would typically be 100, 400, 200, 300, 100, 50, and 300 horsepower respectively. In addition each sawmill will have an air compressor that operates additional equipment throughout the facility and it would typically have power ranging from 100-300 horsepower. Smaller sawmills will usually have similar equipment but the power of the individual motors are typically smaller. Close to 90 percent of the electrical energy used in a typical sawmill will be consumed by motors alone (Lin et al. 2012).

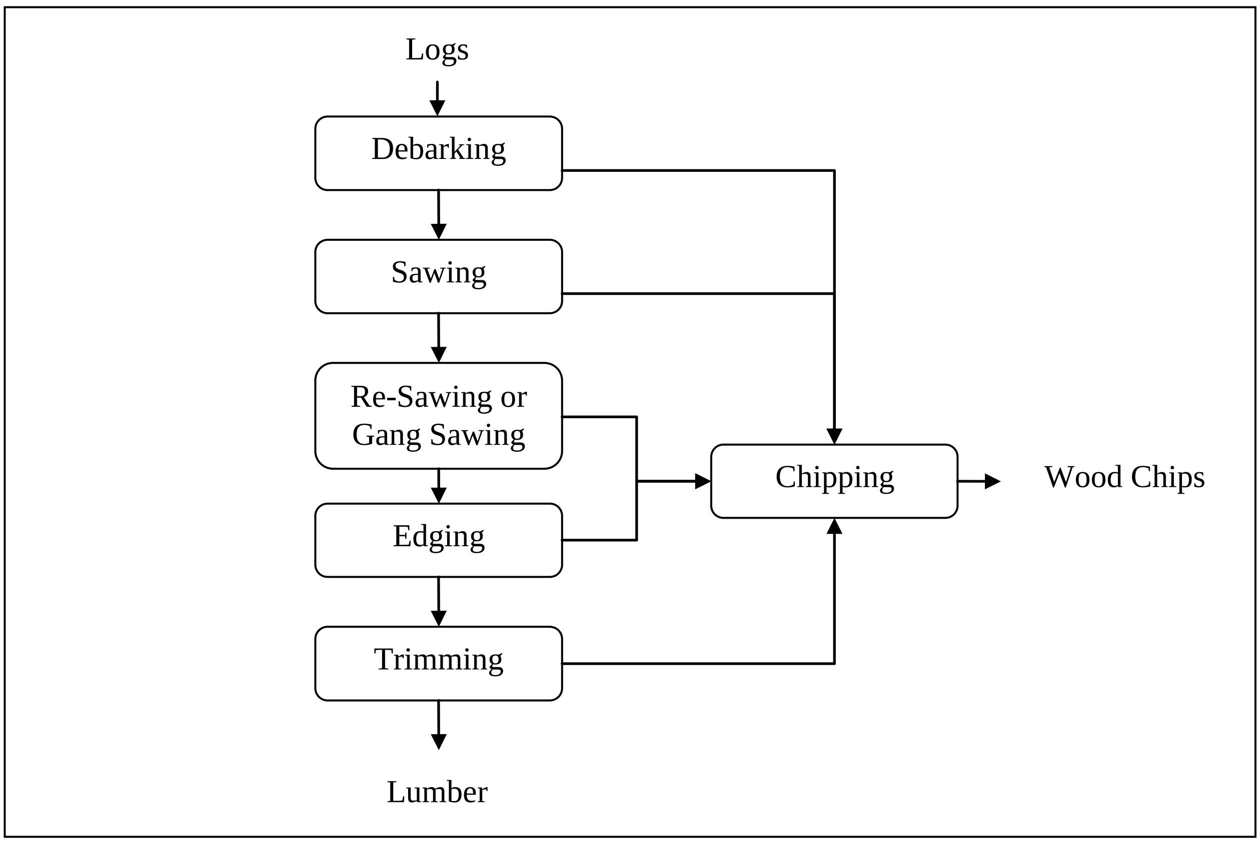


Figure 1.15: Typical Process Flow Diagram for a Hardwood Sawmill sawing operation

The principal product of sawmills is air or kiln dried lumber, which is mainly used by the construction and furniture industries.

Debarking

Debarking is the process of removing the bark from wooden logs. Extra care is taken to minimize the removal of wood from the logs while removing the bark (Denig 1993). The bark removed from the logs is used in pulp products industry for different applications. Bark is also chipped into small pieces to produce low-grade fuel. The main purpose of debarking operation is to reduce the damage from the logs to various sawmill cutting tools employed for sawing logs. Debarking is an essential step and is done at the initial phase of wood processing irrespective of the type of end-product being made from the wooden logs. The logs can be better inspected for their grade and inherent defects after debarking. The equipment used for the debarking operation is called as debarker. Different types of debarkers are cambio, ring, rosser-head, hydraulic - oscillating, ring type and drum type (Williston 1988 Chapter 6). Figure 1.16 shows a rosser-head type debarker.

Figure 1.16: Rosser-Head type Debarker

Sawing

Sawing is the process of cutting wooden logs into lumber and circular and band saws are the most commonly used sawing equipment. Debarked logs from the debarker are first sawn using a band saw or a circular saw into cants. A cant is a wooden log with rectangular cross section formed after removing the circular sides of the log. The equipment used for converting logs into cants is called as a head saw. At the head saw during sawing, the log is moved in a horizontal direction by a carriage and fed to the moving vertical saw blade (in the case of band saw). A circular saw or a band saw can be used for cutting the logs into cants and also cants into lumber (wooden boards). Circular saw blade has a limitation in its diameter to process logs larger than 60 inches in diameter (Williston 1988 Chapter 9). Another circular saw is added on the top instead of using a single saw of larger diameter for logs larger than 60 inches in diameter.

Figure 1.17: Band Saw (on the left) and Circular Saw (on the right)

Band saws can accommodate large-diameter logs very easily. The saw kerf (effective thickness of the blade) for a circular saw is more than the band saw. Therefore, less wood waste will be generated as saw dust by using a band saw instead of circular saw. Because of these advantages, band saws are preferred over circular saws irrespective of higher capital costs. Figure 1.17 shows a band saw and a circular saw.

Re-sawing / Gang Sawing

The cants are further sawn into boards using another band saw or a circular saw down the line. The saw used here is termed as re-saw. In re-saw, the cant is fed to the saw on a guided conveyor or a chain mechanism. Figure 1.18 shows a re-saw. Gang saw is similar to a re-saw in which the entire cant is sawn at once into many boards instead of one board every time as in a re-saw.

Figure 1.18: Re-saw

Edging

Edging is the process of cutting the rough edged wood pieces lengthwise into smooth edged pieces. The wooden boards with rough edges from the re-saw or head-saw are fed into the edger. The edger system will have 2 saws and a guiding mechanism. Circular saws are most commonly used for edging but band saws can also be used with comparatively thinner kerf. Wooden board is held by the guiding system and fed to the rotating saw. It is a best practice in sawmills to run the saw in the opposite direction to the material feed. This feeding direction minimizes any possibility of wood pieces and chips being propelled from the point of cut (Williston 1988 Chapter 11). Figure 1.19 shows an edger used in sawmills.

Figure 1.19: Edger (left) and Trimmer (right)

Trimming

The process of cutting the lumber across the width to form flat ends is known as trimming. The boards are fed from the edger to the trimmer. Trimmer will also have a saw, and a guiding mechanism like edger. Trimmers will be of single or double saw type. In the case of a single saw type trimmer, the wooden board will be fed again to the trim saw in order to trim the other end, which is not the case in a double trim saw where the board is fed only once and both the ends will be trimmed together (Williston 1988 Chapter 12). Figure 1.19 shows a typical trimmer used in sawmills.

Chipping

Sawmills also produce a valuable byproduct in the form of wood chips along with lumber. Wood chips will be usually made from the wood waste obtained from different woodworking processes and occasionally made from wood logs that are not of adequate quality to be processed into lumber. Bark from the debarking process, edges and end pieces from the edging and trimming processes, and wood slabs from the head saws and re-saws are used as a raw material for making chips. Various wood chip sizes are made based on the end use. Chipper is the name of the equipment used to produce chips. Drum and disc type are the two common types of chippers. Wood waste from different sawmill processes, is fed to the chipper using a vibrating conveyor. The chips produced are usually used as a fuel in the plant boiler for generating steam used in lumber drying process or sold in the market. In the case of disc chippers, wood pieces are cut into the desired chip size using knives mounted on the rotating disc of the chipper (Williston 1988 Chapter 20). Figure 1.20 shows a disc chipper used in sawmills.

Figure 1.20: Disc Chipper

Conclusion

Increase in energy costs and reduction in lumber prices are affecting sawmills and sawmill owners are looking for ways to become more productive to compensate for these costs. Sawmill owners can become more productive by benchmarking themselves with better sawmills and there is a need for developing a tool to do benchmarking. Comparing sawmills overall SEC will not give clear picture of sawmill’s performance since the variability of density and size can affect this comparison to a great extent. Hence a method is required to calculate the SEC for sawing a particular size lumber of a particular species and then that can be used for comparison. Also, for a sawmill where electrical data cannot be monitored, an estimation model is required to estimate energy consumption. Along with comparing SEC's between sawmills, manufacturing processes must be compared from the view point of productivity to know about the reasons for inefficiencies in productivity and energy efficiency. Once the sawmill owners know the inefficiencies of their processes, it can help them to make changes to save energy and improve productivity.

2. Literature Survey

2.1 Energy Efficiency Initiatives in Sawmills

Several energy efficiency initiatives have been taken by the U.S. Department of Energy (USDOE BP) as best practices, which were developed through funded research for different industrial sectors. Research is conducted by several other organizations to help the sawmill industry to save energy. The discussion of such few initiatives is given here.

Wengert and Meyer have reported more than 75 economical ways to reduce energy consumption and electric bills to save money without affecting production (Wengert 1992). They have highlighted the importance of understanding the electric utility billing system and its components to help reduce energy costs. The author advices sawmill to get benefit from the free energy audits provided by the utility companies. The article provides a detailed list of recommendations on ways to save energy on all the major energy-consuming areas like lighting, electrical motors, compressors, sawing, boilers, kilns, and HVAC systems. The article mainly stresses that energy audit is the first step for saving energy in sawmills. Some of the important recommendations provided in the article are proper sizing of the electrical motors, using capacitors on motors, reducing electrical demand, shutting off idling motors, using cogeneration to generate in-house electricity, using efficient lighting systems, maintaining teeth of saw blades, boiler burners, monitoring air to fuel ratio of burners, using thinner kerf on saw blades, defrost frozen logs, using air drying before using kiln drying to dry lumber, insulating kiln surfaces, and the use of radiant heaters instead of convection heaters for comfort heating.

Lin conducted a survey to study the profile of Appalachian Sawmills in 2010 (Lin et. al. 2012). Survey was mailed to 776 hardwood sawmills in the Appalachian region that were selected as the sample population. Out of 238 responses received, 58 surveys were usable.

Electricity was the main energy resource used in the surveyed sawmills and very few used natural gas. Average electricity consumption per month per mill was 107,007 kWh, and the average electric bill was $9,278/month. The average electric cost rate was $0.0867/kWh. The electricity consumption ranged from 31 kWh per thousand board feet (MBF) to 588 kWh/MBF and averaged 220 kWh/MBF based on lumber production volume. The electricity cost ranged from $2 to $41.67 per MBF with an average of $17.78/MBF.

Also, Lin summarized the sawmill audits done between 2001 and 2010 by Industrial Assessment Center of West Virginia University in the state of West Virginia (Lin et. al. 2012). The author has information of 17 sawmills and has compared their overall costs of production as well as the ways they could use to increase efficiency. Annual lumber production averaged at 55,444 MBF per sawmill and average energy use was 2,782,659 kWh per mill. Recommendations given by audit team can save approximately 275,110 kWh of electricity/year (14 percent of the annual energy used calculated from % savings of each sawmill) per mill or 4,676,873 kWh for all the mills and total cost savings of $464,995 per year for all the mills. Likewise, the conservation procedures recommended could save the audited mills an average of 587,045 pounds of carbon dioxide emissions per year. The energy saving recommendations given was mainly for lighting, compressor and motor systems.

Bond discusses the increase of natural gas and electrical energy prices and increase of stumpage prices and mentions that sawmill owners are looking for ways to reduce costs (Bond 2008). He further discusses that for a sawmill with kiln-drying operation, thermal energy is the largest part of the energy consumption and one way to dramatically reduce energy in drying is to practice air-drying. Also the author discusses about importance that sawing accuracy has on energy usage during the drying process and variable speed fans can save up to 50% in electric energy use with a 20% reduction in fan speed once moisture content drops below 30%. The author also discusses about importance of free energy assessments by DOE that can save 10 to 15% of energy.

2.2 Energy Efficiency Initiatives in Specific Energy Systems

Northwest Energy Efficiency Alliance has reported a case study on using motor management program by Crown Pacific Lumber to make decisions about the maintenance of the electrical motors (CPL 2001). Crown Pacific Lumber acquired Gilchrist Mill which was an old sawmill facility with over 300 working motors on the process line. The facility's electrical superintendent with the help of a consulting engineer used a motor management program to build inventory of the electrical motors in the plant in 2001. The required information was obtained from the motor nameplate and maintenance history of the motors. The developed inventory was used to make decisions for replacing or rewinding a failed motor, replace a existing motor with an energy efficient motor etc., Replacing an existing 89%-efficient motor with a new 96%-efficient motor, saved on average $3,400 annually per motor with a simple payback of 1.8 years. The company also used data loggers to measure the amperage drawn by the motors over a period of time. Load profiles were developed from the logged data and were used to make decisions regarding proper sizing of the motors. The study revealed that the motors were oversized in most cases and were designed as per the production requirements at the starting of the old mill when the production requirements were different. The facility was able to replace its old, oversized, inefficient motors with new, energy-efficient motors with a payback of less than two years.

Frequency variable drives are common in industrial fans and pumps where the load on the motor varies over time. Research has been done to find out the advantages and disadvantages of a frequency variable drive for the electric motor of a bandsaw (Fenart 2000). This study was carried out in France with beech and oak logs to investigate the effects on productivity, sawing precision, sawing time, and electricity use. Sawing precision and sawing time were not affected, while electricity consumption of the bandsaw with a frequency variable drive decreased by 65%. Payback period for the investment cost of the frequency variable drive was estimated to be within 3 years.

Compressed air systems are found throughout sawmill industry and account for a significant amount of electricity consumed. Applying a system-level strategy to optimize a compressed air system can improve system performance, production and save energy. A case study done by US DOE discusses the use of AIRMaster+ to optimize the compressor performance in a sawmill (DOE 2004). Compressed air was used for air-operated cylinders and various pneumatic tools, and it was particularly critical for proper operation of the quad that saws the logs. The quad uses compressed air to precisely place the logs, and if the compressor pressure goes down, logs get stuck in the quad. To clear the jam, mill personnel had to shut off the quad and cut the logs with chainsaws to remove them. This resulted in production downtime and higher labor costs. It also caused product waste because the jammed logs were unusable. Location of the compressors coupled with the manual control scheme and convoluted piping led to severe pressure fluctuations of 30 psi, (from 65 to 95 psig) that hindered production. To maintain the needed pressure, the mill had tried operating all compressors simultaneously, but that only generated excess air and wasted energy. AIRMaster+ best practice tool was used to analyze the compressed air system. As per the analysis, the sawmill upgraded the compressor controls, stabilized the pressure level, repaired leaks and installed pressure/flow controller with 2,500 gallons of additional storage capacity with the air treatment equipment. The performance of the compressed air system improved substantially after the mill implemented this system-level project. Once these devices were in place, the baseline measurements were retaken and the system pressure was lowered from 95 to 85 psig and a reduction of the flow rate from 2,000-2,300 scfm to 1,750 scfm. The mill was able to satisfy its compressed air demand by just baseloading the 300-hp compressor and operating the 200-hp unit in load/unload mode and keeping the 150-hp unit as a backup compressor. The project yielded annual compressed air energy cost savings of $55,000, with a simple payback of 1 year. In addition, the project served as a blueprint for successful projects at six other company facilities. The aggregate energy savings and energy cost savings resulted from these six facilities' projects were 6.8 million kWh and $250,000.

2.3 Study on Sawmill Energy Consumption and Energy Initiatives through Surveys

A survey (Milota et al. 2005) on life cycle inventory of softwood lumber production in the four western mills and four southern mills was conducted during 1999 and 2000. For western production, the survey was for dimension lumber produced in the states of Oregon, Washington and west of the Cascade Mountains. For southern production, the survey region was the states of Georgia, Alabama, Mississippi, and Louisiana. The primary data in the western survey indicated that 78.1% of the planed, dry lumber produced was Western Hemlock and 21.9% was Douglas-fir. The primary data in the southern survey indicated that planed dry southern pine accounts for nearly all dimension lumber production. This research mainly discusses about the energy used for production of planed dry lumber and CO_2 emissions. Research estimated the SEC for sawing softwood lumber as 67.9 kWh per MBF for 4 sawmills of the southern region and 86.8 kWh per MBF for 4 sawmills of the western region. The conclusion of the research was that even though the electrical energy accounts for major share in sawing, maximum amount of energy consumption and CO_2 emissions was from drying process.

Another study (Bergman & Bowe 2008) was done through survey of 20 sawmills across 20 states in the northeastern region of the United States. The survey indicated that the thermal energy required to produce lumber was generated onsite whereas electrical energy was from both onsite and offsite sources. Based on the results presented in this paper, 274 kWh (608 MJ/m^3, 1 kWh = 3.6 MJ & 1 nominal MBF = 1.623 m^3) of electrical energy and 5.5 MMBtu (5,800 MJ/ m^3, 1 MMBtu = 1,054 MJ) of thermal energy were spent to produce one MBF of planed dry lumber in these mills. The unit processes (sawing, drying, energy generation (boiler operation), and planing) consumed 50, 25, 5, and 20% of the total electrical energy respectively. Based on these percentages, the four unit processes used 137, 68.5, 14, and 54.5 kWh of electrical energy to produce one MBF of planed dry lumber. For hardwood species, 269 kWh and for softwood species 151 kWh of electrical energy were spent to produce one MBF of planed dry lumber in these mills. This research also found that the energy spent widely varies with type of wood species sawn, age of equipment, and drying methods.

A survey was conducted on 188 sawmills in eastern US primary hardwood products manufacturers in 2010 (Espinoza 2011) to find out the impact of high energy costs on wood products manufacturer's profitability and the actions taken by them to respond to energy related challenges. Results show that overall, the share of energy expenses on total production costs of respondents was 7.9%. A majority of respondents (61.8%) agreed that their energy expenses have increased by an average of 18.7% during the last five years. Half of the respondents reported a 5% or higher negative impact of higher energy prices on their profits over the same period. Most companies (63 percent) indicated that they are focusing on improving energy efficiency and/or improving productivity (41.3 and 41.9% respectively) to cope up with the rising energy prices. Around 8.6% of the companies indicated that they have established energy usage baselines and energy performance indicators which helps them to monitor their progress. 67% of the companies indicated that they are training employees on energy saving issues. The most common efficiency measures that were undertaken by the companies were using more efficient lighting, upgrading equipment with energy efficient equipment, and taking measures to minimize wastage of energy.

2.4 Comparison of Sawing Equipment

A bandsaw and a circular saw were compared in a small sawmill in Sweden (Uppgård 1995). The advantages of the bandsaw were that it had higher yield due to small kerf width, could easily handle larger logs, had a short changeover time and consumed less power. The advantages of the circular saw were that it was rugged and was able to saw dense woods easily, had easier blade alignment and needed less frequent manual handling since saw blade didn't required dismantling of the saw for maintenance.

Spinelli conducted a comparison study on two commercial chipper models, a disc and a drum chipper (Spinelli 2013). The effect of chipper type on productivity, power demand, fuel consumption and product quality were studied. Both the chippers had the same diameter capacity, same energy source (farm tractor of 100 kW output) and fed with the same feedstock types. Fifteen replications were conducted per machine for each of the four different feedstock types, resulting in a total of 120 tests. The disc chipper had a higher energy efficiency than the drum chipper and used 19% less fuel per unit product, The reason for this is possibly due to the simpler design of the disc chipper integrating comminuting and discharge system in one synergic device. Drum chipper was 8% more productive (difference was not statistically significant at 5% level), since it cut with the same energy all along the length of its knives. The drum chipper produced smaller chips, with a higher incidence of fines.

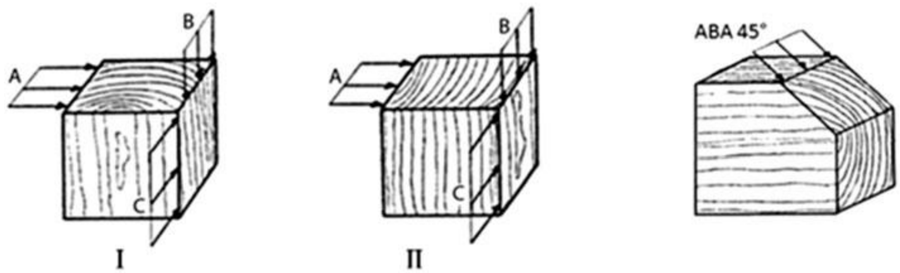
2.5 Research done to Predict Sawing Cutting Forces under various Cutting Conditions

A research (Iris et. al. 2006) was conducted to find the cutting forces for tension, normal and frozen wood of maple in band sawing. This research measured cutting forces for frozen green wood, green and dry normal wood, and green and dry tension wood of sugar maple and red maple. An ice block was cut to compare the magnitude of its cutting forces with those obtained from frozen wood. Tension wood was obtained from leaning trees. Cutting force measures energy to sever a single chip. Three tooth designs of Stellite tips with different rake angles were tested. Saw teeth with larger rake angles required less energy to cut green and dry wood. The tooth with the largest rake angle required the least energy to cut dry and frozen wood, and also performed well when cutting green wood. Specific cutting force for frozen wood was nearly as great as for dry wood; specific cutting force was least for green wood. Increased cutting forces for frozen wood were due to cutting frozen cell walls, because ice alone requires little force to machine. Specific cutting force was less for tension wood than for normal wood. The results for tension wood are apparently due to thinner fiber cell walls and the amount and type of lignin present in tension wood fibers. As expected, green wood registered the lowest principal cutting force, followed by frozen wood. Dry wood generated the greatest value of cutting force but the differences between frozen and dry wood were not significant for sugar maple while for red maple they were significant.

A research (Mihai 2008) was performed in order to establish if the properties of frozen Spruce and Oak wood (in winter) are different from those of unfrozen timber with regard to its processing. Spruce timber specimens, cut from the same log, half of them frozen at –30^{o}C and half left unfrozen, were sawn under absolutely identical conditions (same machine, same tool, same devices and same cutting conditions), in order to determine comparatively the energy consumptions involved in the two cases. Only free water freezes in wood if the temperature does not drop below –30°C. The results revealed that freezing results in a significant decrease of the necessary power for cutting due to lowering of the mechanical strengths of wood. The explanation given was the transformation of liquid water into ice inside the cell lumen develops a certain pressure upon the cell walls; it can be assumed that the generated mechanical energy is capable of breaking some bonds between the bound water molecules and the wooden substance, "squeezing" out a certain amount of water from the cell walls and re-locating it into the cell lumen; due to this compressive stress exerted by the expansion of liquid water into the lumen, it is most likely that certain micro-fissures occur within the cell wall structure, thus diminishing the mechanical properties of wood. Other interesting fact from this paper was about the benefits of freezing for drying lumber. Freezing is a successful pre-treatment method for the drying of both hardwoods and softwoods from temperate and tropical regions, with a view to reducing shrinkage, collapse and warp, simultaneously with decreasing the drying time. Repeated cycles of freezing followed-up by thawing makes it possible to remove free water from wood with minimum energy supply.

The author of above paper mentions that the different results obtained in their study compared to the previous studies might be due to the different cutting conditions, especially the much smaller cutting height and the use of different tool. To this end, an important element noticed and emphasized by all previous authors refers to the high quantity of sawdust generated during the cutting of frozen logs, which gets stuck on the lateral kerf walls thus increasing the friction forces between the blade and the kerf walls. As a consequence, the active power consumption increases. On the other hand, the present research was performed with circular blades, and more important, at much lower cutting height, so that the chip and sawdust evacuation was easily achieved and constituted no significant influence factor upon the active power consumption.

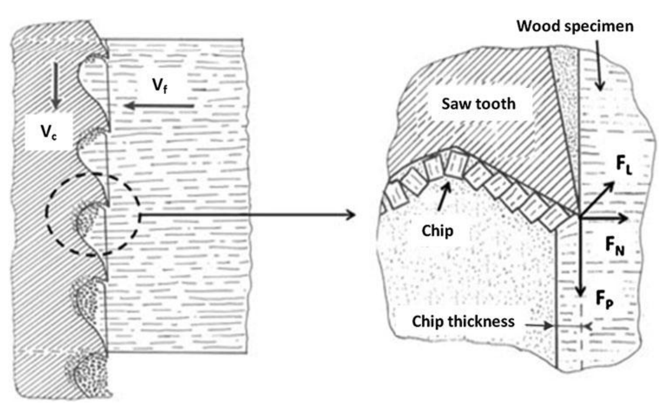
Payam conducted research to investigate the effect of wood moisture content (MC) and cutting directions on the cutting forces in bandsaw processing of oak and beech wood (Payam 2013). Cutting forces in bandsaw processing of oak and beech wood were measured at two levels (about 12 % and Fiber saturation point, MC = 30 %) of wood moisture content for four cutting directions (90^o –90^o, 90^o – 0^o, 0^o – 90^o and 90^o – 45^o) (Figure 2.1).



Mode A = cutting direction 90^o–90^o, mode B = cutting direction 90^o–0^o, mode C = cutting direction 0^o–90^o, mode ABA 45^o = cutting direction 90^o –45^o.

Figure 2.1: Definition of Cutting Directions (Kivimaa 1950)

A constant cutting speed of 40 m/s and a feed rate of 20 m/min were applied. A piezoelectric dynamometer (KISTLER type 9257A) mounted on the carriage of the vertical bandsaw machine (ESTERER model EB 1400) was used to measure the parallel (main), normal and lateral cutting forces (Figure 2.2).



V_c = Cutting speed, V_f = Feed rate, F_P = Parallel Force, F_N = Normal Force, F_L = Lateral Force

Figure 2.2: Cutting Force Components for Wood Band Sawing (Dalois 1990)

Overall, the cutting forces were found to be moisture and cutting direction dependent. All cutting forces decreased by increasing the wood moisture content from about 12 % to Fiber Saturation Point (FSP). The greatest parallel force was observed for oak wood at 12 % MC for $90^{o} – 90^{o}$ cutting direction (44 N/mm) whereas the lowest one was for beech wood at 30 % MC for $0^{o} – 90^{o}$ cutting direction (20 N/mm). In contrast to the little change of lateral force at various cutting directions, the change in parallel force was significant. For both wood species, the normal force was less for green wood compared to dry wood except in $0^{o} – 90^{o}$ cutting direction. Sawing dry wood needs more cutting force than green wood since the dried wood fiber will be hard compared to moist wood fiber. Also, addition or removal of water below the FSP has a pronounced effect on practically all wood properties but addition or removal of water above the FSP has no effect on any wood properties (Matan 2003). Moisture content of the wood sawn in the sawmills will be above FSP.

In Canada, as well as in any northern country producing paper and lumber, debarking of wood logs during the winter months is a source of concern. The colder the logs, the greater the debarking problems are due to stronger bark cohesion and higher wood adhesion. This leads to log volume losses, left-out bark on logs after debarking, and bark content in wood chips. This in turn results in accelerated wear of tool tips, increase in loss of wood chips and reduction in yield of lumber. More importantly, high bark particle content in the chips may lead to rejection of the chips by the pulp mill. It is, therefore, beneficial to raise the temperature of the log prior to debarking. In the past, sawmills used to thaw logs by soaking them in water of 8^{o}C temperature for 20 minutes, but most have stopped this practice due to new environmental regulations that increase water treatment costs. The goal of the project described in this paper (Normand 2009) was to demonstrate, on a semi-industrial prototype, the applicability of using infrared radiation to preheat black spruce logs. The main objectives were to evaluate specific energy consumption and the profitability of the technology. Heating logs before debarking to reach cambium temperature of -10^{o}C to -5^{o}C in the winter could generate an estimated savings of up to half a million Canadian dollars for a sawmill processing half a million cubic meters of wood annually. If all of the economic considerations of bark content in woodchips for the pulp and papermill are considered, the return on investment of an infrared system to preheat frozen logs is believed to be less than one year.

In wood machining, there are three different approaches used to model the main cutting force (Cristóvão 2013). The first approach is based on specific cutting resistance, second approach is based on modern fracture mechanics and third one is based on predictive models using multivariate methods such as multiple linear regression and partial least squares regression. Here, cutting force prediction based on multivariate methods are discussed since the current research is also related to developing of a multivariate estimation model.

Knowledge of the effect of wood cutting parameters on power consumption could increase energy efficiency, reduce operating costs and increase profitability. Measuring power consumption also provides information about other variables, such as tool edge wear, occurrence of catastrophic failures, and other parameters that affect the quality of the sawn boards. In this work, (Cristóvão 2013) power consumption during sawing of Scots Pine using a double arbor circular saw was investigated. The tests were performed in the second saw for resawing (resaw). Both climb-sawing and counter-sawing were considered. Climb-sawing is sawing in the direction of the feed and counter-sawing is sawing in the direction opposite to feeding. The experiments were carried out under normal production conditions in two Swedish sawmills. Theoretical and actual power consumptions were compared. The relationship between cutting parameters and theoretical power consumption was developed according to the general laws (Power = force x velocity) with an additional term describing the energy needed for the chip acceleration as described by Koch (1964) and Orlowski *et al.* (2013).

$$P_i = F_{pi} * v_i + \frac{H * k * S * d * v_i^2}{2}$$

Where,

F_{pi}	=	main cutting force (N)
v_i	=	is the cutting speed (m/s)
H	=	depth of the cut (mm)
k	=	saw kerf width (mm)
S	=	feed speed (m/min)
d	=	wood density (kg/m3)
v_i	=	is the cutting speed (m/s)

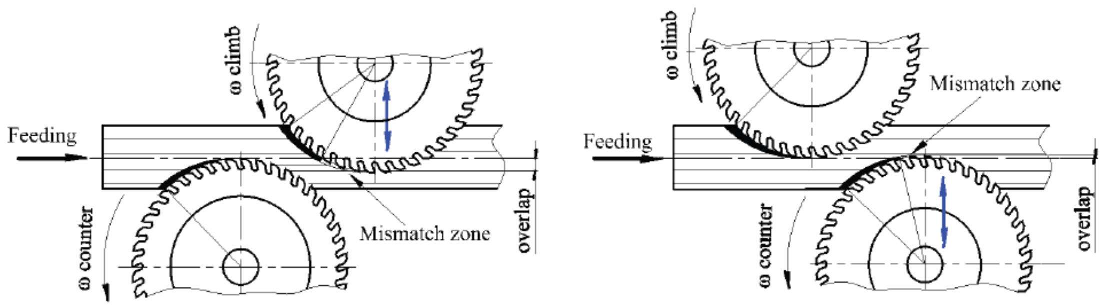
F_{pi} was investigated using the model proposed by Axelsson *et al*. (1993) as shown below.

$$F_{pi} = -7.37 + \delta_m * (0.38 * d8 - 224.5 * \alpha) + 15.61 * KH - 2.6 * KH^3 + 1.31 * r + 0.2 * v_i + U * (0.3 * KH - 0.01 * T)$$

Where,

δ_m	=	average chip thickness (mm)
d8	=	average density at 8% of moisture content (kg/m3),
α	=	rake angle (radian)
KH	=	angle between the cutting speed vector and the wood grain (radian)
r	=	edge radius (μm)
v_i	=	is the cutting speed (m/s)
U	=	moisture content (%)
T	=	temperature (°C)

The experimental power consumption increased by 11 to 35% during an 8-hour shift, mainly due to an increase in the tooth radius of the cutter. Based on experience, the tooth edge radius was estimated to be 5 μm at the beginning and 50 μm at the end of the test. The predicted model showed lower power consumption than the experimental. The differences between the predicted and experimental results might be due to the presence of wiper slots on circular saws, back sawing, motor efficiency, and other losses between the interaction of the cutting tool and work piece, which were not considered in the theoretical model. Additionally, this study showed that climb-sawing consumed more power than counter-sawing. The difference between climb-sawing and counter-sawing was more pronounced in sawmill B. Surprisingly, the theoretical and experimental power consumption data converged with an increase of cutting tool edge radius. The power consumption was higher in sawmill B than in sawmill A due to a high saw kerf width, cant height, high mismatch, and low overlap between saw blades (Figure 2.3).



(a) (Cristóvão 2013) (b) (Cristóvão 2013)

Figure 2.3: Mismatch Zone and Overlap between Saw Blades: (a) Sawmill A, (b) Sawmill B

Determination of cutting parameters is required to optimize cutting processes, machines and tools in the cutting operations. This determination would enable the forestry and wood sector to achieve higher productivity and efficiency. Samples of a lesser-known wood species ‘ntholo’ and a well-known wood species ‘ironwood’ were machined in a test apparatus (Cristovao 2012). The wood species selected were hard to cut. A standard single saw tooth mounted on a piezoelectric load cell was used to evaluate the main cutting force. Three levels of chip thickness, rake angle, edge radius, moisture content, and cutting directions were used for the experiment. The experimental set-up used response surface methodology for developing predictive models. The experiment clearly determined the relationship (R^2 = 0.89) between the main (parallel) cutting force and edge radius, wood density, rake angle, chip thickness, moisture content and cutting direction as shown.

$$F_{P\,Ntholo} = 1.94 - 0.04*\alpha + 0.21*r + 0.24*D + 0.66*t + 0.09*MC - 0.35*CD \;\; N\,mm^{-1}$$

$$F_{P\,Iron\,wood} = 2.23 - 0.1*\alpha + 0.21*r + 0.07*D + 0.77*t - 0.09*MC - 0.39*CD \;\; N\,mm^{-1}$$

Where,

α	=	rake angle, degrees
r	=	edge radius, μm
D	=	wood density, kg/m^3
t	=	chip thickness, mm
MC	=	moisture content, %
CD	=	cutting direction, radian

Among the studied variables, chip thickness, edge radius and cutting direction had the highest effect on the main cutting force level while wood density, moisture content and rake angle had the lowest effect. The conclusion was wood density alone is not a good estimator of main cutting force for the tested wood species, lower rake angle generates higher main cutting force for both species, main cutting force increases when the edge radius increases and when processing hard-to-cut woods it is necessary to use small chip thickness and use sharp edge radius to achieve low cutting force.

2.6 Energy Profiling, Data Logging and Energy Measurement Activities in Other Industries

Pawlik et al. in their article, ‘Analyzing Facility Energy Use: A Balancing Act’ discuss that while doing energy audit, it is important to know the energy usage of the main equipment in a particular facility. To focus on the equipment with most energy consumption, he says it is also important to know the proportion of the energy usage of particular equipment in a facility to the total energy consumption of that facility. He further says, developing energy profiles of all the equipment in a facility requires extensive data collection over a period of time which in not practical in all the cases and hence he provides a different approach to determine the energy usage of any equipment by using a system energy balance (Pawlik, et.al 2001).

Carole et al. in their article on ‘Energy efficiency and use in the chemical industry’ says chemical industry is very energy intensive and in some processes, energy for heat, power, and feedstocks can account for up to 85% of production costs and hence says energy efficiency is an important issue in chemical industry (Carole et.al 2001). The paper presents a summary of the energy profile in chemical industry and also refers to a study performed by the Office of Industrial Technologies (OIT) examining the energy and environmental profiling of the chemical industry. Six most energy-intensive chemical product chains, which account for more than 50 percent of the total chemical industry’s process energy, are considered in the analysis. The article provides data on process flows, feedstock, energy usage for different processes, air emissions and hazardous waste streams. The article also provides a comparison of the theoretical minimum energy usage with the actual energy consumption based on previous studies. The article also discusses about utilizing DOE BestPractice Software tools like MotorMaster+, Pump System Assessment Tool, Adjustable Speed Drive Master, Steam System Scoping Tool, AirMaster+ and 3Eplus.

Ramırez has developed a methodology to measure the energy efficiency in the Dutch food industry (Ramírez, C., 2006). The method involves a comparison between the actual energy usage for the annual production based on the energy bills and a baseline energy level. Author defines baseline energy as the energy usage when no energy efficiency improvements are made. Energy consumption per unit of product is calculated to make better comparison of energy efficiency. Author also mentions that energy policies are developed based on modeling incorporating the real-time indicators, such as the specific energy consumption. He concludes that energy efficiency indicators should be used to determine the trend of energy efficiency and says they should be based on the physical output.

Mozzo discusses about the importance of correctly setting the baseline for the energy projects in performance contracting business (Mozzo 2000). Performance contracting involves conducting energy audits and finding opportunities to save energy in a facility and also verifying the savings that will be generated from the implementation of those opportunities. The energy cost savings from the implementation of an opportunity serves as a source of funding for the suggested improvements. Hence, it is very important to set the existing energy usage level accurately for the particular system under study. After implementation the new energy consumption is measured and will be expected to be lower than the original consumption. The difference in these two levels of energy usage will be the energy savings and will depend on how accurate the baseline is set. Further, the author presents four types of methodologies to set a baseline: stipulation, standardization, manufacturer specifications, and actual measurements. Each of the methods has its own advantages and disadvantages. Author concludes saying setting a baseline from actual measurements requires extensive and accurate data collection with the help of reliable data monitoring equipment such as data loggers.

2.7 Developing Energy Profiles through Data Logging in Sawmills

There has been very little empirical work completed on the impacts of motor size, product characteristics and equipment configuration on production economics in hardwood sawmills.

A study (Li 2006) called 'energy demand in wood processing plants' was done in a sawmill in New Zealand. Energy consumption and production data were collected for a period of one year. Three electrical meters were used to record the energy consumption for every 30 minutes. Log dimensions and timber volume details were collected from the sawmill on a daily basis. From the results of this study, it was observed that the lumber production increased as the smaller thickness lumber processed was increased since drying thinner lumber boards was faster in the kiln. An empirical model of energy demand was developed based on data collected from one commercial operation. With lumber production and board thickness as input parameters, the model predicted that unit thermal energy demand to produce dried lumber is constant at 422 kWh/m³ regardless of lumber thickness. The unit electricity demand varied with the lumber thickness, increasing from 26 kWh/m3 for producing 20 mm lumber to 41 kWh/m³ for producing 50 mm lumber. The corresponding lumber production decreased from 357 to 202 tons/day. The ratio of electricity to thermal energy increased from 0.062 to 0.098 since the electricity consumption was not going down at the same ratio as the heat consumption. With 50% of the logs converted to dry timber, wood residues generated in the sawmill was more than enough to meet the energy demand in the forms of both heat and electricity.

Adams discusses about the usefulness of data logging equipment like power meters, to measure the power consumed by different equipment at sawmills (Adams 1982) and says, that research conducted with the help of wattmeter measurements can answer important questions like:

- Can the use of one type of equipment over another type of equipment reduce the energy consumption?
- What should be the typical energy usage of a mill designed for a specific operation?
- Will savings from the installation of capacitor banks for improving the power factor justify their implementation costs?
- What will be the difference in energy consumption for using a thin kerf saw versus a standard kerf saw in sawing logs?

Adams observed that wattmeter can be used to monitor most of the sawmill equipment that used three-wire and three-phase circuits. Adams states that power monitoring studies had no importance in the past due to low energy costs, but increase in energy costs has now made such studies inevitable and beneficial to energy users and concludes saying that knowing the energy usage for the different equipment used in sawmills will provide a better picture of the overall energy costs.

Poole in his article discusses about developing energy-load profiles for sawmills in the Amazon region (Poole and Pinheiro 2003). Author says development of equipment-load profiles can help to estimate the power and energy requirements of sawmills in the region, and hence can be used to identify any opportunities for onsite power generation using wood waste. The authors also felt that developing load profiles can help to identify a baseline for energy use by sawmills. Two sawmills were selected for their first visit. The instrumentation used was electrical sensors, data loggers, amperage meters, and necessary software. Five data loggers for measuring the AC current were used on major equipment motors with time interval set at 3 seconds for monitoring data. Amperage meters were used as a backup and also to validate measurement accuracy of loggers. Load profiles were generated for saws, chippers, and planers. The main findings were that sawing hardwoods influenced peak demand more than softwoods. The authors also thought that most of the electrical motors being used were inefficient and could be replaced with new energy efficient motors. The authors felt that there was an opportunity to use ‘disconnect controls’ on idling motors to reduce their energy consumption.

Garner discusses about the energy profiling and energy conservation for pulp, paper, and wood products industry in his article (Garner 2002). The article differentiates the pulp and paper industry from the wood products industry in terms of specific energy consumption. SEC for thermal processes, such as boilers and kilns used in sawmill is provided in the paper. Garner discusses about responsibility of the energy managers for energy conservation programs in some large facilities in the past. Garner believes that with proper instrumentation and control and energy monitoring, conservation practices are possible. In the end, the article lists tools like energy auditing, energy measurement and monitoring, and development of an energy balance for the system for achieving effective energy conservation and management.

Gopalakrishnan et al. in their article on energy efficiency measures in the wood manufacturing industry present an energy utilization profile for nine wood facilities (Gopalakrishnan 2005). The SEC of nine wood facilities was calculated by dividing the total kWh consumed by total board feet of lumber produced. Two of the facilities had kiln operation in addition to sawmill operation. The SEC of facilities that had only sawmills varied over a broad range of 93 to 404 kWh/MBF and in-depth analysis was not made to compare the SEC's of different sawmills. The possibility of the actual implementation of six prominent energy efficiency measures was discussed. The article also provides an electricity bill analysis for the nine facilities visited. Gopalakrishnan et al. discusses about the importance of the development and implementation of the EEMs to help reduce the energy costs in the wood industry.

Mardikar developed a model called "Baseline Electrical Energy Consumption in Wood Processing Sawmills". His work mainly involved calculating theoretical energy consumption for different sawmill equipment and calculating savings achievable for the motors of those equipment from implementation of standard motor 'energy conservation measures' (ECM's). Also the actual amperage consumption data for few hours (less than a day) was collected for these equipment from different sawmills and the actual energy consumption was calculated. Base line energy consumption was developed by subtracting savings achievable from ECM's from actual energy consumption for each equipment. Theoretical, baseline and actual energy consumptions were compared. Theoretical consumption was too low compared to actual consumption. Also, the actual consumption was calculated for only 3 species namely, red oak, white oak and maple and was not calculated for individual lumber sizes sawn. (Mardikar 2007).

Most of the work mentioned above provides gross estimates of energy use in hardwood sawmills and recommendations to save energy for a particular energy system. The prediction models developed were mainly for predicting the cutting forces for sawing under various cutting conditions and they don't deal with the energy consumption of a sawmill as a whole. There are no comparisons done between sawmills to find out which sawmill is more efficient and what are the reasons for that particular sawmill to be more efficient than other sawmills. No one has tried to find out the energy efficiency of a sawmill by looking at individual motor configuration, process and product characteristics and their relationships to energy usage. Hence, a through research is needed to find out the efficiency of the sawmill based on motor, process and product characteristics and finding ways to improve it.

Conclusion

Studies mentioned above have not dealt in detail to develop specific energy consumption profiles for each species and sizes sawn and also looked at sawmill from view point of productivity and hence, a thorough research is needed to address these things. This research will help the industry for bench marking and also the model that can estimate the energy consumption based on product, process and system parameters will greatly help the sawmill industry to known its level of performance and the opportunities to improve. Studying sawmill from productivity view point will identify opportunities to improve in terms of both productivity and energy efficiency. SMEEP that can estimate the energy consumption, compare it with the best achievable energy consumption and come up with methods to save energy and improve productivity with estimated savings can greatly help sawmill industry.

3. Data Collection

3.1 Need for Data Collection

As seen in the literature review, research done so far has used the total energy consumption directly from the energy bills to calculate specific energy consumption. Total energy bills will have energy consumption of sawmill motors along with energy consumption of other things like HVAC, lighting, kiln motors if they have kilns and any other equipment that is not directly used for sawing logs. Hence, using energy bills is not an accurate way to calculate SEC. Also, energy bills give energy consumption for entire month and this consumption cannot be used to calculate SEC of individual species and sizes that will be sawn in different production shifts throughout the month.

Hence electrical energy consumption data of major equipment that are used for sawing logs along with the production data must be collected during the production of a particular species of lumber to find out the SEC of that particular species more accurately. Once the data is collected, further processing can be done to calculate SEC for particular sizes sawn and then to find out the best achievable SEC. Data collection of species sawn, sawing time, quantity of lumber sawn of different sizes, horse power of motors used for sawing and electrical energy consumption is required to develop the model that can estimate energy consumption of sawing process. This model can be used to estimate energy consumption of a new sawmill.

Three sawmills with single sawing line and two sawmills with double sawing lines were selected in state of West Virginia to do data collection. Three medium sized sawmills (weekly production between 40 to 200 MBF, Lin et al. 2012) and two large sized sawmills (weekly production > 200 MBF) were selected to get a good mix of different production sizes.

3.2 Data Collection Plan

Visits to five sawmill facilities with varying production capacities were made on two days. First day activity in each sawmill began with discussions with the plant manager about the facilities manufacturing process and energy usage. After listing the types of products being made at the facility, a brief outline of the manufacturing process was developed. Information was gathered about the types of wood species processed at the facility. Further discussions focused upon the major energy consuming equipment used at the facility. Data collection questionnaire prepared prior to the visits was given to the plant manager to collect production data. The plant manager then gave a detailed tour of the facility. A detailed equipment list was generated and necessary digital images and videos of the process were taken. Major energy consuming equipment was then short-listed based on its rated capacity. The second half of the day was used for data collection activities using an advanced electrical data collection device and installing data loggers on major energy consuming equipment. One month after deploying the loggers, one more visit was made to each sawmill to collect the data loggers. Data collected from the loggers was downloaded and the production data was obtained and discussed with the plant manager.

3.3 Electrical Data Collection

Electric panels in each sawmills were accessed with the help of plant electrician to monitor electrical energy consumption. During the original visit to each mill, Energy, Current, Voltage and Power factor data were collected using an advanced electrical data collection device (AMPROBE) for approximately 20 minutes on each motor. This was done to measure the power factor for each of the motors and to have baseline data so that the results could be compared with those from the continuous monitoring equipment. Power factor measures the ratio of real power to the apparent power and is critical for calculating power consumption of the induction motor.

Data Sample Size

Before staring the discussion on how to use the data loggers for electrical data collection, it is important to know how many motors should be logged and the duration of data collection for a particular motor.

Number of Motors to be Logged

Any sawmill facility has the basic set of main equipment that uses electrical motors, such as the debarker, head saw, re-saw, edger, trimmer, and chipper. In addition to these motors, there will be equipment for material handling and compressed air production. The electrical motors on the main equipment in the sawmill facilities contribute to approximately 70 to 80 percent of the total electrical energy usage. The remaining 20 to 30 percent energy is used by the additional equipment in the process and by the HVAC and lighting. Therefore, collecting electrical data on the main equipment is necessary to know the sawing energy consumption.

Duration of Data Logging

Data loggers were used to collect amperage data of motors in each sawmill for duration of one month. Data collection frequency was selected based on the storage capacity of the data loggers. The maximum storage capacity of data loggers was 43,000 data points and the best frequency of data collection that can be achieved by utilizing the complete storage capacity of the data loggers was one minute since total number of data points that will be collected in 30 days with one minute frequency is 43,200. Since amperage data was collected for every minute and not every second, there were chances that the logged data did not represent the real amperage consumption of that minute. Motor used for lumber sawing will be either loaded or unloaded depending on whether the saw blade is cutting the wood or not. Usually, a saw blade makes few cuts in a minute and the data loggers may or may not record the cutting amperage and hence may not represent the average amperage used during that minute. So, a sample data (Figure 3.1) was collected on the main saw of sawmill 1 for duration of nine hours (data in Appendix Table A.2) to find out how many one minute frequency amperage data points must be collected to estimate the real average. The average of nine hours data was 84.6 amps and is assumed as real average. Also data was collected for every second using another device for 20 minutes and the average of that data was around 82 amps.

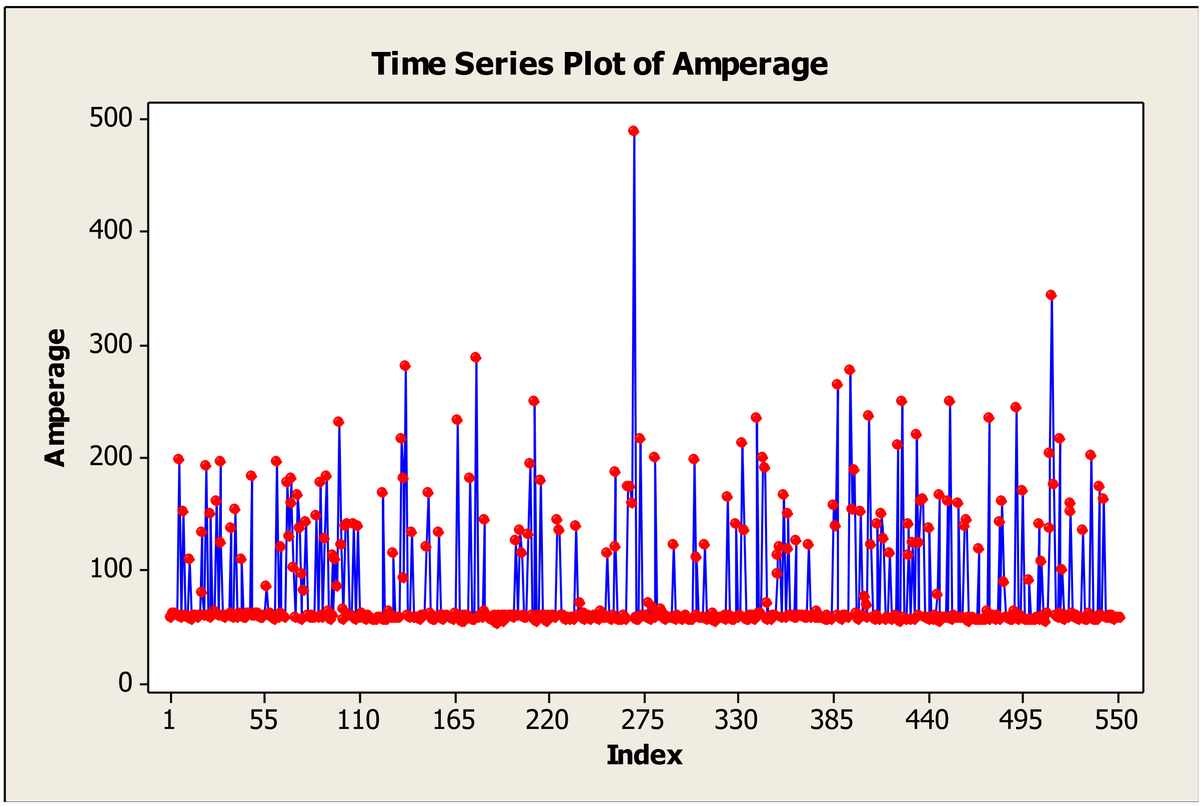


Figure 3.1: Sample Amperage Data of Main Saw collected in Sawmill 1

The frequency plot of the sample data is shown in Figure 3.2 and it didn't follow any particular probability distribution. Most of the values were located near 60 amps or motor unloaded condition and others were spread out between 80 and 240 amps. Since the sample data didn't follow any distribution, no formula was available to calculate number of data points to be collected to estimate the real mean.

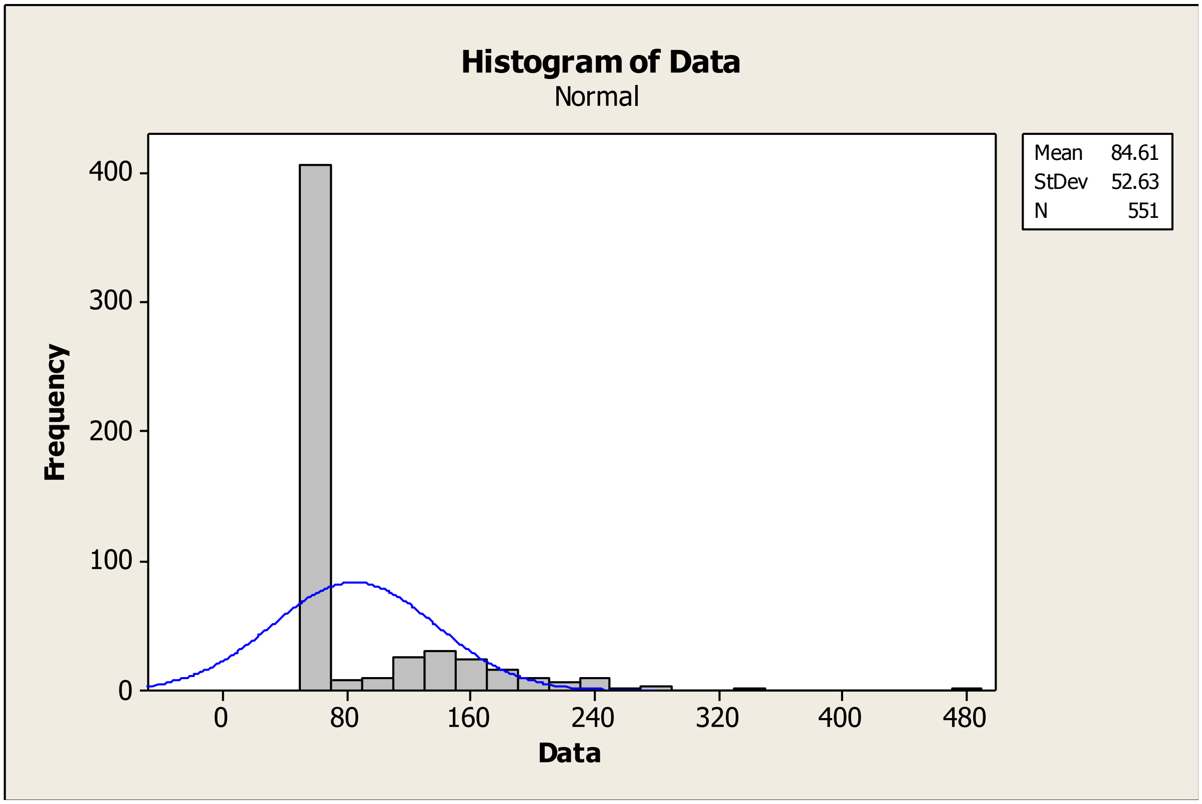


Figure 3.2: Histogram of Sample Amperage Data of Main Saw collected in Sawmill 1

Since there were no formula to calculate the number of data points to be collected to estimate the real mean, sample data was split into groups of 30 data points each and average for each group was calculated. The calculated averages are shown in Table 3.1.

Table 3.1: Calculated Averages of Groups taken from Sample Data

89.06	71.76	100.36	85.72	89.79	77.90
74.57	76.63	91.25	70.79	72.07	94.98
75.37	94.74	96.91	84.19	82.79	100.39

From the sample data, totally 18 groups of 30 data points each was formed. Out of the 18 group averages calculated, 11 averages were outside ± 10% of the average amps range (76.5 ~ 93.5). The grand average of these group averages was 84.96 amps. The averages of these 18 groups were tested for normality (Figure 3.3) and they followed a normal distribution as per the 'Central Limit Theorem'.

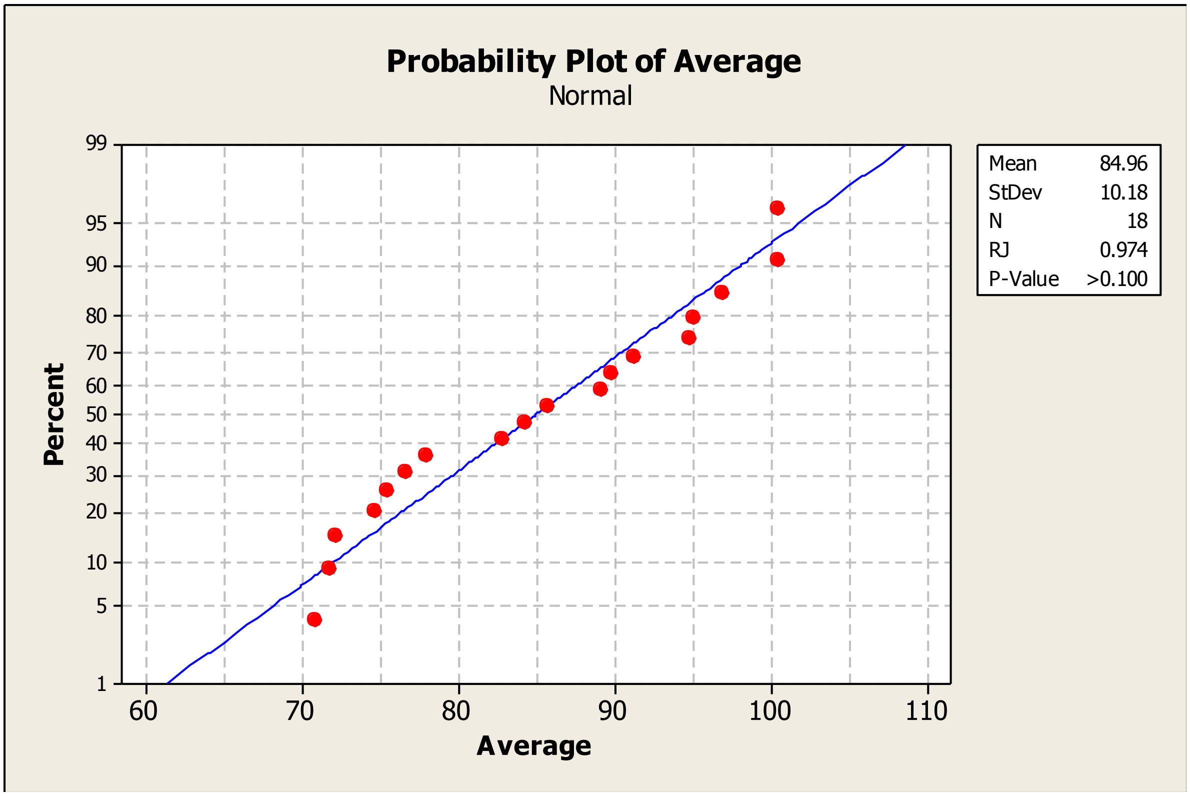


Figure 3.3: Normal Probability Test Results for Group Averages

Since the group averages followed a normal distribution, these averages were used to calculate number of group averages required to estimate the true mean or number of data points (groups x 30) required to estimate the true mean.

The following strategy was used to determine the actual number of group averages to be collected to estimate the true mean. Let the sampling outcome include the following:

N_i = Total number of group averages obtained when the equipment is actually cutting the wood during pilot study

X_i = Value of each group average amperage when the equipment is cutting the wood during pilot study

N_1 = Total number of group averages to be collected for each data set to estimate mean within a particular range from the true mean

The sample variance (s^2) for the pilot study when the equipment is actually cutting the wood is given by Equation 3.1 (Montgomery 2003 Chapter 6):

$$s^2 = \frac{\sum_{i=1}^{N_1} X_i^2 - \frac{\left[\sum_{i=1}^{N_1} X_i\right]^2}{N_i}}{N_i - 1} \qquad (3.1)$$

Knowing the sample variance from the pilot study, the total number of group averages N_1 to be collected during the actual data collection can be determined. N_1 can be determined by using Equation 3.2 (Montgomery 2003 Chapter 8):

$$N_1 = \left[\frac{Z_{\alpha/2} * s}{e}\right]^2 \qquad (3.2)$$

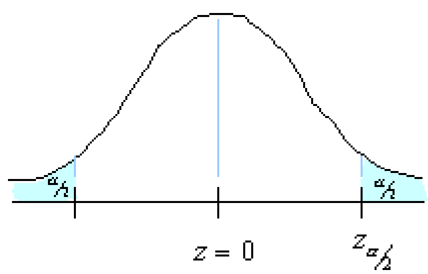


Figure 3.4: Standard Normal Distribution and Critical Area

Where,

N_1 = Sample size for the data collection set

$Z_{\alpha/2}$ = Critical value, for the area of $\alpha /2$ in the right tail of the standard normal distribution. (Figure 3.4)

s = Sample standard deviation from the pilot study, (Amps)

e = expected margin of error, (% of sample mean in Amps)

For the group averages calculated the sample standard deviation was determined to be 10.18 amps. For a confidence level of 95 percent; i.e. $\alpha = 0.05$, and $\alpha/2 = 0.025$, $Z_{\alpha/2} = 1.96$

(from standard Z tables). If the expected margin of error is taken as ± 10% of the true mean amps 84.6 (assuming pilot study mean is an approximate estimator of true mean), then the sample size N_1 required for the data collection is given by Equation 3.2 as follows;

$$N_1 = \left[\frac{1.96*10.18}{84.6*0.1}\right]^2$$

N_1 = 5.56 group averages

Or

N_1 = 5.56 x 30 = 167 data points

Thus a sample of at least 167 data points or 2.75 hours data (since 60 data points are collected every hour) will be needed for each data set to estimate mean with in ± 10% error with 95 percent confidence level. Each sawmill produces one species or more than one species of lumber every day and each species is treated as a data set. Also, if the same species is sawn for more than one day, each day is considered as a data set since the operating parameters will vary every day. On days when more than one species were sawn on the same day and if the sawing time of any of these species is less than 2.75 hours, then there is a possibility that, the data collected for that species can have higher rate of error than ± 10% and may not represent the true mean. Also, when a sawmill switches from one species to another, there will be mix up of two species and the electrical data collected during that time will not represent either of the species and it may take around 2 hours to completely clear the previous species from the line.

3.4 Real Time Data Monitoring using Data Loggers

Data loggers (HOBO) with current transducers (Onset) were used to collect electrical energy consumption data in the sawmills. The loggers were installed on each motor and were set to collect amperage data every minute for one month. Data loggers have different options of setting the time interval between each recording to be made. A data logger can collect maximum of 43,000 data points in different frequency intervals. Hence, the duration for which the electrical data on a motor can be collected will depend on the time interval set between two successive readings.

Data Logger: A data logger (Figure 3.5) is an electronic device that records data over time either with a built in instrument or sensor or via external instruments and sensors. Increasingly, but not entirely, they are based on a digital processor (or computer). They generally are small, battery powered, portable, and equipped with a microprocessor, internal memory for data storage, and sensors. Some data loggers interface with a personal computer and utilize software to activate the data logger and view and analyze the collected data, while others have a local interface device (keypad, LCD) and can be used as a stand-alone device. The data logger selected for data collection uses a 12-bit resolution with a memory of 64 k bytes and can record up to 43,000 measurements.

Figure 3.5: Data Logger

Current Transducer: A current transducer is a device that detects electrical current in a phase (legs) and generates a signal proportional to it. The current transducer used is a split core type as shown in Figure 3.6 and this transducer can measure AC current up to 600 amps for power supplies with voltage less than 600 Volts AC. This current transducer is connected to one of the phases (legs) in the electrical motor's control cabinet to monitor the current consumed by the motor.

Figure 3.6: Current Transducer

The data logger is provided with software required to initialize the unit before starting the actual data logging. It is also required when the data logging is complete and data is ready for downloading to a computer. The initialization step is called as device launching and is shown in Figure 3.7. In the software screenshot shown in Figure 3.7, the user can enter equipment information to be monitored, the logger channel to be used for monitoring the data, the type of transducer to be used, the time interval between consecutive data measurements, and the start time or push button option for starting data logging. The set up will show the duration of data collection depending on the specified frequency for data collection. The device can then be used along with the particular transducer for monitoring the data. The recorded data can be downloaded to a personal computer using a USB (universal serial bus) cable. The software provides data in tabular as well as graphical formats as shown in Figure 3.8. It also provides some descriptive statistics on the data. The software can also be used to export the data to a Microsoft Excel™ spreadsheet for further analysis. The amperage data collected (Figure 3.8) for each motors was split into individual shifts and average amperage was calculated for each shift after removing the machine down time periods during break, lunch or machine break down.

<u>The Advanced Data Collection Device:</u> This is an electrical unit that measures and records current and voltage from 3 phases simultaneously. It can also measure power factor, reactive, real and apparent power. Figure 3.9 shows the device used for measuring power factor, voltage, current, and kW.

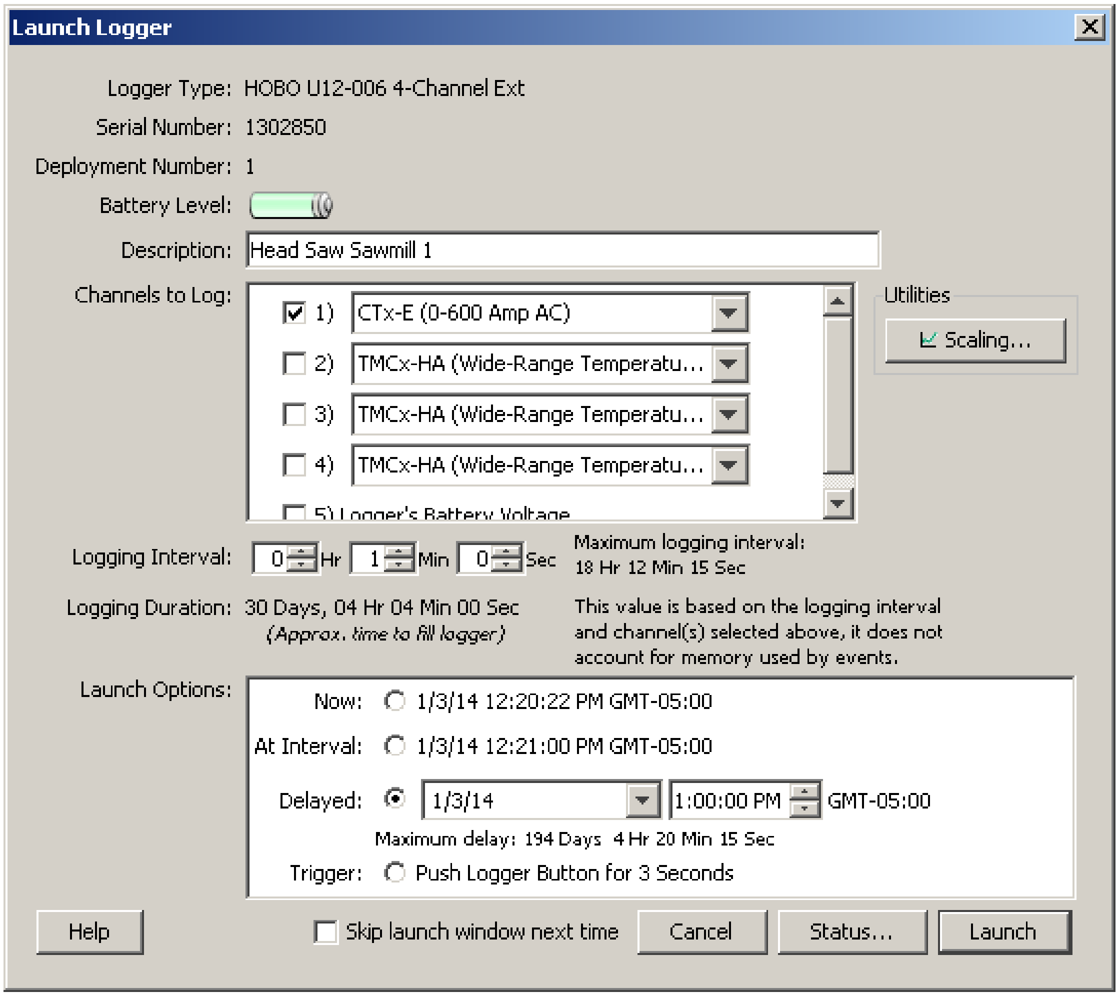


Figure 3.7: Data Logger launching screen for Data Logging (Onset 2013)

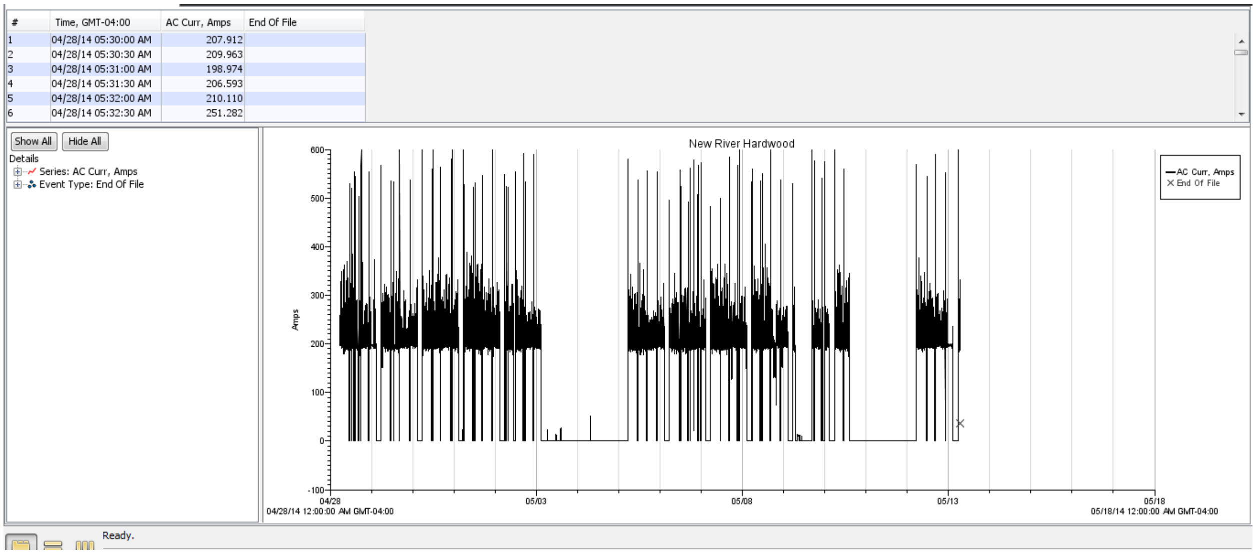


Figure 3.8: Graphical Representation of Amperage Consumption (Onset 2013)

Figure 3.9: Advanced Data Collection Device

Electrical data collection was not easy due to the possibility of electric arching due to the flammable environment of sawmill with sawdust flying everywhere. Hence, lot of safety precautions like wearing electrical safety gloves and shoes was done along with staying away from the terminals while opening control panels and taking electrical measurements. Electrical data monitoring was done during winter months in some sawmills and since sawmills are open facilities, there were lot of chances of data loggers getting moisture condensation and hence, data loggers were kept inside a plastic sealable bag for the duration of data logging. Lot of waiting was done to open some of the control panels since their doors were connected to switches and to open them, the equipment had to be switched off and that was possible only during lunch or break times. Ambient temperature data for different sawmill locations for the data logging period was obtained from website weatherunderground.com and is shown in Appendix (Table A.3).

Of the 5 mills sampled, the sawmill 2 and 4 had a different production flow in that they were lacking a re-saw. In sawmills 1 and 3 the head saw converted logs into cants and then a re-saw or a gang-saw was used to saw the cants into lumber. In sawmill 5 there were both resaw and gang saw for sawing the cants coming from the head saw. In sawmill 2 and 4 the head saw performed all of the log breakdown. Sawmill 3 and 4 had two sawing lines. Manufacturing configurations of all the five sawmills are shown in Figure 3.10.

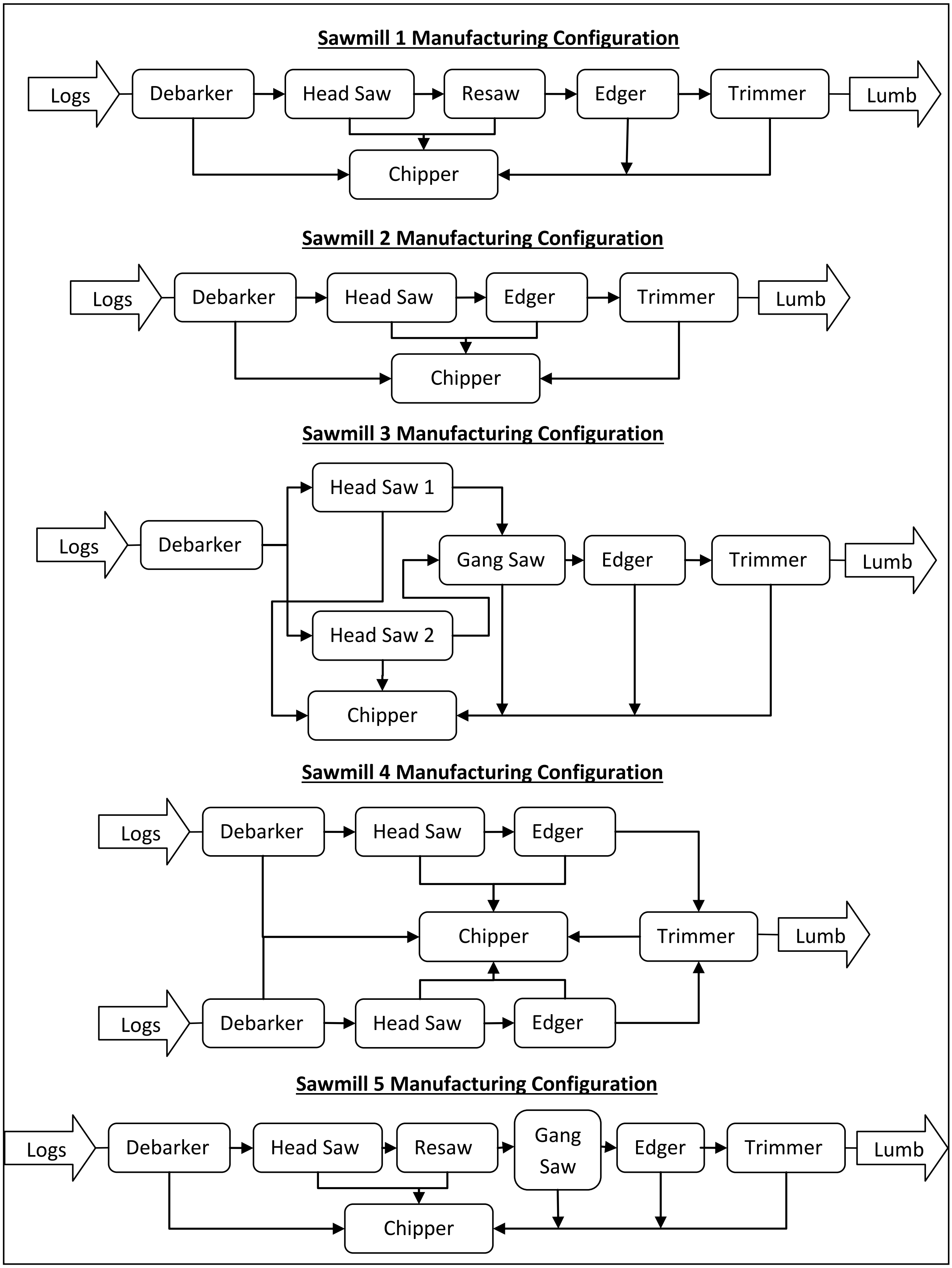


Figure 3.10: Manufacturing Configurations of Sawmill 1 to 5

Eight main motors were selected for monitoring in all the five sawmills (Table 3.2). These motors were selected for data logging because they were the main energy consumers at each facility. Other motors were also selected based on their sizes. Several other motors were sampled using advanced data collection device (Unlogged motors list in Appendix Table A.26) along with the motors that were selected for monitoring in all the 5 sawmills.

Table 3.2: Characteristics of Major Motors in each Sawmill

	Sawmill 1		**Sawmill 2**		**Sawmill 5**	
No.	**Motor Name**	**Motor Size (hp)**	**Motor Name**	**Motor Size (hp)**	**Motor Name**	**Motor Size (hp)**
1	Head saw	200	Head Saw	200	Head Saw	150
2	Carriage feed motor	100	Carriage feed Motor	150	Carriage feed motor	100
3	Chipper	150	Chipper	150	Chipper	300
4	Debarker	50	Debarker	85	Debarker	130
5	Edger	50	Edger	50	Edger	50
6	Air compressor	60	Air Compressor	40	Air Compressor	300
7	Re-saw	60	-	-	Re-saw	150
8	Trimmer	10	Trimmer	25	Trimmer	100
9	Dust collector	15	Dust Collector	37	Gang Saw	100
10	Chip blower	30	Chip Blower	30	Log Deck	20
11	Log turner	40	Conveyor Motor	15	Log Turner	20
12	Top saw	40	Barn Sweep Motor	5	Line Bar Hyd	10
13	Unlogged Motors	163	Unlogged Motors	30	Unlogged Motors	256
	Total	**968**	Total	**817**		**1,686**

	Sawmill 3			**Sawmill 4**		
No.	**Motor Name**	**Line 1 Motor Size (hp)**	**Line 2 Motor Size (hp)**	**Motor Name**	**Line 1 Motor Size (hp)**	**Line 2 Motor Size (hp)**
1	Head saw	172.5	172.5	Head Saw	200	150
2	Carriage feed motor	150	150	Carriage feed Motor	150	100
3	Chipper	200	-	Chipper	200	-
4	Debarker	210	-	Debarker	40	40
5	Edger	200	-	Edger	100	75
6	Air compressor	150	-	Air Compressor	100	-
7	Gang Saw	418	-	-		-
8	Trimmer	180	-	Trimmer	57.5	-
9	Sorter Chain	50	-	Log Turner	20	-
10	Hydraulic Pump	60	-	Unlogged Motors	301.5	-
11	Unlogged Motors	517.5	-			-
	Total	**2,630.5**		Total	**1,534**	

The voltage and power factor data collected using advanced data collection device is shown in Appendix (Table A.21). The subpanel used to supply power to each of the sample motors was located and the data logger and transducer were installed in each panel (Figure 3.11). The current transducer was secured around one of the demand side legs in the motor control panel of each motor and the transducer's output was connected to the data logger. The data logger was set to record current data every minute during the duration of data collection. The transducers and loggers were installed for a period of 30 days at each mill except for sawmill 5.

Figure 3.11: Data Logger and Current Transducer Setup

3.5 Production Data Collection

Data sheets that were provided to the sawmills and asked them to record production data during the time-period of energy usage sampling is shown in appendix (Table A.1). Each mill provided their production schedule that included species sawn as well as the different size and grade of the lumber produced during data collection. Data were provided at the shift level for each mill, which included new runs each morning as well as when the mill changed to a different species or production line. After the data collection period at each mill, data were downloaded from the loggers and associated production data were recorded.

A total of 133 separate shifts, where both production data and electrical consumption data corresponded, were collected at the three sawmills with single sawing lines and two sawmills with double sawing lines during the study period. Around 4 million board feet of lumber were sawn during the data logging period in these 5 sawmills. The board-foot is a specialized unit of measure for the volume of lumber in the United States and Canada. It is the volume of a one-foot length of a board with one foot width and one inch thickness. The data sets typically corresponded to a particular species that was sawn during a particular period (am/pm) and represented multiple hours of data collection. Typically one or two species were sawn during an eight to ten hour work period. A total of 15, 23, 18, 18 and 11 days of production and energy consumption data were collected from sawmill 1, 2, 3, 4 and 5 respectively (Appendix Table A.3, A.4). Sawmill 5 worked 2 shifts during the data collection period and hence only 11 days data was collected from it. Red oak was the most common species sawed during the study period, followed by Yellow Poplar (Table 3.3).

Table 3.3: Data Points for Hardwood Species sawn, Species grouped assigned (HHW: Hard-hardwood SHW: Soft-hardwood) and Total Board Feet sawn.

Species	Species Group	No. Data Points	Board Feet	Percentage
White Ash	HHW	5	124,822	3.18
Black Birch	SHW	1	43,716	1.11
Black Cherry	SHW	4	122,655	3.13
Hickory	HHW	7	114,901	2.93
Hard Maple	HHW	18	412,634	10.52
Red Oak	HHW	41	1,157,489	29.51
Soft Maple	SHW	16	589,886	15.04
Sycamore	SHW	3	34,240	0.87
White Oak	HHW	20	481,275	12.27
Yellow-poplar	SHW	18	840,978	21.44
Total		**133**	**3,922,596**	**100**

Logs were combined based on their density into hard-hardwoods and soft-hardwoods. The hard-hardwood group included White Ash, Hickory, Hard Maple, Red Oak, and White Oak. The soft-hardwood group included Black Birch, Black Cherry, Soft Maple, Sycamore and

Yellow-poplar. A total of 2,296,736 board feet of hard-hardwoods and 1,603,671 board feet of soft-hardwoods were sawn at the five mills during this study.

Each mill sawed various lumber thicknesses during each shift. Lumber thicknesses are specified in quarter of an inch size for board lumber. For example 4/4 lumber thickness means that there are 4 quarter inches in the thickness of that lumber or it is 1 inch thick. Similarly 5/4 inch thick lumber will be 1.25 inch thick and so on. The width of these lumber pieces varied between 3” to 12”. Pallet size lumber will be usually 1 inch thick and the width varied between 6 to 8 inches. Cants and timber are bigger lumber sizes and cants will be of sizes 3” thick x 8” width, 5” thick x 6” width, or 4” thick x 14” width and timber is usually 7” thick x 9” width. The length of these lumber pieces varied between 8 feet to 16 feet. By far, 4/4 lumber was the most common thickness representing 61 percent of the total lumber sawn (Table 3.4). Pallet parts, industrial cants, and railroad ties and timbers were also sawn by each of the mills during the study period. Overall, 75.5 percent of the lumber produced was of 4/4, 5/4, 6/4 and 8/4 (board size lumber) size and the remaining 24.5 percent was in pallet, cant and timber sizes.

Table 3.4: Lumber Thickness Characteristics measured in Board Feet at 5 Sawmills

SAWMILL	Total Lumber	Four Quarter	Five Quarter	Six Quarter	Eight Quarter	Pallet	Cant	Timber
Sawmill 1	460,994	327,363 (71%)	23,905 (5%)	7,618 (2%)	9,820 (2%)	64,850 (14%)	17,403 (4%)	10,035 (2%)
Sawmill 2	420,687	158,100 (38%)	25,866 (6%)	12,284 (3%)	14,262 (3%)	14,666 (3%)	86,499 (21%)	109,010 (26%)
Sawmill 3	1,431,387	1,031,633 (72.5%)	0 (0%)	31,020 (2%)	382 (0%)	246,408 (17%)	0 (0%)	121,944 (8.5%)
Sawmill 4	660,379	296,280 (45%)	0 (0%)	31,070 (5%)	182,383 (28%)	6,974 (1%)	106,688 (16%)	36,984 (6%)
Sawmill 5	949,149	594,681 (62.5%)	173,337 (18.5%)	0 (0%)	34,029 (3.5%)	57,221 (6%)	67,872 (7%)	22,009 (2.5%)
Total	**3,922,596**	**2,408,057** (61%)	**223,108** (6%)	**81,992** (2%)	**240,876** (6.5%)	**390,119** (10%)	**278,462** (7%)	**299,982** (7.5%)

From the Table 3.4, it can be seen that sawmill 2 had the highest percentage of cants and timbers where as sawmill 1 had the lowest. Also, sawmill 2 had the lowest percentage to 4/4 lumber where as sawmill 3 had the highest.

Each of the hardwood mills sampled focused on grade lumber production. The commercial lumber is graded by some specific rules established by manufacturer's association that make purchasing uniform throughout the nation. In 1898, the National Hardwood Lumber Association was formed to standardize the grading of hardwood lumber (McDonald 1898). Grades are established based on the size and number of individual pieces that can be obtained during cutting process from a board of lumber. There are eight commonly used lumber grades in today's market. FAS is the highest grade whereas No.3B common is the lowest grade out of them. Here is a brief description of the common lumber grades.

FAS: The term FAS stands for "First and Seconds" and is considered as the highest grade of lumber and its width will be at least 6 inches with a length of 8-16 feet.

F1F: It is also called as FAS 1-Face and the minimum width is 6 inches.

Selects: The minimum width is 4 inches and the price of this grade lumber is almost the same as FAS.

No. 1 Common: The minimum width is 3 inches and is suitable for making furniture.

No. 2A, 2B, 3A, 3B Common: The letter A represents clear cuttings and letter B represents that cuttings are required to free from rot, pith, shake, and wane (Cassens 2001). 2A and 2B are the standard grades for making cabinets. 3A and 3B are suitable for flooring and pallets [Sawmill Magazine 2010]. The minimum width of these grades is 3 inches. As explained above, there are no standard widths specified for each grade and only minimum width is specified as shown in Table 3.5.

Table 3.5: Minimum Width of Different Grade Lumber

Grade	Minimum Width (Inches)
FAS	6
F1F	6
Selects	4
No.1, 2A, 2B, 3A, 3B Common	3

All thicknesses were combined with respect to their grade while reporting total lumber produced in board feet for that grade since thickness is not considered in grading lumber. During the study period, sawmill number 5 produced the largest amount of common and better lumber, about five times that of sawmill 2 (Table 3.6). The upper NHLA grades (FAS—1COM) accounted for 50 percent of the grade lumber sawn.

Table 3.6: National Hardwood Lumber Association Graded Lumber produced in Board Feet at 5 Sawmills

SAWMILL	FAS	FAS 1-Face	1 Common	2 Common	3 Common	COMBET*
Sawmill 1	0	135,953	65,532	95,442	71,779	201,485
Sawmill 2	26,371	16,279	61,769	75,870	30,223	104,419
Sawmill 3	237,059	94,171	37,282	332,736	343,219	368,512
Sawmill 4	90,245	55,616	161,071	185,104	17,697	306,932
Sawmill 5	177,249	96,370	237,314	248,211	42,903	510,933

*COMBET = FAS + FAS 1-Face + 1 Common

3.6 Data Collection of Saw Blade Material and Maintenance

As discussed earlier, in a sawmill head saw and re-saw are the main equipment involved in sawing operation. The material details and maintenance procedures of these saws were collected from all the 5 sawmills (Sample in Appendix Table A.28). Maintenance of saw blades is critical to reduce energy consumption during lumber sawing (Cristóvão 2013) and also to improve quality of lumber produced. In the study conducted, the experimental power consumption increased by 11 to 35% during an 8-hour shift, mainly due to an increase in the tooth radius of the cutter due to lack of maintenance of saw blades. The material details and dimensions of the saws and maintenance procedures are shown in Table 3.7 and Table 3.8.

Table 3.7: Specifications of Saws in Sawmills

	Main saw			Re-saw		
	Type of Saw	Material	Dimensions	Type of Saw	Material	Dimensions
Sawmill 1	Circular Saw	Carbon Steel (Carbide Tips)	Diameter: 58 inch Thickness: 0.176 inch Tooth Angle: 35^o to 37^o Hook Angle: 45^o	Band Saw	Carbon Steel	Length:21 feet Width:4.75 inch Thickness:0.048 inches Hook Angle: 30^o
Sawmill 2	Band Saw	Carbon Steel	Length:45 feet Width:12 inch Thickness:0.071 inches	-	-	-
Sawmill 3	Band Saw	Carbon Steel (Udelholm)	Length:42.5 feet, 38 feet Width:11 inch Thickness:0.078 inches Tooth Angle: 44^o Hook Angle: 30^o	Circular - Gang	Carbon Steel (Peerless)	Diameter: 30 inch Thickness: 0.12 inch Tooth Angle: 50^o Hook Angle: 30^o
Sawmill 4	Band Saw	Carbon Steel (Swedish)	Length:40 feet Width:10 inch Thickness:0.078 inches Hook Angle: 30^o	-	-	-
Sawmill 5	Band Saw	Carbon Steel	Length:47 feet Width:12 inch Thickness:0.078 inches Hook Angle: 30^o	Band Saw	Carbon Steel	Length:40 feet Width:11 inch Thickness:0.078 inches Hook Angle: 30^o

Table 3.8: Maintenance Procedures of Saws

	Main Saw			Re-saw			Average Runtime	Maintenance Index
	Runtime	Grinding Time*	Saw Changing Time#	Runtime	Grinding Time*	Saw Changing Time#		
Sawmill 1	3.5 Hours	10 Minutes	10 Minutes	3.5 hours	1 hour	15 Minutes	3.5	4
Sawmill 2	4 Hours	2 Hours	15 Minutes	-	-	-	4	3
Sawmill 3	4 hours	2 Hours	8 Minutes	6 hours	10 Minutes	30 Minutes	5	2
Sawmill 4	5 hours	1.75 Hours	18 Minutes	-	-	-	5	2
Sawmill 5	5 hours	3 hours	5 Minutes	5 Hours	3 Hours	5 Minutes	5	2

*Grinding of saws is done off line, #Changing of Saws is done during lunch or break times.

A maintenance index was assigned to each sawmill based on the average saw blade life of main saw and re-saw (Table 3.8). Since the power consumption goes up as the saw blade is used for longer time, higher maintenance index was assigned to sawmills using saw blades for shorter time. For average saw blade life (main saw and re-saw) between 3 to 3.9 hours, maintenance index value given was 4, for average between 4 to 4.9 hours, index value was 3, for average between 5 to 5.9 hours, index value was 2 and the typical range for maintenance index will be 1 to 5.

Conclusion

Three sawmills with single sawing line and two sawmills with double sawing lines were selected to monitor their electrical energy consumption. Energy, Current, Voltage and Power factor data was collected using an advanced electrical data collection device for duration close to 20 minutes. The data loggers were set on all major motors to record current data every minute for the duration of 1 month. Manufacturing configurations along with the type of equipment used for sawing were studied. Data of the saw blade material used in different machines were collected along with the maintenance schedules of the saws.

Overall, production and electrical consumption data of 133 separate shifts, was collected from the five sawmills during the study period. From the collected data, sawmill 3 had the highest production and sawmill 2 the lowest.

4. Data Analysis

4.1 Energy Consumption Calculation of Motors

The electrical and production data collected were used to calculate energy consumption for the lumber produced during a particular shift. Data were matched to production records based on the timestamps recorded by the data loggers. Total energy consumption in kWh for each motor was calculated for a particular time period using the logged data as follows:

$$EC_{logged} = \sqrt{3} * V*I*\cos\Phi* \text{No. of hours}/(1000) \qquad (4.1)$$

Where,

EC_{logged} = Energy Consumption

V = Voltage

I = Amperage

$\cos \Phi$ = Power Factor measured using Amprobe

For example, the energy consumed by the main saw for sawing Hickory on 23rd shift of data collection (Appendix Tables A.3 production data, A.7 amperage data, A.12 run time data, A.21 voltage and power factor data, A.17 energy consumption data) in sawmill 2 is calculated as,

$$EC_{logged} = \sqrt{3}*487*142.34*0.41*(278/60)/1000$$

$$= 228.08 \text{ kWh}$$

The number of hours used to calculate EC_{logged} were those recorded by the data loggers and not those provided by the mill. While they were similar, the data loggers captured the true operating time without any introduction of human error. Similarly, the energy consumption was calculated for all other motors logged. The logged and unlogged motor horsepower of sawmills along with percentage logged and unlogged is shown in Table 4.1.

Table 4.1: Logged, Unlogged and Total Motor Horse Power of Sawmills

Sawmill #	Logged hp	Unlogged hp	Total hp	% Logged	% Unlogged
1	805	163	968	83	17
2	787	30	817	96	4
3	2,113	517.5	2,630.5	80	20
4	1,232.5	301.5	1,534	80	20
5	1,430	256	1,686	85	15

The total energy consumption of the logged motors was 866.06 kWh and the average load factor for the logged motors is calculated as,

$$\text{Load Factor} = \frac{\text{Total kWh x Motor Efficiency}}{\text{Motor hp x Hours x 0.746}} \tag{4.2}$$

$$\text{Load Factor} = \frac{866.06 \text{ x } 0.866}{787 \text{ x } (270/60) \text{ x } 0.746} = 0.2839$$

The electrical energy consumption of motors that were not logged was estimated based on average load factor of the logged motors and the total operating hours using the following relationship:

$$\text{EC (Unlogged Motors)} = \frac{\text{Horsepower x Load Factor x Operating Hours x } 0.746\left(\frac{\text{kW}}{\text{hp}}\right)}{\text{Average Motor Efficiency}} \tag{4.3}$$

For example, the energy consumed by the motors that were not logged for sawing hickory on 23rd shift of data collection (Appendix Table A.3 production data, A.7 load factor data, A.12 run time data, A.17 energy consumption data) in sawmill 2 is calculated as,

$$\text{EC (Unlogged Motors)} = \frac{30 \text{ x } 0.2839 \text{ x } (270/60) \text{ x } 0.746 \text{ (kW/hp)}}{0.757}$$

$$\text{EC}_{\text{(Not Logged Motors)}} = 37.77 \text{ kWh}$$

Table 4.2 lists the average motor load factor, efficiency of logged motors, efficiency of unlogged motors with average motor sizes used for calculating efficiency in parenthesis.

Table 4.2: Motor Load Factors and Efficiencies

Sawmill	Average motor Load factor	Efficiency for logged motors#	Efficiency for unlogged motors#
1	0.307	87.4 (200 hp)	78.6 (7.5 hp)
2	0.265	86.6 (150 hp)	75.7 (15 hp)
3	0.485	91.2 (200 hp)	87.7* (20 hp)
4	0.358	88.5 (200 hp)	79.2 (15 hp)
5	0.362	88.6 (150 hp)	85.6* (20 hp)

*Have more large sized unlogged motors, #Obtained from MotorMaster+ International (USDOE 2015)

The energy consumption calculated for various motors were tallied and combined with the corresponding shift production (Table 4.3, Appendix Table A.17). Total energy consumption (kWh) was calculated by adding consumption from both logged and unlogged motors.

Table 4.3: Example of Energy Consumption in kWh recorded for Motors used during the Sawing of Hickory logs in a WV Hardwood Sawmill

Head Saw	Carriage feed motor	Edger	Trimmer	Compre -ssor	Chipper	Debarker	Other logged motors	Unlogged motors	Total kWh	MBF[a]
228.07	94.79	33.03	33.38	121.18	133.98	191.22	30.41	37.77	903.83	10.141

a- Thousand board feet sawn during a given sampling period

Energy consumption for lighting and HVAC was calculated based on the collected data from sawmills. The total energy consumption of motors, lighting and HVAC was closely matching with the actual electricity bills except for sawmill 5 since it was working for 2 shifts and some equipment like compressor was running even in the 3rd shift. (Table 4.4)

Table 4.4: Total Energy Consumption of Motors, Lighting, and HVAC in each Sawmill along with Energy Bills

Sawmill	Motors (kWh)	HVAC (kWh)	Lighting (kWh)	Calculated Total (kWh)	Energy Bill (kWh)
Sawmill 1	39,767	-	1,650	41,417	42,988
Sawmill 2	35,154	-	1,150	36,304	36,524
Sawmill 3	148,553	14,784	29,260	192,597	196,423
Sawmill 4	80,904	-	12,426	93,330	96,682
Sawmill 5	106,418	10,733	16,099	133,250	146,052
Total	**410,796**				

Once consumption data were developed, it was then used to create a standardized metric for each shift based on the total lumber production for the shift (specific energy consumption in kWh per thousand board feet - SEC). The specific energy consumption (SEC) or total kWh consumed per thousand board feet (MBF) was determined by dividing the total energy consumption during a set time period by the total lumber production for the same period.

$$\text{SEC} = \frac{\text{Total Energy Consumption}}{\text{MBF}} \tag{4.4}$$

For example, SEC for sawing Hickory on 23rd shift of data collection (Appendix Table A.3) in sawmill 2 is calculated as,

$$\text{SEC} = \frac{903.83}{10.141}$$

$$= 89.13 \text{ kWh/MBF}$$

Board feet sawn per hour was calculated to know the production rate of each sawmill. For example, board feet sawn per hour for sawmill 2 is calculated as,

$$\frac{\text{Board Feet}}{\text{Hour}} = \frac{420{,}687}{191} = 2{,}203$$

The highest board feet rate per hour was for sawmill 3 and the lowest was for sawmill 2.

Board feet sawn per kWh was calculated to see how much quantity of board feet is produced from each sawmill per kWh of energy consumed. Board feet sawn per kWh is calculated as,

$$\frac{\text{Board Feet}}{\text{kWh}} = \frac{420{,}687}{35{,}154} = 11.97$$

The highest board feet produced per kWh was for sawmill 2 and the lowest was for sawmill 4.

Data from all the shifts for all the 5 sawmills (Table 4.5) were processed similarly and the results are summarized (Table 4.6). From the summarized results, SEC of sawmill 2 looks better than the other sawmills and SEC of sawmill 4 the worst. Sawmill 3 has the highest production rate and sawmill 2 the lowest. Load factor of sawmill 1 and 2 are lower than the other sawmills. SEC of each mill is calculated both as total energy consumed by total board feet and average SEC's of each shift. There is some difference between these two SEC's due to round off error.

Table 4.5: Calculated SEC Values of 5 Sawmills for Various Shifts

Sl. No.	Sawmill 1	Sawmill 2	Sawmill 3	Sawmill 4	Sawmill 5
1	70.05	89.13	105.28	115.22	106.13
2	57.49	73.99	124.48	108.23	113.76
3	79.48	91.16	104.00	99.65	153.86
4	86.37	79.47	111.63	103.05	137.55
5	79.31	76.00	111.68	109.70	67.71
6	77.59	57.54	85.78	100.94	84.87
7	79.62	61.25	104.21	116.97	67.73
8	85.66	60.79	103.86	98.44	129.64
9	90.42	70.04	111.65	137.93	98.24
10	95.95	94.01	105.06	147.41	139.94
11	94.75	85.15	108.29	169.34	113.82
12	83.83	80.82	86.33	154.92	137.99
13	88.84	94.05	89.69	78.61	113.90
14	81.51	87.07	81.33	105.08	102.01
15	116.38	76.63	84.82	90.29	117.99
16	77.42	88.53	108.37	140.53	96.29
17	119.23	84.54	124.17	144.54	112.49
18	98.66	91.35	82.45	156.76	115.82
19	95.50	68.88	140.73	111.76	138.43
20	94.74	69.25	105.32	120.46	119.39
21	90.76	107.59	110.70	120.26	151.36
22	86.94	85.95	108.55	117.52	115.25
23		101.26	103.72	159.87	126.86
24		81.96	130.79	129.35	128.95
25		87.31	107.44	146.91	171.11
26		80.49		138.38	
27		86.72			
28		81.71			
29		88.09			
30		88.15			
31		100.14			
32		79.64			
33		125.07			
34		89.72			
35		80.51			
Average	**87.75**	**84.11**	**105.61**	**123.93**	**118.44**

Table 4.6: Lumber Production and Energy Consumption Information of Sawmills

Mill #	Total motor hp	# of hours	# of days	Board Feet	Board feet/ hour	Total kWh	SEC (kWh/ MBF)	Average of Shift SEC's	Motor Load Factor	Board Feet/ kWh
1	968	156.5	15	460,994	2,946	39,767	86.26	87.75	0.307	11.59
2	817	191	23	420,687	2,203	35,154	83.56	84.11	0.265	11.97
3	2,630.5	143.5	18	1,431,387	9,975	148,553	103.78	105.61	0.485	9.64
4	1,534	169.75	18	660,379	3,890	80,904	122.51	123.93	0.358	8.16
5	1,686	205.6	11	949,149	4,616	106,418	112.12	118.44	0.362	8.92
Total				**3,922,596**	**-**	**410,796**	**101.65**	**103.97**	**-**	**-**

4.2 Test for Normality

As per the requirement for comparing sawmill means, data was tested for normality. Ryan-Joiner (similar to Shapiro-Wilk) normality test was conducted for calculated SEC using Minitab software for each sawmill and the normality assumptions were met (p-value > 0.05) for all the five sawmills (Figure 4.2, 4.3, 4.4, 4.5 & 4.6). The calculated SEC followed normality distribution at the sawmill level since it was coming from the same population. The normality test was conducted on data from all the 5 sawmills, but it failed at p-value <0.01 (Figure 4.1).

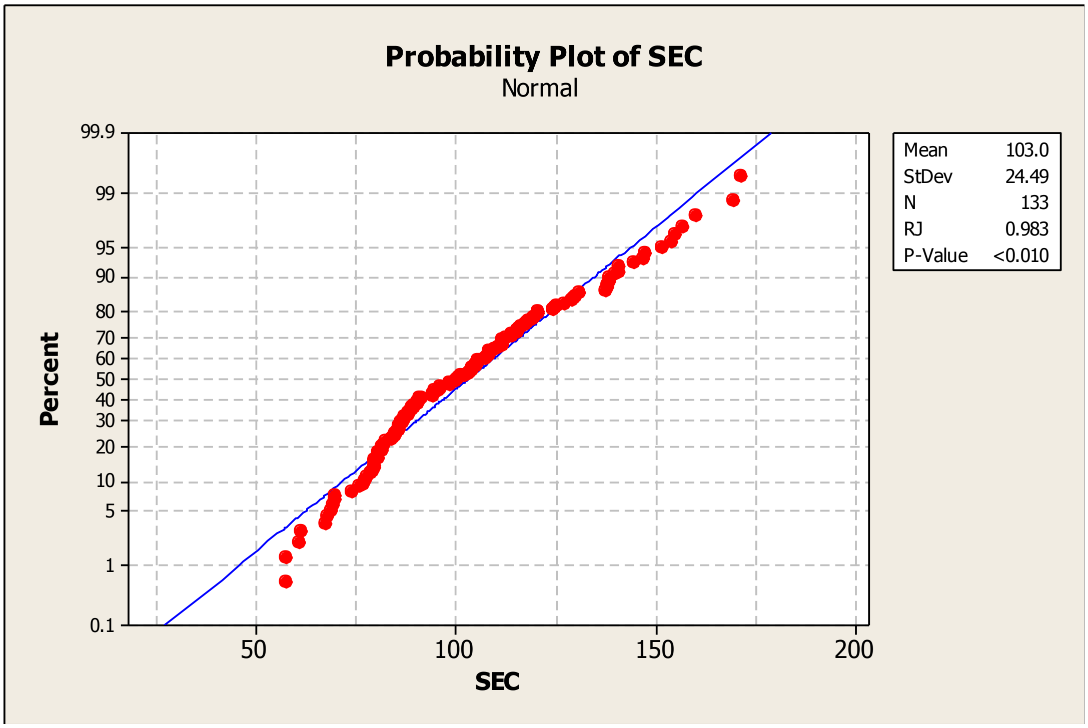


Figure 4.1: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for all the Sawmills

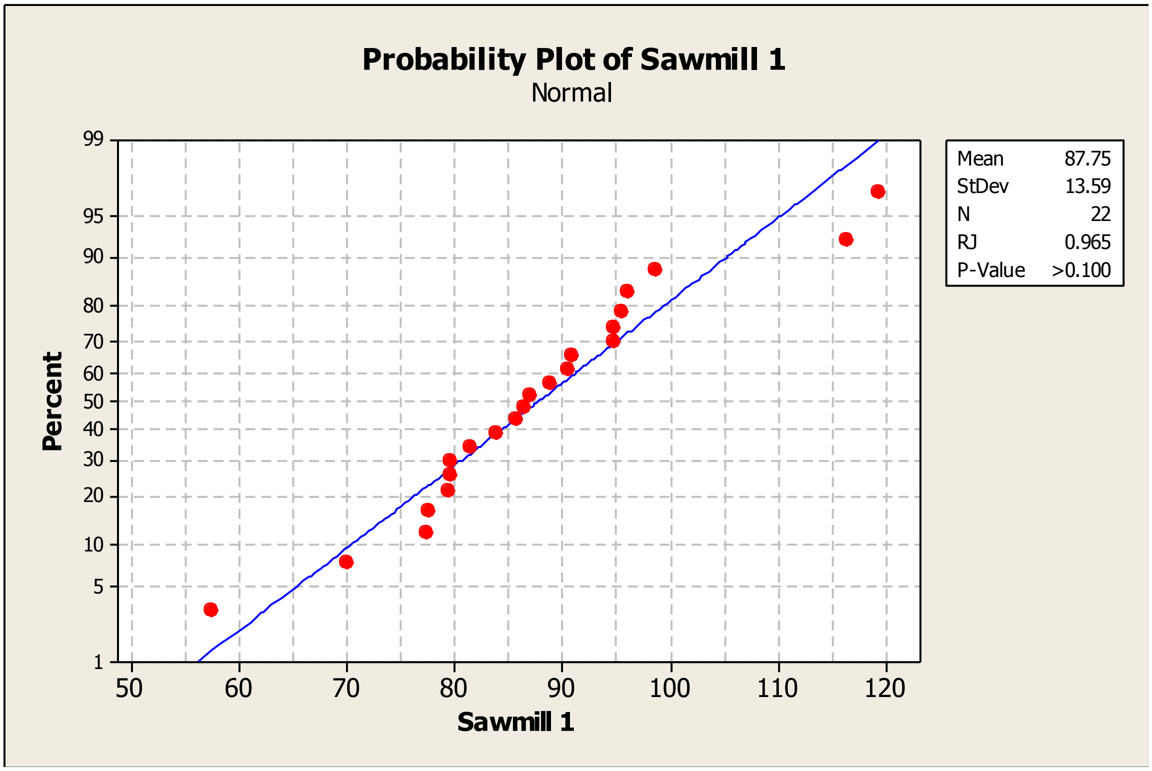


Figure 4.2: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for Sawmill 1

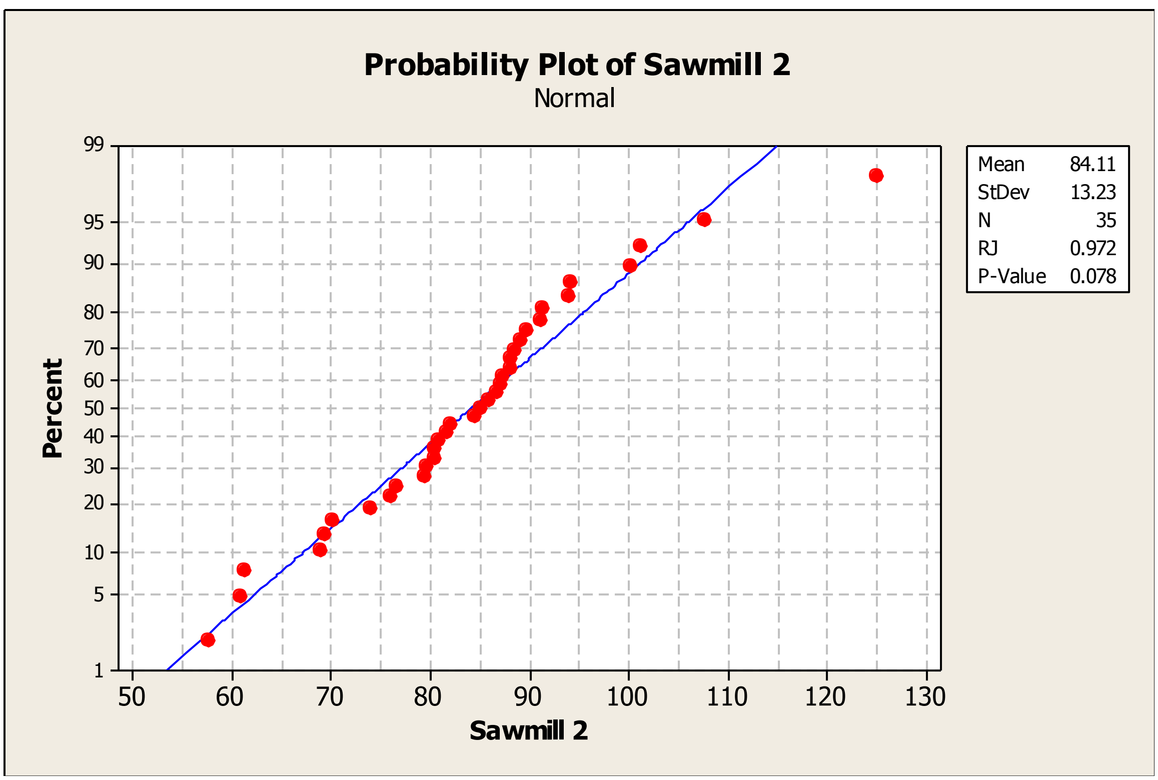


Figure 4.3: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for Sawmill 2

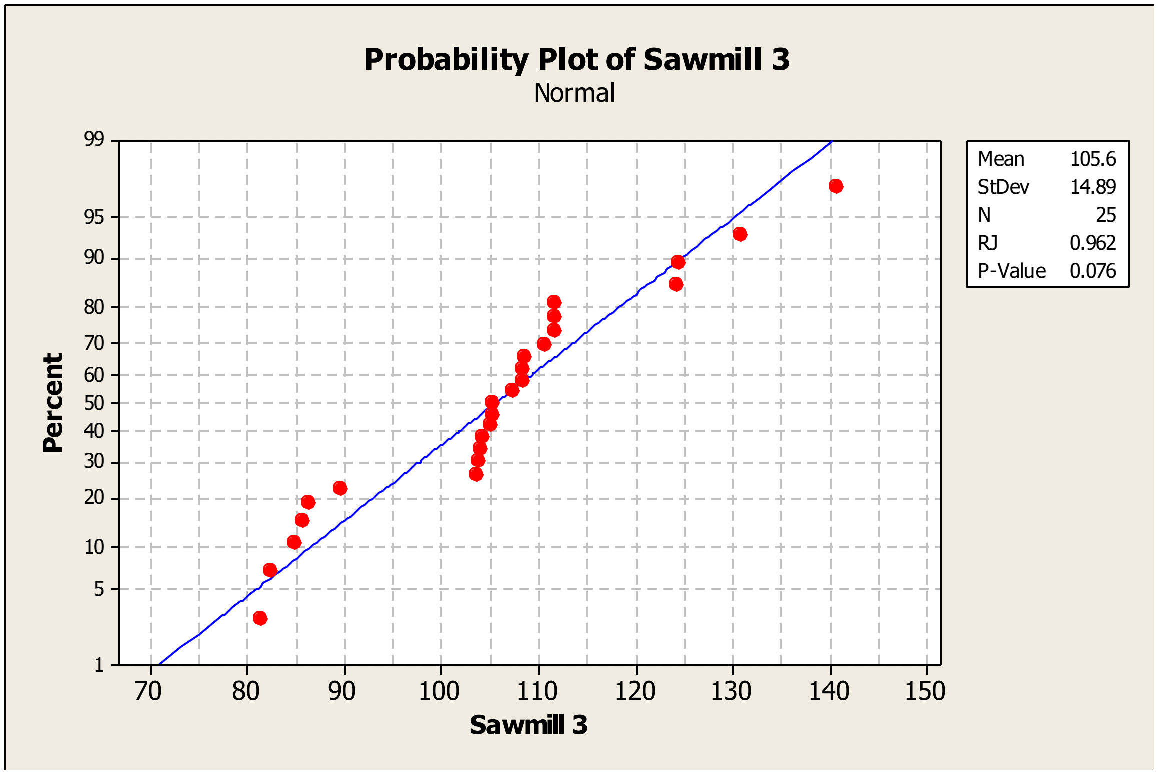


Figure 4.4: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for Sawmill 3

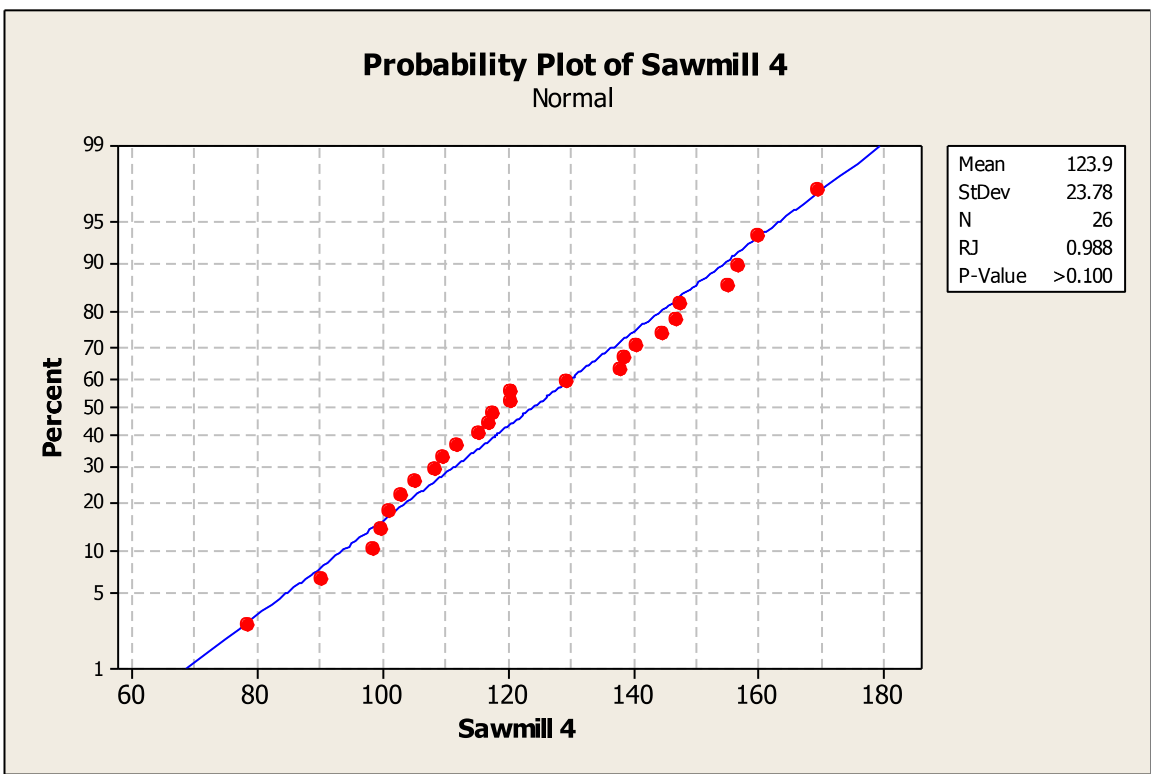


Figure 4.5: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for Sawmill 4

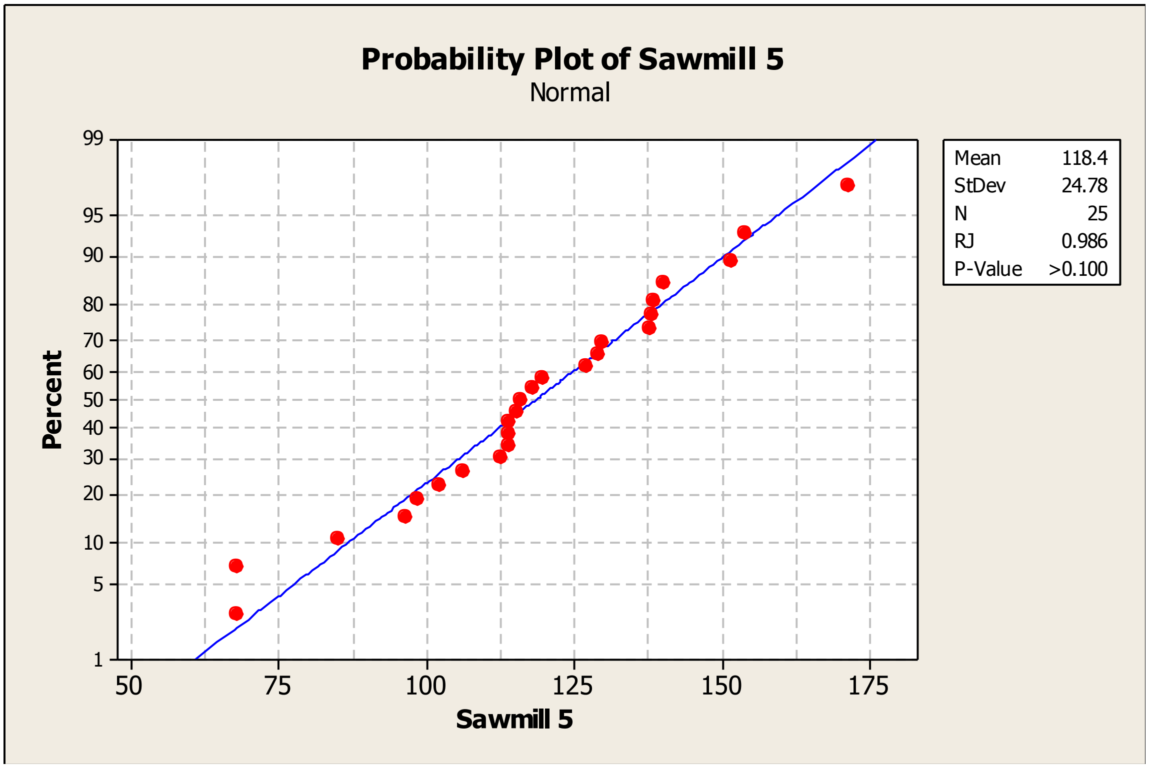


Figure 4.6: Ryan-Joiner (similar to Shapiro-Wilk) Normality Test for Sawmill 5

Since the data of all the five sawmills passed normality tests individually and the largest standard deviation from the 5 samples is less than twice the smallest standard deviation of the 5 samples, one way ANOVA (F-test) was conducted (data from Table 4.5) to find whether the SEC means of each sawmill are from the same population or not. The ANOVA results obtained (F = 25.53 and P = 0.000) are in Table 4.7 and 4.8. The null and alternative hypotheses are;

$H_0 : \mu_i = \mu_j$ for all i,j $\qquad$ $H_0 : \mu_i \neq \mu_j$ for at least one i,j

Table 4.7: Means and Standard Deviations of Sawmill SEC

Sawmill	N	Mean	Standard Deviation
1	22	87.75	13.59
2	35	84.11	13.23
3	25	105.61	14.89
4	26	123.93	23.78
5	25	118.44	24.78
Pooled Standard Deviation			18.55

Table 4.8: Results of Comparing Sawmill SEC Means using ANOVA

Sawmill	N	Mean	Grouping		
4	26	123.93	A		
5	25	118.44	A		
3	25	105.61		B	
1	22	87.75			C
2	35	84.11			C

P.S.: 1. Grouping information using Fisher Method
2. Means that do not share a letter are significantly different.
3. All Pairwise Comparisons, Simultaneous confidence level = 71.77%

SEC means of sawmill 1 and 2 were concluded to be from the same population. SEC means of sawmill 4 and 5 were concluded to be from the same population. SEC mean of sawmill 3 was concluded to be different from the other 4 sawmills. Another point to be noted is higher the SEC value, higher is the standard deviation (sawmill 4 and 5).

The above F-test result gives an overall picture and is not accurate since the data has lot of variability due to different species and sizes that were sawn in each sawmill. Better way of comparing sawmills energy consumption will be to compare a particular size of a particular species lumber from each sawmill. This method of comparison will eliminate the variability due to wood species and lumber sizes. To calculate the energy consumption of a particular species, we have particular data points or shifts during which a particular species was sawn. But for calculating the energy consumption of a particular size lumber, we don't have any data points during which only a particular size lumber was sawn. More than one size lumber was sawn during each shift and each sawmill has sawn different proportion of lumber sizes during the data collection period (Table 3.4). To find out the relation between the percentage of different sizes of lumber sawn and energy consumption, Pearson correlation coefficients were calculated (Data in Appendix Table A.5). All the board size lumber (four-quarter to eight-quarter) were grouped together and also cants and timbers were grouped together to calculate the correlation coefficient.

Even though Pallet was of four quarter size, it was kept separately to see its effect on energy consumption since its percentage was closer to the percentage of cants and timber. SEC and total kWh were positively correlated to the percentage of four to eight quarter lumber and negatively correlated to percentage of cants and timber being sawn (Table 4.9). Percentage of pallet was negatively correlated to the SEC but was positively correlated to total kWh, but the negative correlation with SEC was not significant. Thus, as the mills sawed more grade lumber, as opposed to industrial type products like cants and timbers, the energy consumption and SEC increased. Conversely, as the production percentage of cants and timbers increased, the total kWh and SEC decreased (Table 4.9).

Table 4.9: Pearson Correlation Coefficients for SEC and Total kWh vs. Lumber Sizes

	Percent Four to Eight Quarter	Percent Pallet	Percent Cant + Timber
SEC	0.363	-0.006	-0.31
P Value	<0.0001	0.947	<0.0001
Total kWh	0.442	0.315	-0.503
P Value	<0.0001	<0.0001	<0.0001

These findings follow the common view held by those in the industry. Most operators feel that their energy consumption was greater when sawing standard grade lumber versus sawing industrial products because of the increased number of lumber pieces. When the correlations were further investigated by comparing individual motor relationships (Data in Appendix Table A.5), a cause for the consumption difference becomes apparent.

The percentage of timbers and cants sawn was negatively correlated to the head saw, re-saw, edger, trimmer, chipper, and compressor usage in minutes (Table 4.10). As the percentage of industrial products sawn increased in a shift, less work was performed by the head saw, re-saw, edger, trimmer, chipper and compressor. Debarker usage also reduced when cants and timbers were sawn, but the correlation was not significant, this indicates that debarker has to be used irrespective of the lumber size sawn which is a valid statement. Percentage of pallets had positive correlation with re-saw, edger, trimmer, chipper, and debarker usage, but the correlation was not significant except for resaw. Percentage of pallets was negatively correlated to head saw and compressor usage, but the correlation was not significant.

Table 4.10: Pearson Correlation Coefficients for Equipment Usage in Minutes vs. Lumber Sizes

Equipment Usage	Values	Percent Four to Eight Quarter	Percent Pallet	Percent Cant + Timber
Head Saw	Coefficient	0.348	-0.029	-0.288
	P - Value	<0.0001	0.739	0.001
Re-saw	Coefficient	0.532	0.439	-0.627
	P - Value	<0.0001	<0.0001	<0.0001
Edger	Coefficient	0.403	0.018	-0.354
	P - Value	<0.0001	0.834	<0.0001
Trimmer	Coefficient	0.374	0.085	-0.354
	P - Value	<0.0001	0.332	<0.0001
Chipper	Coefficient	0.378	0.030	-0.337
	P - Value	<0.0001	0.730	<0.0001
Debarker	Coefficient	0.075	0.066	-0.090
	P - Value	0.390	0.452	0.303
Compressor	Coefficient	0.350	-0.104	-0.261
	P - Value	<0.0001	0.235	0.002

Also, it is important to note that the percentage four to eight quarter lumber processed is positively correlated to head saw, re-saw, edger, trimmer, chipper, debarker and compressor usage in minutes. Again debarker usage is not significantly correlated to percentage four to eight quarter lumber similar to pallet percentage and cant + timber percentage. This indicates that irrespective of the lumber size sawn, debarker has to work. This helps to validate the data that were collected; as more four to eight quarter lumber was processed in a shift, all the equipment did more work or those shifts were longer than the shifts that had more percentage of cant and timber and hence has resulted in higher energy consumption. Hence, this will result in an increase in overall SEC for board size lumber.

4.3 Energy allocation Methodology

As seen from Pearson correlation coefficients, board size lumber consumes more energy than other sizes or energy consumption for sawing is inversely proportional to the size of the lumber sawn. Hence, energy consumed for sawing must be allocated to a particular size lumber based on the work done to produce that size lumber. Work done for sawing depends on the surface area to be cut to make that lumber. Consider sawing the cant and the boards shown in Figure 4.7 having same board feet. It is obvious from the figure that for sawing boards, more time and energy is required than for sawing cant. The energy required to saw the boards is approximately 3 times of the energy required for sawing cant.

Figure 4.7: Comparison between a Cant and Lumber of equal Board Feet

Hence energy allocation must be done based on the surface area cut for that particular size of lumber in that particular equipment. Even though the percentage of different size lumber has strong correlation with the energy consumption, their effect cannot be eliminated by using statistical method like 'Analysis of Covariance' (ANCOVA) since the actual effect is produced not just by the percentage of different size lumber, but by the surface area cut for different size lumber. Surface area cut was calculated for head saw/resaw/gang saw, edger and trimmer as shown in the example. Surface area cut for the rest of the motors was taken as the sum of the surface areas cut by head saw/resaw/gang saw, edger and trimmer since they are not directly involved in sawing particular size lumber. Widths of grade lumber sawn varied and had minimum widths based on the grade sawn (Table 3.5), but for the energy allocation purpose, an average width of 6" is assumed. Later, sensitivity analysis based on different widths produced is done to calculate SEC.

<u>Example for Sawmill 2:</u>

Hickory 4/4 size (1" thick x 6" wide x 10' long) sawn in 1st shift (Appendix Table A.4 no 23)

Total board feet of 4/4 cut	= 4,652 Bft
Total length cut	= Total board feet cut / (Width x Thickness)
	= 4,652 Bft / (0.5 feet x 1 inch) (1 bft = 1 ft x 1 ft x 1 inch)
	= 9,304 ft
Surface area cut by Head saw	= Total length cut x Width
	= 9,304 ft x 0.5 ft
	= 4,652 sq. ft
Surface area cut by Edger	= Total length cut x Thickness
	= 9,304 ft x (1/12) ft
	= 775 sq. ft
No. of pieces cut	= (Total length cut/Average piece length)
	= 9,304 ft / 10 ft
	= 930 pieces
Surface area cut by Trimmer	= Width x thickness x No. of pieces cut
	= 0.5 ft x (1/12) ft x 930 pieces
	= 39 sq. ft
SA for Rest of the Motors	= Surface area cut by (Head saw + Edger + Trimmer)
	= 4,652 + 775 + 39
	= 5,466 sq. ft.

Even though the edger and trimmer will have two saws and will cut twice the surface area calculated above, only one side surface area cut is considered since it is enough for calculation. Also, generally cants and timbers doesn't go to edger and trimmer for sawing since they are usually made at the end of sawing a log or left over part of a log and hence the edger and trimmer surface area is not used for allocating energy to them and they will not have the share of energy consumed by edger and trimmer. Similarly, surface areas cut for other lumber sizes were calculated using the above method. The total surface area cut from head saw/resaw/gang saw, edger and trimmer for 1,000 board feet of each size lumber is shown in Figure 4.8.

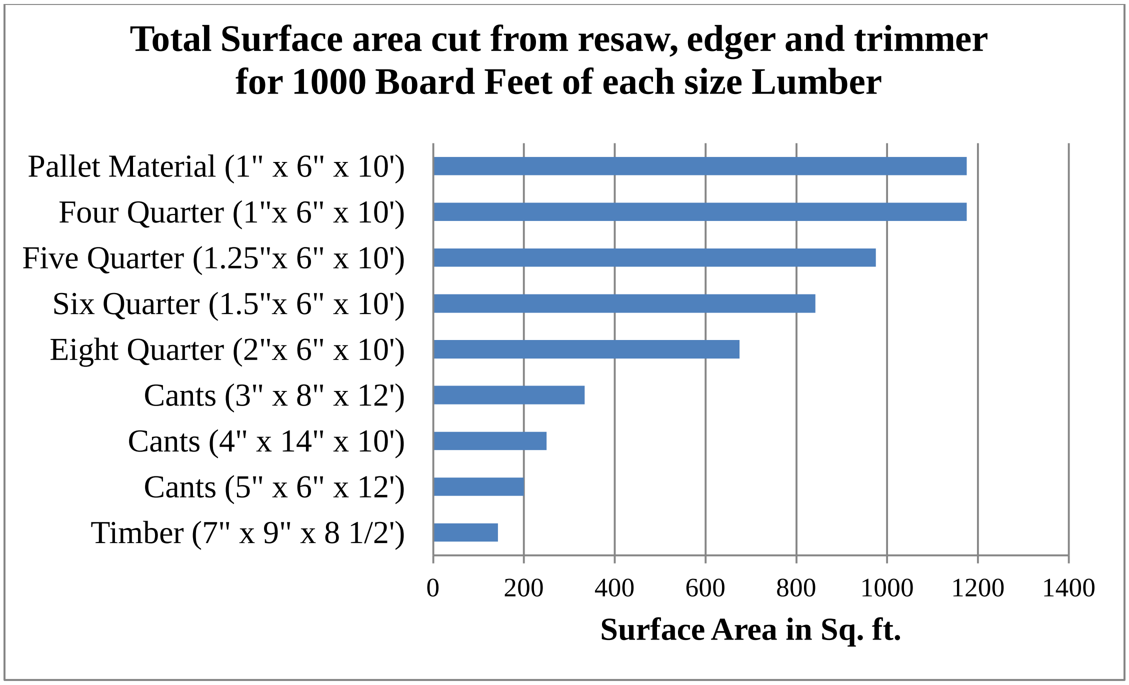


Figure 4.8: Surface Area Cut for 1,000 Board Feet of each Size Lumber

Energy was allocated to individual size of lumber by a factor that was calculated as the ratio of the surface area cut for that particular size in each machine to the total surface area cut by that machine during that period. For example for the same Hickory sawn in 1st shift (Appendix Table A.4 shift no. 23), the factors are allocated as follows:

Factor for head saw for 4/4 = Surface area cut for 4/4 size / Total Surface area cut by head saw

= 4,652 / 5,793

= 0.8030

Similarly, other factors are calculated and are shown in Table 4.11. Table 4.12 shows the total energy consumption of different motors for sawing Hickory (Appendix Table A.17 shift no 23).

Table 4.11: Surface Area Cut and Factors allocation in Sawmill 2

Size	Board Feet	Surface Area Head Saw	Surface Area Edger	Surface Area Trimmer	Surface Area Rest	Factor Head Saw	Factor Edger	Factor Trimmer	Factor Rest
4/4	4,652	4,652	775	39	5,466	0.8030	0.9486	0.9512	0.8218
1"x 6"x10'	252	252	42	2	296	0.0435	0.0514	0.0488	0.0445
5" x 6" x 12'	2,470	494	0	0	494	0.0853	0.0000	0.0000	0.0743
7"x 9"x10"	2,767	395	0	0	395	0.0682	0.0000	0.0000	0.0594
Total	**10,141**	**5,793**	**817**	**41**	**6,651**	**1**	**1**	**1**	**1**

Table 4.12: Energy Consumption in kWh by various Motors for Sawing Hickory

Mainsaw + Carriage Feed	Edger	Trimmer	Rest of the Motors	Total
322.86	33.03	33.38	514.56	903.83

Energy consumed by particular size lumber was allocated based on the factors calculated before i.e., by multiplying the total energy consumption by that motor with the factor for that particular size. Total energy consumption was calculated by adding consumption from all the motors for that particular size. SEC was calculated by dividing the total energy allocated for that size by the MBF sawn for that particular size. Table 4.13 shows the energy consumed on various motors for sawing different size lumber and the total kWh consumed per thousand board feet of lumber.

Table 4.13: Energy Consumed for Sawing Different Size Lumber of Hickory

Size	Board Feet	Main saw Motor kWh	Edger Motor kWh	Trimmer Motor kWh	Rest of the Motors kWh	Total kWh Consumed	kWh/ thousand Board Feet
4/4	4,652	259.26	31.33	31.67	422.86	745.11	160.17
1"x 6"x10'	252	14.04	1.70	1.71	22.91	40.36	160.16
5" x 6" x 12'	2,470	27.53	0	0	38.21	65.75	26.62
7"x 9"x10"	2,767	22.03	0	0	30.58	52.61	19.01
Total	**10,141**	**322.86**	**33.03**	**33.38**	**514.56**	**903.83**	**-**

Similarly, SEC was calculated for hickory sawn at different times during the one month logging period and the average was determined. Similarly, SEC for other species with different size lumber was calculated for all the 5 sawmills. Calculated average SEC based on surface area cut for all the species and sizes of entire sawmill production is summarized in Table 4.14. It can be noted that calculated SEC is lowest for sawmill 1 and highest for sawmill 4 (Figure 4.9).

Table 4.14: SEC Calculated based on Surface Area Cut

Sawmill 1: Overall SEC: **86.26** kWh/MBF, **87.75** kWh/MBF				
Size	**Board Feet**	**kWh/Board Feet**	**kWh/MBF**	**Total kWh**
1” x 6” x 10’	327,363	0.095	94.46	30,123.86
1.25” x 6” x 10’	23,905	0.076	77.21	1,852.14
1.5” x 6” x 10’	7,618	0.073	73.89	562.77
2” x 6” x 10’	9,820	0.046	47.34	508.40
Pallet	64,850	0.095	95.39	6,160.40
Cants	17,403	0.027	25.32	441.73
Timber	10,035	0.012	10.86	117.97
	460,994			**39,767.27**
Sawmill 2: Overall SEC: **83.56** kWh/MBF, **84.11** kWh/MBF				
Size	**Board Feet**	**kWh/Board Feet**	**kWh/MBF**	**Total kWh**
1” x 6” x 10’	158,100	0.153	153.42	22,292.49
1.25” x 6” x 10’	25,866	0.144	144.17	3,892.90
1.5” x 6” x 10’	12,284	0.095	94.85	1,151.85
2” x 6” x 10’	14,262	0.085	85.32	1,254.12
Pallet	14,666	0.157	157.12	2,188.07
Cants	86,499	0.029	29.20	2,141.13
Timber	109,010	0.019	18.51	2,233.10
	420,687			**35,153.66**
Sawmill 3: Overall SEC: **103.78** kWh/MBF, **105.61** kWh/MBF				
Size	**Board Feet**	**kWh/Board Feet**	**kWh/MBF**	**Total kWh**
1” x 6” x 10’	1,031,633	0.118	118.31	116,260.99
1.5” x 6” x 10’	31,020	0.067	66.73	2,069.07
2” x 6” x 10’	382	0.054	53.72	20.521671
Pallet	246,408	0.119	119.46	28,344.08
Timber	121,944	0.015	14.55	1,882.64
	1,431,387			**148,577.30***

Table 4.14: SEC Calculated based on Surface Area Cut

Sawmill 4: Overall SEC: **122.51** kWh/MBF, **121.95** kWh/MBF				
Size	**Board Feet**	**kWh/Board Feet**	**kWh/MBF**	**Total kWh**
1” x 6” x 10’	296,280	0.173	172.98	50,012.52
1.5” x 6” x 10’	31,070	0.128	127.72	3,480.64
2” x 6” x 10’	182,383	0.119	118.69	20,884.13
Pallet	6,974	0.184	183.78	1,281.73
Cants	106,688	0.039	38.80	3,818.25
Timber	36,984	0.031	31.12	1,330.11
	660,379			**80,807.38***
Sawmill 5: Overall SEC: **112.12** kWh/MBF **118.44** kWh/MBF				
Size	**Board Feet**	**kWh/Board Feet**	**kWh/MBF**	**Total kWh**
1” x 6” x 10’	594,681	0.124	124.29	71464.68
1.25” x 6” x 10’	173,337	0.118	118.33	23,624.78
2” x 6” x 10’	34,029	0.057	56.71	1,844.05
Pallet	57,221	0.133	133.31	7,234.80
Cants	67,872	0.032	31.84	1796.89
Timber	22,009	0.019	19.44	452.54
	949,149			**106,417.74**

*Calculated total kWh is little different from the values in Table 4.6 due to round off error

The result obtained by energy allocation based on surface area cut is completely different from the result obtained by just calculating overall SEC in which sawmill 2 had the lowest (Table 4.6) and it became 2nd highest now. The main reason for the change in the result for sawmill 2 can be attributed to higher percentage (47%) of larger lumber sizes like cants and timbers that were sawn in it (Table 3.4). Also, it can be noted that the SEC of the lumber sawn in sawmill 4 went up very high after energy allocation based on surface area was done since they produced lower board feet per kWh compared to other sawmills and also produced higher percentage (22%) of larger lumber sizes like cants and timbers compared to sawmill 1, 3 and 5. The other thing to be noted is both sawmill 2 and 4 does not have resaw or gangsaw and hence their production rate in terms of grade lumber was lower compared to other sawmills.

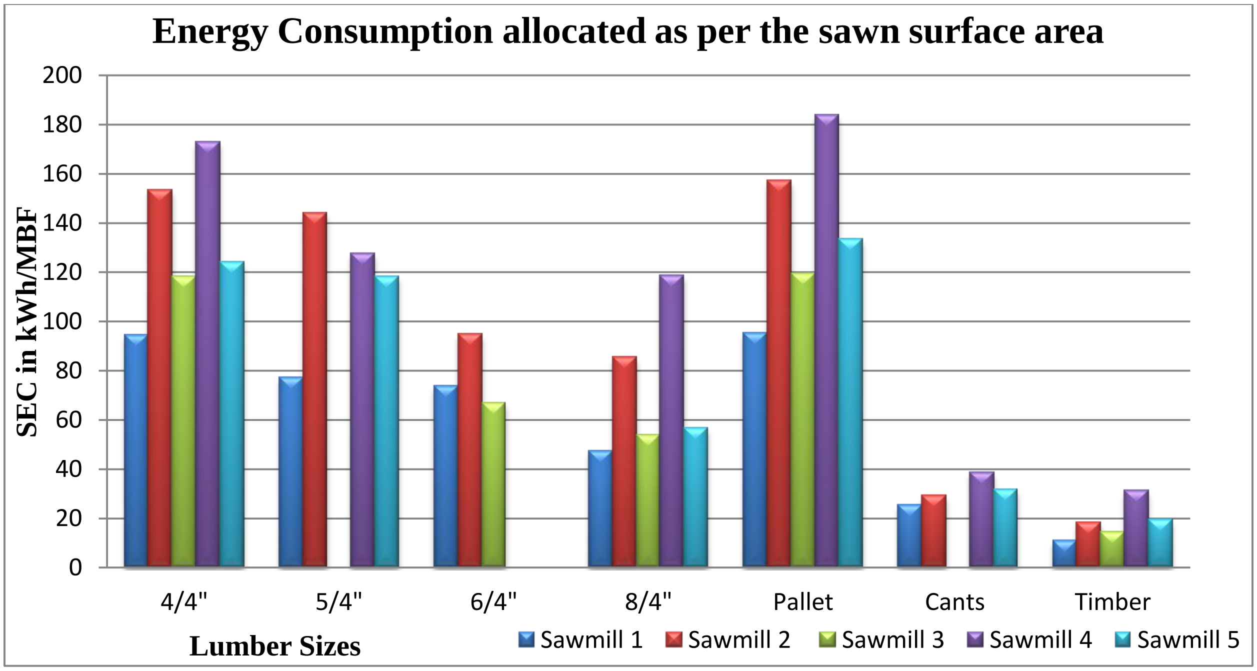


Figure 4.9: SEC of Sawmill 1 to 5 Calculated as per Surface Area Cut

Calculated SEC based on surface area cut for 4/4 size lumber for each shift of all the 5 sawmills are shown in Table 4.15. SEC of 4/4 size lumber for sawmill 1 and 2 didn't pass normality test where as the other 3 sawmills passed the normality test. In order to verify whether the SEC of 4/4 lumber of each sawmill are from the same population or not, non parametric Kruskal-Wallis Test (Table 4.16) was used since all the sawmills data didn't follow normal distribution. Box plots were plotted to verify whether the data follows symmetric distribution and although the data had some outliers, more or less all the sawmill's data followed symmetric distribution (Figure 4.10).

Table 4.15: Calculated SEC Values for 4/4 Lumber of 5 Sawmills for various Shifts*

Sl. No.	Sawmill 1 4/4	Sawmill 2 4/4	Sawmill 3 4/4	Sawmill 4 4/4	Sawmill 5 4/4
1	74.88	160.17	117.76	158.76	109.78
2	66.55	122.02	143.46	150.46	113.76
3	91.05	142.30	122.40	134.54	153.86
4	91.75	129.22	127.36	144.55	137.55
5	87.10	131.74	111.68	149.60	85.73
6	81.72	124.43	89.52	132.36	102.60
7	83.36	108.52	116.53	181.82	82.54
8	90.47	169.40	116.05	194.26	130.99
9	92.21	139.54	168.35	200.56	101.93
10	100.66	132.28	105.06	185.85	143.04
11	100.28	196.87	112.18	167.70	116.56
12	88.37	168.44	86.33	171.91	139.44
13	94.80	143.16	89.69	187.75	116.97
14	83.53	158.54	81.33	141.75	107.32
15	118.31	147.90	90.74	156.37	143.75
16	91.45	139.09	112.59	159.81	114.33
17	132.13	144.44	179.73	190.27	136.45
18	126.46	142.70	90.85	242.60	120.85
19	101.12	209.77	140.73	202.21	128.56
20	99.40	125.41	120.16	194.17	128.95
21	92.65	128.03	127.79	185.28	195.04
22	89.76	139.19	126.51		
23		113.13	130.41		
24		132.57	135.91		
25		189.55	114.65		
26		373.35			
27		160.03			
28		123.92			
Average	**94.46**	**153.42**	**118.31**	**172.98**	**124.29**

* Some of the shifts didn't saw 4/4 and hence those shifts SEC are not shown (Refer Appendix Table A.4)

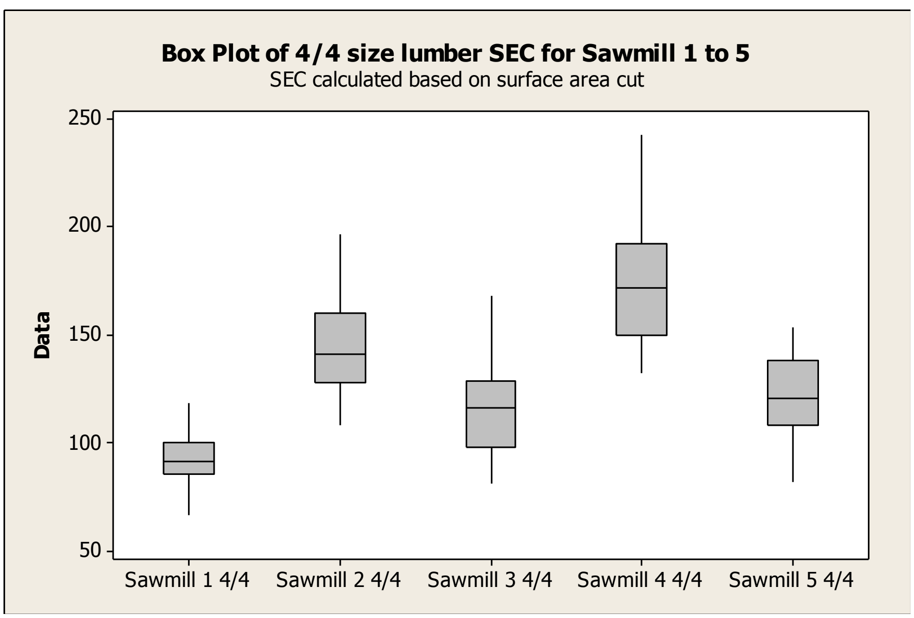


Figure 4.10: Box Plot of 4/4 Size Lumber SEC's of all the 5 Sawmills

Table 4.16: Kruskal-Wallis Test on 4/4 Lumber SEC Data

Multiple Comparisons				
Sawmill	N	Median	Ave Rank	Z
1	22	91.60	20.9	-5.85
2	28	140.92	77.1	3.25
3	25	116.53	45.2	-2.29
4	21	171.91	97.2	5.70
5	21	120.85	53.0	-0.90
Overall	117	-	59.0	-
H = 67.18 DF = 4 P = 0.000				

Pairwise Comparison Results of the Groups that showed Significant Differences		
Groups	Z vs. Critical value	P-value
1 vs. 4	7.37160 >= 2.326	0.0000
1 vs. 2	5.81915 >= 2.326	0.0000
3 vs. 4	5.17823 >= 2.326	0.0000
4 vs. 5	4.22618 >= 2.326	0.0000
2 vs. 3	3.42248 >= 2.326	0.0006
1 vs. 5	3.09657 >= 2.326	0.0020
2 vs. 5	2.47054 >= 2.326	0.0135
1 vs. 3	2.44981 >= 2.326	0.0143

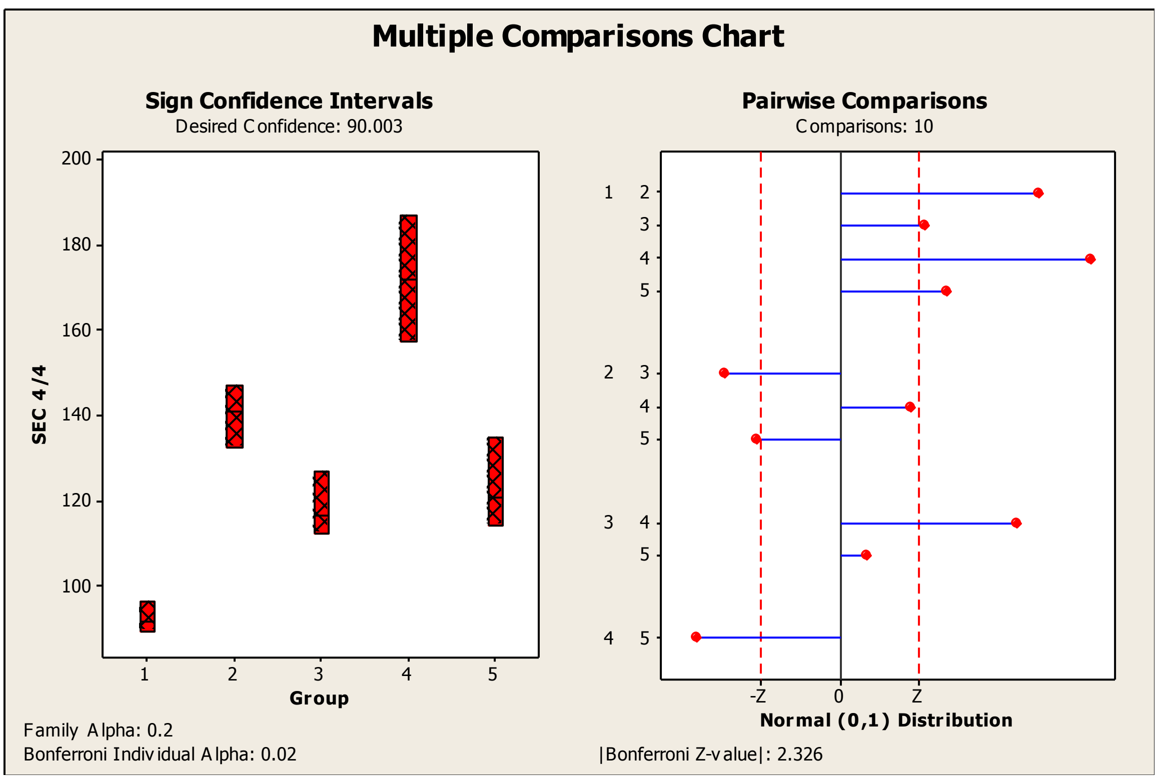


Figure 4.11: Kruskal-Wallis Test Results for 4/4 Lumber SEC's of all the 5 Sawmills

From the Kruskal-Wallis Comparison test (Figure 4.11) it was evident that sawmill 4 had the highest energy consumption followed by sawmill 2. There was no difference between the median's of Sawmill 3 and 5 and they stayed below sawmill 4 and 2. Sawmill 1 had the lowest energy consumption compared to all the other sawmills.

The calculation of 4/4 lumber size SEC based on surface area cut has still the variability of species. So, SEC for only the species of red oak of size 4/4 was calculated (Table 4.17) as an example for all the 5 sawmills and is shown in Figure 4.12.

Table 4.17: Calculated SEC Values for 4/4 Red Oak Lumber of 5 Sawmills for various Shifts

Sl. No.	Sawmill 1 4/4 RO	Sawmill 2 4/4 RO	Sawmill 3 4/4 RO	Sawmill 4 4/4 RO	Sawmill 5 4/4 RO
1	66.55	108.52	117.76	158.76	109.78
2	91.05	169.40	143.46	167.70	130.99
3	91.75	139.54	112.18	171.91	101.93
4	87.10	132.28	112.59	187.75	143.04
5	90.47	143.16	135.91	200.98	116.56
6	99.40	158.54	114.65		139.44
7	92.65	147.90			116.97
8	89.76	139.09			120.85
9		125.41			128.56
10		128.03			128.95
11		139.19			195.04
12		373.35			
13		160.03			
14		123.92			
Average	**88.59**	**156.31**	**122.76**	**177.42**	**130.19**

Again a Kruskal-Wallis Comparison test was conducted on the calculated values and the test results (Table 4.18) followed the similar pattern as 4/4 lumber test results.

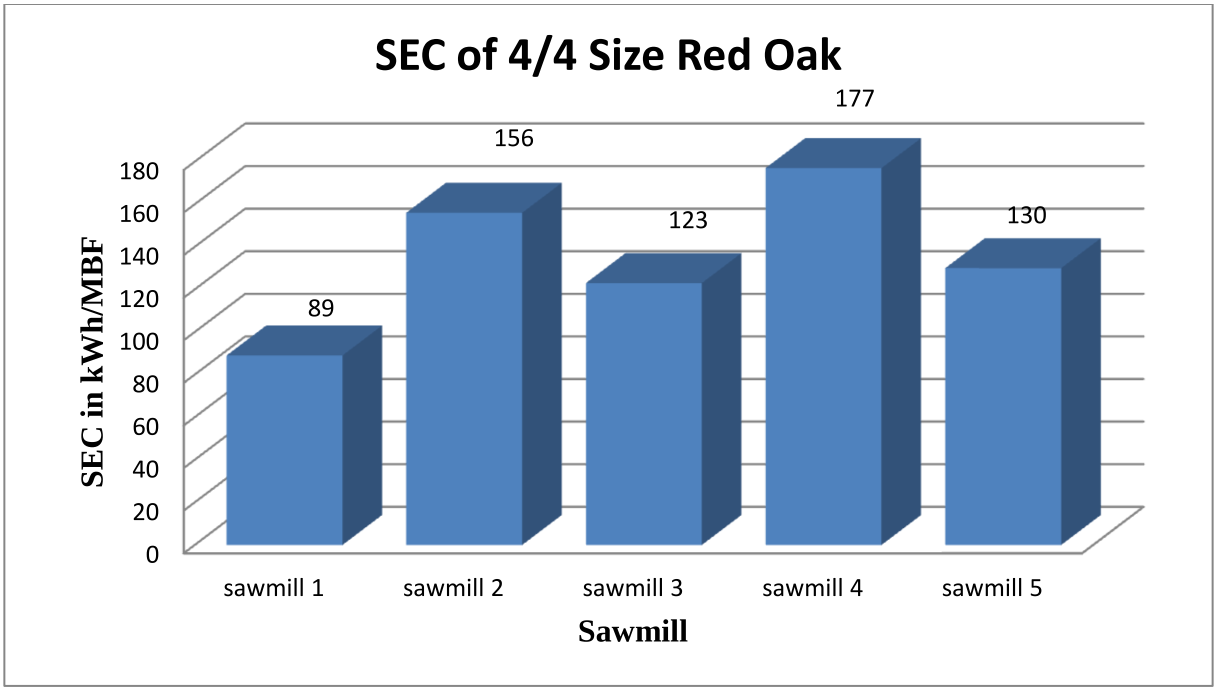


Figure 4.12: SEC of 4/4 Red Oak Lumber for Sawmill 1 to 5 Calculated as per Surface Area Cut

Table 4.18: Kruskal-Wallis Test on 4/4 Red Oak Lumber SEC Data

Multiple Comparisons				
Sawmill	N	Median	Ave Rank	Z
1	8	90.76	4.5	-4.38
2	14	139.36	28.6	2.17
3	6	116.20	19.2	-0.68
4	5	171.91	39.6	3.16
5	11	128.56	21.8	-0.20
Overall	44		22.5	
H = 28.21 DF = 4 P = 0.000				

Pairwise Comparison Results of the groups that showed significant differences		
Groups	Z vs. Critical value	P-value
1 vs. 4	4.79318 >= 2.326	0.0000
1 vs. 2	4.24077 >= 2.326	0.0000
1 vs. 5	2.90152 >= 2.326	0.0037
3 vs. 4	2.62701 >= 2.326	0.0086
4 vs. 5	2.56658 >= 2.326	0.0103

4.4 Discussion

From Figures 4.9 and 4.12, SEC of sawmill 2 and 4 are way more higher than the other sawmills and SEC of sawmill 1 is the lowest of all the sawmills. SEC of sawmill 3 and 5 are somewhere in the middle of all the sawmills.

Higher SEC of sawmills 2 and 4 can be attributed to the lack of re-saw (Figure 3.10). Although Sawmill 2 had the highest board feet produced per kWh spent (11.97 in Table 4.6), it is producing more of larger size lumber like cants and timbers (47% in Table 3.4) and hence ended up in consuming more SEC per board feet after energy allocation based on surface area was done. Sawmill 4 has the least board feet produced per kWh (8.16 in Table 4.6) due to lack of resaw and also produced higher percentage (22% in Table 3.4) of larger lumber sizes like cants and timbers compared to sawmill 1,3 and 5 and hence its SEC went up really high after energy allocation based on surface area was done. Without a resaw or a gangsaw, only one machine i.e., head saw will be sawing all the lumber and hence slows down the production rate. Once the head saw production slows up, other machines will be idling due to this. In sawmills 1, 3 and 5 there is either a resaw or a gangsaw in addition to headsaw to increase the production rate.

Sawmill 2 is no longer in business, it would have improved its productivity and energy efficiency by adding a resaw to its production line. Sawmill 4 has reported operating cost loss in some of the shifts during data collection period (Appendix Table A.27) due to working extra hours (overrun) than planned. That data is not discussed in detail since similar data from other sawmills is not available for comparison. Sawmill 4 can increase its production by adding a resaw or a gang saw. Also the board lumber price is higher than dimension lumber and timber and hence will increase the profitability of sawmill if it produces more of board lumber. If a sawmill can produce more of board lumber than dimension lumber and timber, then it has both productivity and profit compared to other sawmill that produces less of board lumber.

Even though sawmill 3 had the highest production rate in terms of board feet per hour (9,975 in Table 4.6), its board feet production per kWh was moderate (9.64 in Table 4.6) and also it ended up in the lower middle position after energy allocation based on surface area cut was done. There are two production lines in sawmill 3 with only one gangsaw for both the lines (Figure 3.10). From the sample amperage data taken from sawmill 3, it can be seen that Line 1 was working more (Figure 4.13) than line 2 (Figure 4.14) during data logging period. It looks like gang saw was unable to handle the production (Figure 4.15) from both the lines and forced one line to slow down and hence ended up in higher energy consumption than it could have achieved if the capacities were matched. Figure 4.13, 4.14 and 4.15 shows the production/energy consumption of line 1 head saw, line 2 head saw carriage feed and gang saw. Saw will be sawing the log at the point where there is a peak in the energy consumption in the plotted graphs. It is clear that Line 1 is more busy than Line 2 and gang saw is the busiest of all the three saws. Gang saw of sawmill 3 is of very high horse power 418 hp and the motor is loaded only to around 60% of its maximum capacity (Figure 4.15). The motor load factor (LF) is given by,

$$LF = (\sqrt{3} * V*I*\cos\Phi/(1000))/(\text{Motor hp} \times 0.746) \quad (4.5)$$

Where,

V = 470
I = 250 (Approximate Average of maximums in Figure 4.15)
cosΦ = 0.88
Motor hp = 418

$$LF = (\sqrt{3}*470*250*0.88/(1000))/(418 \times 0.746)$$
$$= 0.57$$

If they had two gang saws of say 200 hp each, definitely their production would have increased and also would have reduced energy consumption.

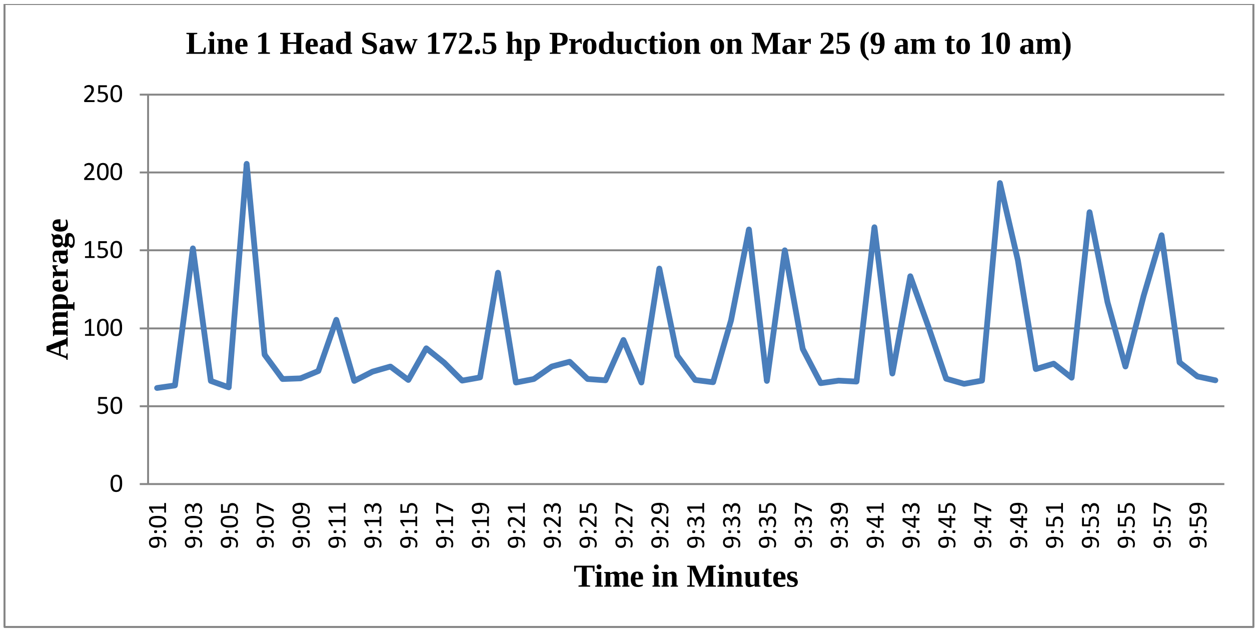


Figure 4.13: Sample of Line 1 Head saw Production of Sawmill 3

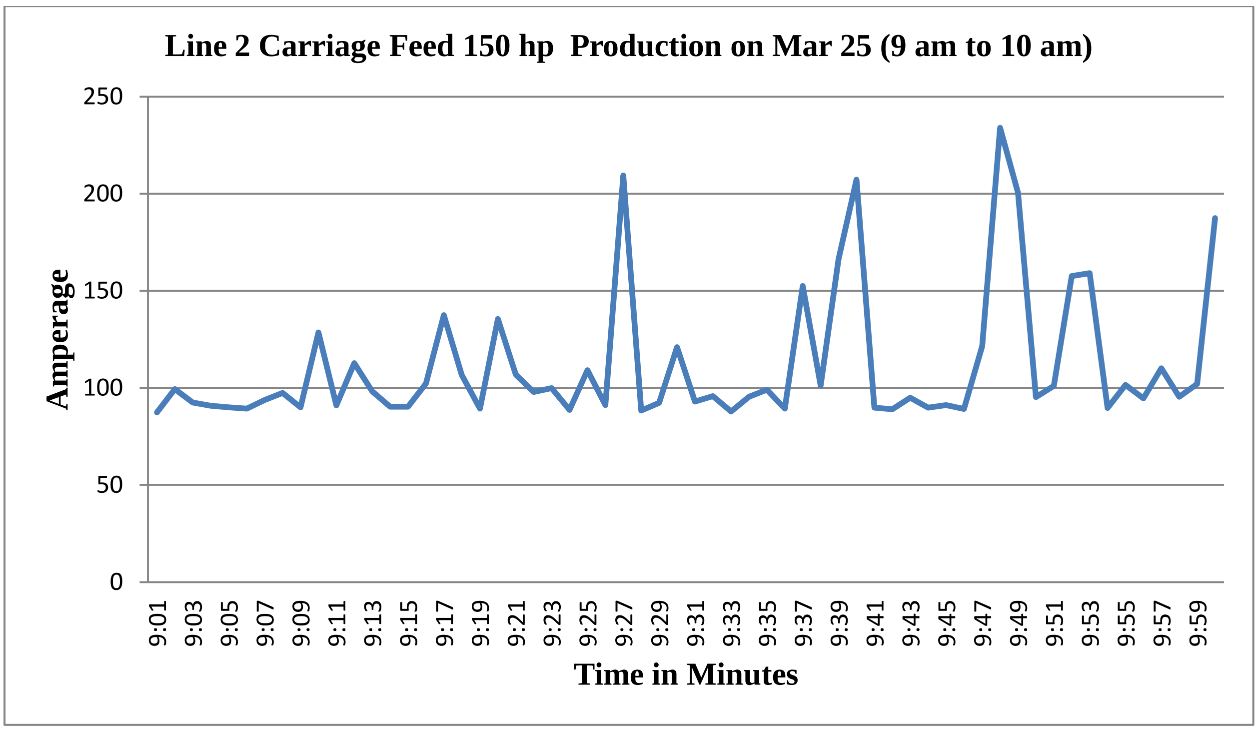


Figure 4.14: Sample of Line 2 Head Saw's Carriage Feed Production of Sawmill 3

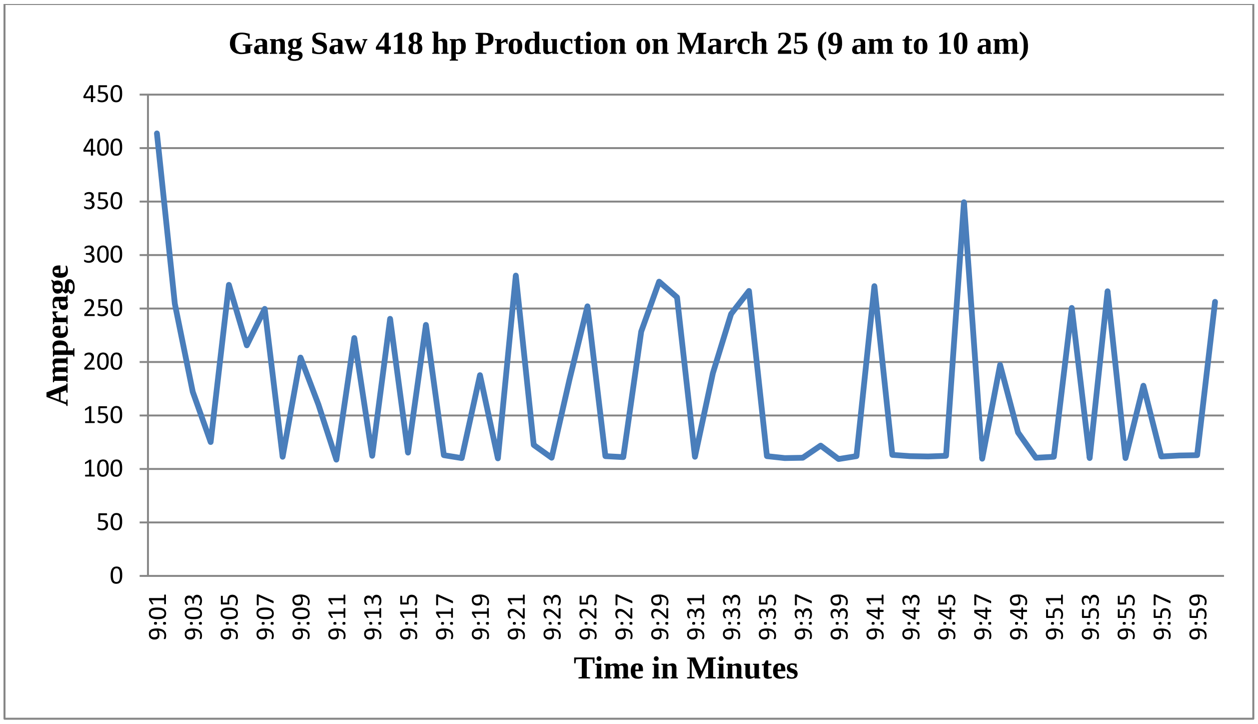


Figure 4.15: Sample of Gang Saw Production of Sawmill 3

SEC of sawmill 5 was in the middle and it stayed there even after energy allocation was done. SEC before energy allocation was 118.44 and after was 124.29 for 4/4 size lumber and hence didn't change much. Actually sawmill 5 worked two shifts during data collection period and there was clear difference between the energy consumption from day shift to night shift. Night shift consumed more energy per board feet by sawing less lumber in the same time compared to day shift (Table 4.19). If only the day shift's energy consumption is considered, then average SEC will be 108.23 and for night shift it will be 133.77. After energy allocation as per surface area cut is done, for 4/4 size lumber, it will be 112.68 for day shift and 143.14 for night shift. Day shift SEC of 112.68 is lower than SEC of sawmill 3 (118.31) obtained after energy allocation.

Another interesting thing to notice from Table 4.19 data is row number 4 which has a higher SEC in shift 1. This happened since the data collection duration was only 1.5 hours and data of smaller data points will not represent the true mean as discussed in the data collection plan.

Table 4.19: Production and Energy Consumption of Day and Night Shifts of Sawmill 5

Sl. No.	Date	Start Time	End Time	Species	4/4 to 8/4 (Board Feet)	Cant + Tim (Board Feet)	Sawmill 5 SEC
1	4/28/2014	6:00 AM	10:00 AM	RO	21,909	-	106.13
2	4/28/2014	10:00 AM	4:00 PM	HM	26,052	-	113.76
3	**4/28/2014**	**5:00 PM**	**2:30 AM**	**HM**	**32,150**	**-**	**153.86**
4	4/29/2014	6:00 AM	7:30 AM	HM	8,160	-	137.55
5	4/29/2014	7:30 AM	4:00 PM	YP	50,813	9,975	67.71
6	**4/29/2014**	**5:00 PM**	**2:30 AM**	**YP**	**50,448**	**10,698**	**84.87**
7	4/30/2014	6:00 AM	3:30 PM	YP	63,128	11,645	67.73
8	**4/30/2014**	**3:30 PM**	**2:30 AM**	**RO**	**43,450**	**-**	**129.64**
9	5/1/2014	6:00 AM	4:00 PM	RO	55,938	-	98.24
10	**5/1/2014**	**5:00 PM**	**2:30 AM**	**RO**	**37,107**	**-**	**139.94**
11	5/2/2014	6:00 AM	4:00 PM	RO	46,659	-	113.82
12	**5/2/2014**	**5:00 PM**	**2:30 AM**	**RO**	**36,535**	**-**	**137.99**
13	5/5/2014	6:00 AM	7:15 AM	RO	8,813	-	113.90
14	5/5/2014	7:15 AM	2:45 PM	AS	36,489	-	102.01
15	**5/5/2014**	**5:00 PM**	**2:30 AM**	**SM**	**33,653**	**10,096**	**117.99**
16	5/6/2014	6:00 AM	4:00 PM	SM	43,846	11,156	96.29
17	**5/6/2014**	**4:30 PM**	**12:00 PM**	**SM**	**24,196**	**7,068**	**112.49**
18	5/7/2014	6:00 AM	4:00 PM	WO	39,585	6,796	115.82
19	**5/7/2014**	**5:00 PM**	**2:30 AM**	**WO**	**32,131**	**4,912**	**138.43**
20	5/8/2014	6:00 AM	4:00 PM	WO	40,343	4,147	119.39
21	**5/8/2014**	**5:00 PM**	**2:30 AM**	**WO**	**23,758**	**7,228**	**151.36**
22	5/10/2014	6:00 AM	2:30 PM	RO	38,448	1,834	115.25
23	5/12/2014	6:00 AM	6:45 AM	RO	6,000	-	126.86
24	5/12/2014	6:45 AM	4:00 PM	HM	36,454	-	128.95
25	**5/12/2014**	**5:00 PM**	**2:30 AM**	**HM**	**23,203**	**4,326**	**171.11**
Average							**118.44**

Sawmill 5 has an additional gang saw along with resaw (Figure 3.10) to boost up the production and hence was better than sawmill 3 for day shift production. But the head saw cannot produce (Figure 4.16) enough cants to keep both resaw (Figure 4.17) and gang saw (Figure 4.18) busy and hence gang saw stays idle sometimes and consumes energy without producing anything and results in higher energy consumption than sawmill 1. Sawmill 5 can improve both its productivity and energy efficiency by installing an additional head saw.

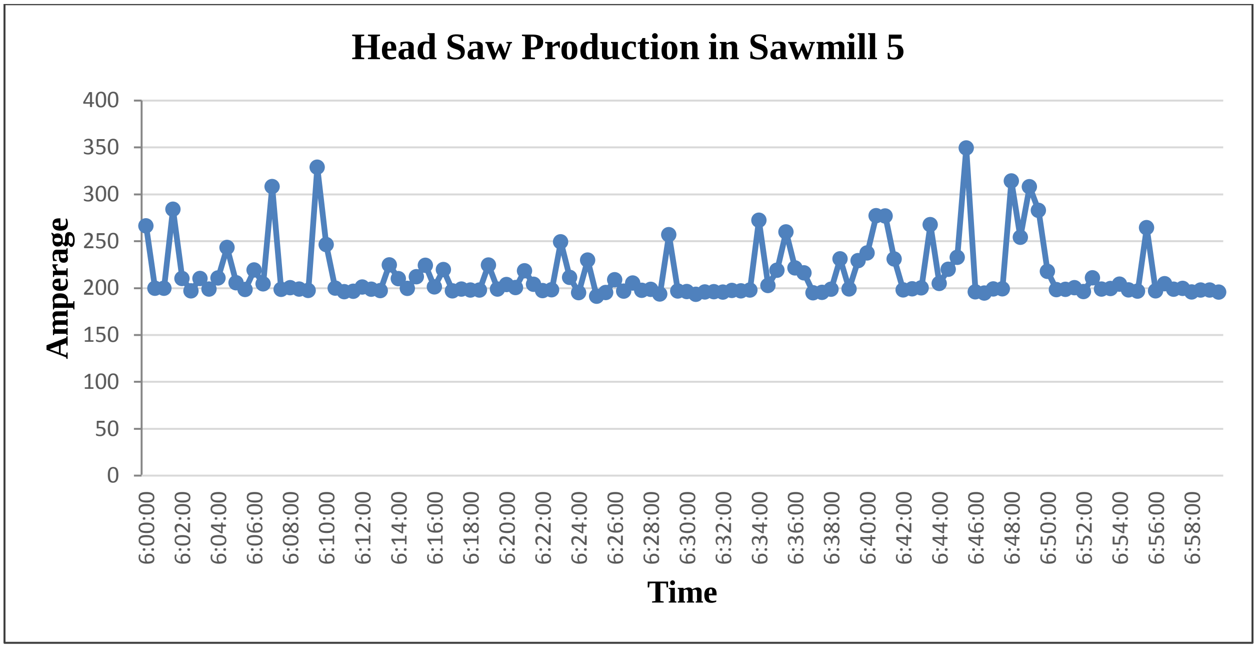


Figure 4.16: 250 hp Head Saw Amperage Consumption in Sawmill 5

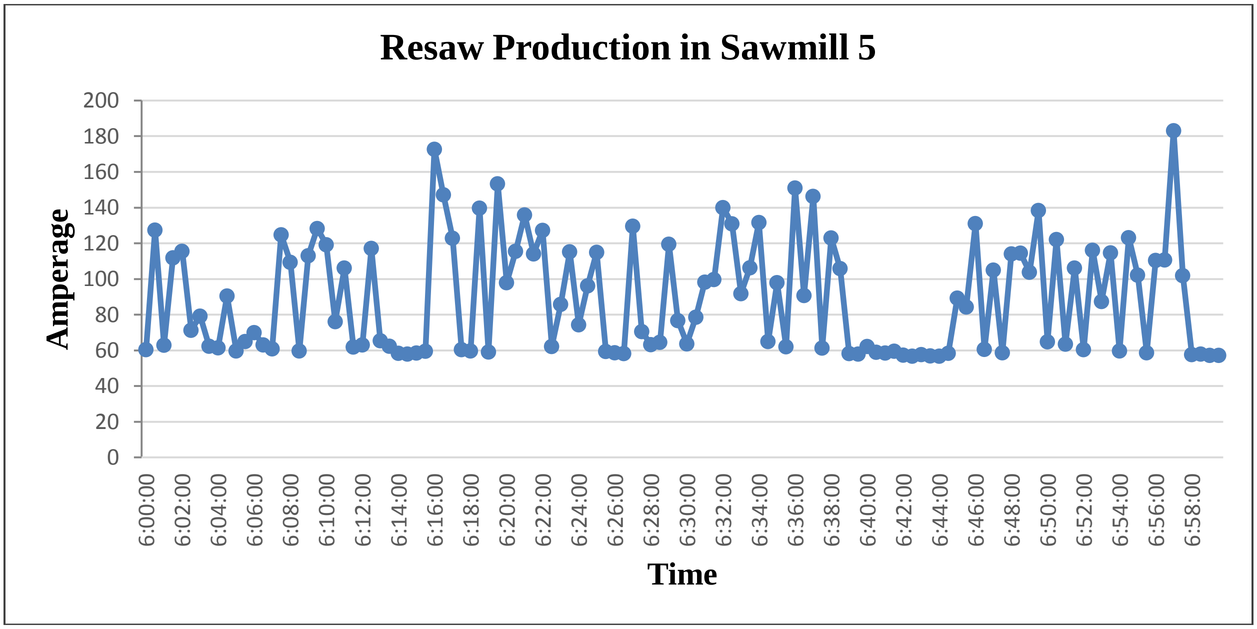


Figure 4.17: 150 hp Re-saw Amperage Consumption in Sawmill 5

Out of the five sawmills, sawmill 1 had the lowest energy consumption after energy allocation based on surface area was done. It looks like the manufacturing configuration of sawmill 1 is perfectly balanced to produce lumber at minimal energy consumption. Other thing to be noted about sawmill 1 is most of its motors capacity is small compared to other sawmills.

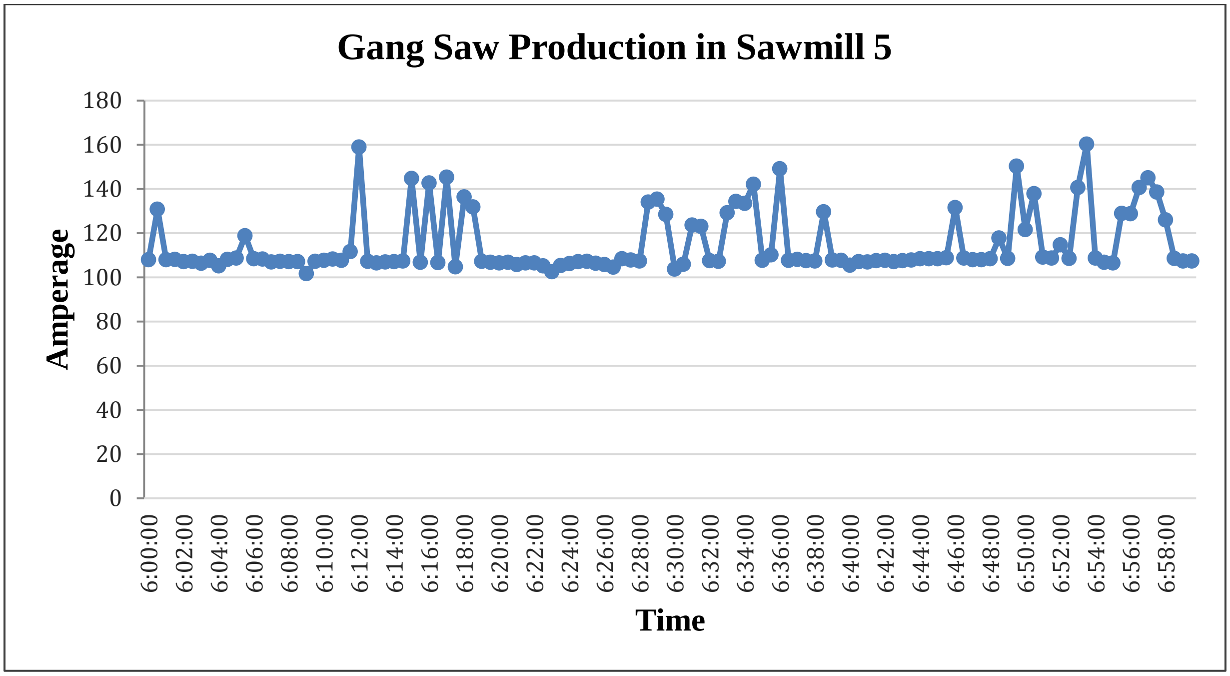


Figure 4.18: 100 hp Gang Saw Amperage Consumption in Sawmill 5

Average motor load factors of all the five sawmills are shown in Table 4.6. Except sawmill 5, all the other sawmills have load factor of less than 40%. Load factor is the percentage of motor capacity used on average for doing the particular mechanical work.

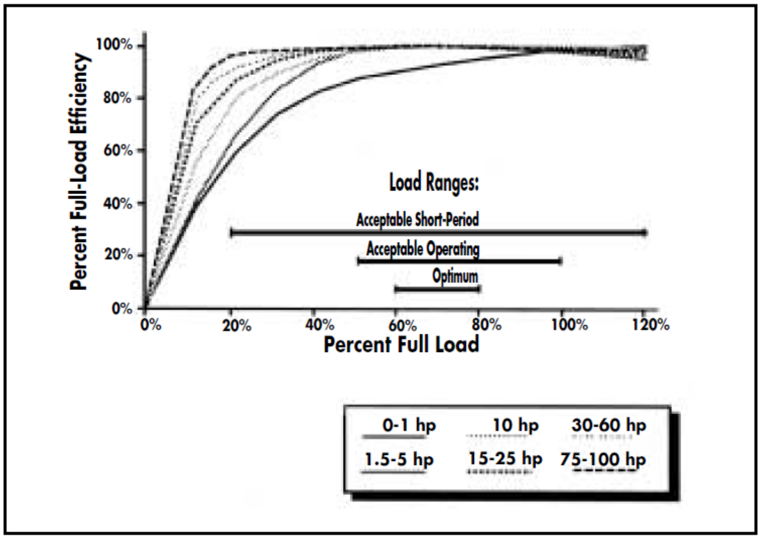


Figure 4.19: Motor Part –Load Efficiency (as a function of % Full-Load Efficiency)

Using of larger capacity motor to do small tasks compared to using smaller motors to do the same task will result in higher energy consumption for larger motor since motor efficiency goes down at loads lower than 40% (Figure 4.19, Rutgers 2015). Sawmill 1, 2, 4 and 5 can save energy by re-sizing its motors. Other energy efficiency measures similar to re-sizing of motors that were discussed in the literature review like improving the efficiency of compressor, using VFD on motors etc., will help sawmills to reduce their energy consumption. These energy efficiency measures were not mentioned here since they are standardized and were recommended during the energy assessments conducted by Industrial Assessment Center of West Virginia University at these facilities and are also available in the literature.

Conclusion

Looking at gross energy consumption and calculating overall energy consumption per board feet and using it to estimate the energy efficiency of a sawmill or using it for benchmarking like the authors did in the literature review will lead to wrong conclusions. Sawmills energy efficiency must be analyzed at a deeper level by taking the sizes and species of lumber sawn into account and allocating the energy consumption based on surface area cut for that particular size. The energy allocation method developed in this research will give a better picture of the sawmill performance in terms of both energy efficiency and productivity.

From the comparison of sawmills, it was evident that having a resaw or a gang saw in sawmill will improve productivity and energy efficiency to a great extent. Both sawmills 2 and 4 didn’t had either a resaw or a gang saw and hence ended up with high SEC compared to other sawmills. Also, it was clear that matching of machine capacities plays a major role to improve the productivity of a sawmill and sawmills 3 and 5 can improve their productivity and energy efficiency from matching their machine capacities.

5. Development of Estimation Model

5.1 Selection of Product, Process and System Parameters

A model that can estimate the energy consumption of a sawmill without data logging was developed by using the information collected from 4 sawmills on which this study was done. Data from Sawmill 1, 2, 4 and 5 was used to develop the model and the energy consumption of Sawmill 3 was estimated using the developed model. Production data that was collected from the 5 sawmills had information of the following sawmill parameters.

Product Parameters
- Species Sawn
- Board Feet sawn of different sizes

Process Parameters
- Sawing Time
- Ambient Temperature
- Level of Maintenance

System Parameters
- Motor horse power
- Equipment used
- Production Line Configuration

Product Parameters

The type of wood species sawn and the board feet of different size lumber sawn was considered as product parameters and they are quantitative (numerical) estimator variables. As discussed in the need for research, species is an important factor which affects the sawing energy consumption. There are 10 different species that were sawn during the study and the wood density of these species in lb/ft^3 (Engineering ToolBox 2015) was considered as one of the variable to estimate the energy consumption. Table 5.1 shows the range of density values for different species sawn during the research and also the values used in developing the model.

Table 5.1: Densities of different Wood Species sawn in Sawmill 1 to 5

Sl. No.	Species	Density Range (lb/ft^3)	Selected Value (lb/ft^3)
1	Soft Maple	33~50	35
2	Red Oak	37~56	44
3	White Oak	40~59	47
4	Ash	34~52	40
5	Hard Maple	42~59	47
6	Hickory	48~64	64
7	Cherry	43~56	56
8	Yellow Poplar	22~31	24
9	Birch	42~57	44
10	Sycamore	24~37	26

The values of the density that was selected from the density range are the ones that minimized the estimation error. Also, the developed model is able to estimate the sawing energy consumption of a new species other than the 10 species considered in this study if the density of the new species is known.

From the data analysis, it was clear that lumber sizes were significantly affecting the sawing energy consumption. There are around 7 lumber sizes that were sawn in the sawmills during this study. These lumber sizes were broadly classified into three types as board, dimension or cant and timber sizes. All the 7 lumber sizes were not sawn in all the shifts in all the 5 sawmills. So, grouping of variables with common characteristics was done. All the board size lumber (4/4 to 8/4 and pallet size, pallet will be usually of size 4/4) was grouped together since they are smaller thickness lumber. Point to be noted is 5/4, 6/4 and 8/4 lumber sizes are in very low quantity when compared to 4/4 size lumber (Table 3.4). Cants and timbers were grouped together since they are larger thickness lumber.

Process Parameters

The process efficiency of a manufacturing process can be basically evaluated by looking at the production rate or how much lumber is produced in a unit time for a sawmill. The variable that drives the production rate is sawing time and hence it will be one of the significant variable to estimate sawing energy consumption and was included as a quantitative estimator variable.

As discussed in literature review, maintenance of saw blades is critical to reduce energy consumption during sawing (Cristóvão 2013) and also to improve quality of lumber produced. In the article discussed, sawing energy consumption increased by 11 to 35% during an 8-hour shift, mainly due to an increase in the tooth radius and hence the level of maintenance of saw blades is considered as a process predictor variable for predicting energy consumption. Table 3.8 shows the collected data about maintenance procedure in different sawmills and the maintenance index assigned to each sawmill based on it. The maintenance index will be quantitative (numerical) discrete variable.

Sawmill data was collected in different periods of the year and the temperature of the logs sawn was different in different sawmills. Within each sawmill, temperature varied significantly from beginning to the end of the data collection period. Temperature or effect of seasonal variation was found to have some effect on the cutting force of sawing in one of the literature reviews and hence was included in the model and was tested for its significance.

The other process parameter, moisture content was discussed in the literature review and was found that it doesn't affect the sawing energy consumption significantly since the moisture content of the logs sawn in sawmills will be above fiber saturation point. Hence, atmospheric humidity which affects the moisture content of the wood was not considered as a parameter for developing estimation model.

System Parameters

The main system parameter identified is the motor horsepower of the equipment used for sawing process and it is a quantitative variable. Each sawmill has different total motor horsepower and produce different production quantities and hence there is a direct relationship between the energy consumed for sawing and motor horse power used for it. If a sawmill has higher motor horsepower then it must produce higher quantity of lumber proportionate to its motor horsepower to be energy efficient, else it will lose its efficiency.

The other system parameters considered are lack of resaw vs. having resaw, single production line vs. double production lines and ring debarker vs. rosser-head debarker. All these variables were considered as qualitative (categorical) variables. Since sawmill 3 and 5 had ring debarker and also gang saw, gang saw was not considered as a variable due to the problem of collinearity. Since sawmill 3 does not have resaw, gangsaw was considered as resaw for the lack of resaw vs having resaw variable. Table 5.2 lists the qualitative and quantitative discrete variables considered in all the five sawmills.

Table 5.2: Qualitative (Categorical) and Quantitative Discrete Variables for Sawmill 1 to 5

Mill #	Ring Debarker	Resaw	Double Line	Maintenance Index
1	0	1	0	4
2	0	0	0	3
3	1	1	1	2
4	0	0	1	2
5	1	1	0	2

The other system parameters like type of equipment used for ex: Bandsaw vs Circular Saw, and disc chipper vs. drum chipper were not considered since only sawmill 1 had circular saw and none of the sawmills had drum chippers. Also, type of saw blade material was not considered as an estimator variable since, all the sawmills were using same saw blade material for their saws (Table 3.7). Totally ten estimator variables were considered for developing the estimation model.

5.2 Estimation Model Development

Estimation model can be developed using many techniques. The basic technique used is ordinary least square regression model for independent variables that doesn't have substantial uncertainties. The ordinary least-squares model minimizes the sum of squared residuals, a residual being the difference between an observed value and the fitted value provided by a model. Least squares models can be linear or non-linear, depending on the relationship of the independent variable with the dependent variable. A multiple linear regression model with interaction effect will be of the form,

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i2} x_{i3} + \ldots \beta_p x_{ip} + \varepsilon_{i,} \quad i = 1, \ldots, n.$$

Where,

y	*= dependent variable*
x_1, x_2, x_3, x_p	*= independent variables*
$x_2 x_3$	*= interaction effect*
β_0	*= Y intercept*
$\beta_1, \beta_2, \beta_3, \beta_p$	*= regression parameters*
i	*= represents the i^{th} observation or data point*
n	*= total number of observations*
p	*= total number of regression parameters*
ε	*= residual*

The assumption of the above model is residuals are normally distributed with mean 0 and variance σ^2 and variance is estimated by s^2 and the formula to estimate s^2 is shown below. s^2 is also known as mean squared error or MSE.

$$s^2 = \frac{\sum e_i^2}{n - p - 1}$$

Estimation model development was tried using the variables from product, process and system parameters using multiple linear regression technique to estimate SEC (Table 4.5). Bidirectional elimination stepwise regression was used to select the significant variables from the 10 estimator variables. Alpha value used for both adding and removing the variable from the model was 0.15. Data from sawmill 1, 2, 4 and 5 (Appendix Table A.3) was used to select the estimator variables using stepwise regression in Minitab. Totally there were 108 data points from sawmill 1, 2, 4 and 5 to develop estimation model. Traditionally, 70% of the data is used for model development and 30% will be used for validation. But due to the necessity of developing a robust estimation model, it was decided to use data from 4 sawmills to develop the model and use data from 5th sawmill for validation.

The results of stepwise regression are shown in Appendix Table A.22. From the stepwise regression, 6 variables out of 10 were selected. Some estimators are highly correlated with each other and hence, Mallows' Cp is not displayed in the stepwise regression output. Mallows' Cp for the model with only the selected variables in stepwise regression is 7 which tell that the model fits the data well. The selected variables are Density, Lumber sizes (4 to 8 Qtr + Pallet, Cant + Tim), Minutes, Motor horsepower, and Resaw. Density was selected as expected since it was affecting energy consumption as discussed in the literature review. Motor horsepower and minutes were selected since they are the key variables that are used to calculate energy consumption of a motor. Lumber sizes were selected in stepwise regression since they affect the energy consumption as discussed in energy allocation methodology. As discussed in data analysis while comparing different sawmills, resaw was significantly affecting energy consumption and hence was selected in the stepwise regression. The other variables Debarker, Temperature, Double Line, and Level of Maintenance were rejected and hence can be considered as not significant. A multiple linear regression model (Model 1) was developed using the above 6 estimator variables in Minitab and the results are shown below. Residual plots (Figure 5.1) show that there are some outliers in the data and residuals follow a normal distribution and are distributed within ±15 kwh/MBF.

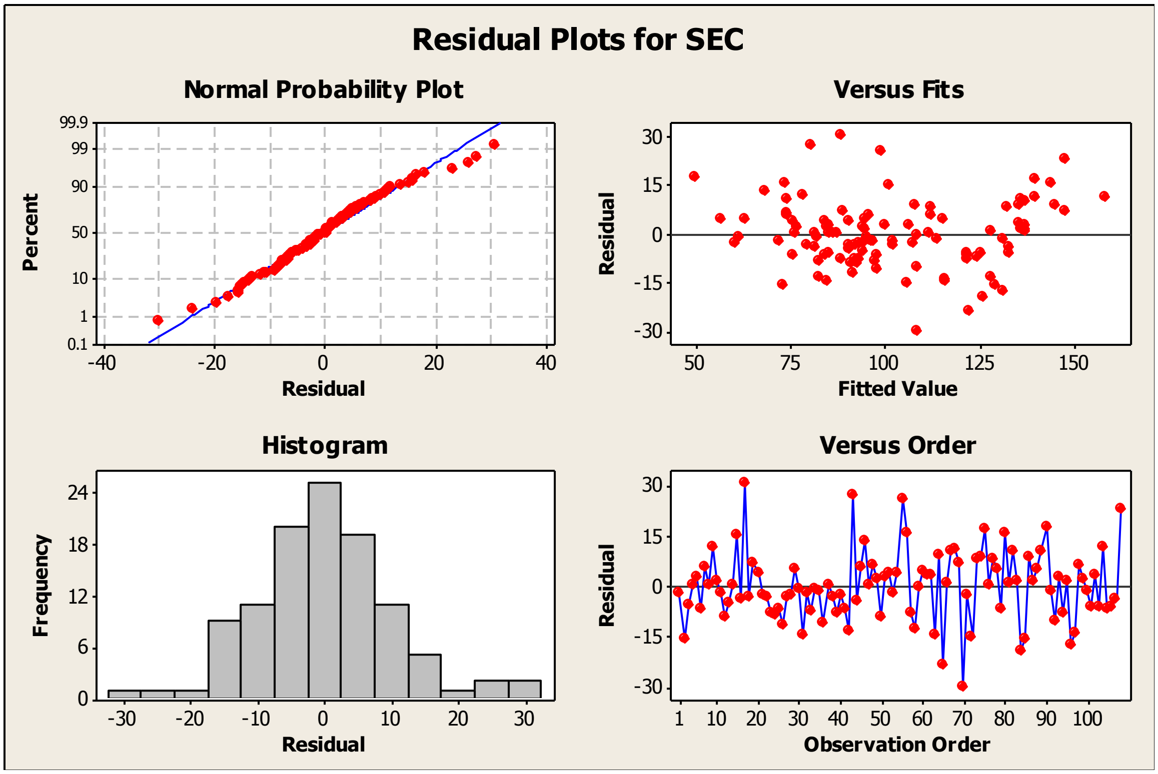


Figure 5.1: Residual Plots of Regression Model 1

Regression Equation

```
SEC  =  -28.1881 + 0.0817785 Motor hp + 0.106858 Min + 0.780301 Density -
        0.00163478 4 to 8 Qtr + Pallet - 0.00231198 Cant + Tim - 10.973 Resaw
```

Coefficients

Term	Coef	SE Coef	T	P	VIF
Constant	-28.1881	7.45123	-3.7830	0.000	
Motor hp	0.0818	0.00397	20.5983	0.000	2.12048
Min	0.1069	0.01096	9.7542	0.000	3.94462
Density	0.7803	0.12891	6.0533	0.000	1.47212
4 to 8 Qtr + Pallet	-0.0016	0.00019	-8.6071	0.000	6.97387
Cant + Tim	-0.0023	0.00038	-6.0118	0.000	1.76591
Resaw	-10.9730	2.99182	-3.6677	0.000	2.12070

Summary of Model

```
S = 10.5852      R-Sq = 84.63%        R-Sq(adj) = 83.72%
PRESS = 13304.6  R-Sq(pred) = 81.93%
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	6	62303.9	62303.9	10384.0	92.676	0.0000000
Motor hp	1	32676.2	47540.1	47540.1	424.292	0.0000000
Min	1	119.0	10660.6	10660.6	95.145	0.0000000
Density	1	13314.0	4105.6	4105.6	36.642	0.0000000
4 to 8 Qtr + Pallet	1	11917.7	8300.6	8300.6	74.082	0.0000000
Cant + Tim	1	2769.8	4049.5	4049.5	36.141	0.0000000
Resaw	1	1507.2	1507.2	1507.2	13.452	0.0003927
Error	101	11316.6	11316.6	112.0		
Total	107	73620.5				

R^2 adjusted of the developed model 1 was 83.72%, the R^2 predicted was 81.93% and MSE was 112. The interesting thing to notice is the signs of the regression coefficients. Motor hp, minutes and density have positive signs since they are directly proportional to energy consumption. Lumber size 4 to 8 Qtr + Pallet, Cant + Tim have negative signs, which means that if more lumber is sawn in a given time, lesser will be the energy consumption per board feet. Also, another interesting thing to notice is the value of regression coefficient. The value of '4 to 8 Qtr + Pallet' regression coefficient is higher than 'Cant + Tim' coefficient by 41.4%, which means that 41.4% more energy is consumed when board size lumber is sawn compared to cants and timbers. This percentage will be higher if only four quarter lumber is compared to timbers, since here all the board lumber sizes are grouped together and also cants and timbers are grouped together. The sign of the resaw is negative which tells that if a resaw is used in a sawmill, lesser will be the energy consumption per board feet. SE (standard error) coefficient measures the precision of the estimate of the coefficient and hence tells which variable can estimate better than the other variables. From the results it can be seen that '4 to 8 Qtr + Pallet' variable is the best estimator followed by 'Cant + Tim' and 'Motor hp'. The least precise estimator is the variable 'Resaw'. From the ANOVA (Analysis of Variance), and T test, it can be seen that all the estimator variables are significant with P value less than 0.01 and variance inflation factor of less than 10 and hence estimator variables are not correlated. The variable that is explaining the maximum variance is 'Motor hp' and then 'Minutes' and the variable that is explaining the least variance is 'Resaw'. Estimator variable 'Resaw' is significant in both T test and F test and has the least P value. The SEC values estimated from the fitted model 1 are shown in Table 5.3.

Table 5.3: Estimated SEC values from Regression Model 1

No.	Mill #	Motor hp	Run time (Minutes)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	SEC	Estimated SEC	Error
1	1	968	555	35	29,726	2,648	1	70.05	71.90	-1.85
2	1	968	**75**	44	5,656	0	1	57.49	73.10	**-15.61**
3	1	968	630	44	33,160	984	1	79.48	85.17	-5.69
4	1	968	630	44	32,004	1,416	1	86.37	86.06	0.30
5	1	968	235	44	12,188	1,187	1	79.31	76.78	2.53
6	1	968	395	47	19,329	1,294	1	77.59	84.29	-6.70
7	1	968	240	40	12,954	832	1	79.62	73.76	5.87
8	1	968	390	44	17,708	816	1	85.66	85.17	0.49
9	1	968	120	47	6,765	0	1	90.42	78.44	11.98
10	1	968	510	47	22,100	240	1	95.95	94.49	1.46
11	1	968	570	47	24,663	312	1	94.75	96.54	-1.79
12	1	968	630	47	29,521	1,320	1	83.83	92.68	-8.86
13	1	968	630	47	28,348	1,640	1	88.84	93.86	-5.02
14	1	968	630	35	31,129	1,056	1	81.51	81.30	0.21
15	1	968	240	64	8,489	192	1	116.38	101.26	**15.12**
16	1	968	285	47	12,093	2,613	1	77.42	81.32	-3.90
17	1	968	**105**	56	3,337	435	1	119.23	88.46	**30.77**
18	1	968	630	56	19,746	7,241	1	98.66	102.00	-3.34
19	1	968	195	56	8,815	676	1	95.50	88.56	6.94
20	1	968	435	44	17,670	552	1	94.74	90.65	4.09
21	1	968	630	44	28,526	744	1	90.76	93.30	-2.54
22	1	968	630	44	29,629	1,240	1	86.94	90.35	-3.41
23	2	817	270	64	4,904	5,237	0	89.13	97.29	-8.16
24	2	817	240	47	5,863	3,925	0	73.99	82.29	-8.29
25	2	817	510	47	10,301	6,540	0	91.16	97.84	-6.68
26	2	817	510	47	11,034	8,891	0	79.47	91.20	-11.73
27	2	817	180	47	3,975	3,867	0	76.00	79.09	-3.09
28	2	817	270	24	5,858	7,166	0	57.54	60.06	-2.52
29	2	817	120	24	2,598	4,194	0	61.25	56.23	5.01
30	2	817	390	24	7,967	10,652	0	60.79	61.38	-0.58
31	2	817	510	44	13,481	8,950	0	70.04	84.73	-14.68
32	2	817	510	44	8,162	7,840	0	94.01	95.99	-1.98
33	2	817	510	44	10,465	7,593	0	85.15	92.79	-7.64
34	2	817	300	44	7,211	4,914	0	80.82	81.87	-1.05
35	2	817	150	64	1,852	2,775	0	94.05	95.15	-1.10
36	2	817	330	64	5,706	7,104	0	87.07	98.07	-11.00
37	2	817	150	44	3,231	3,307	0	76.63	76.06	0.58
38	2	817	510	44	9,196	8,931	0	88.53	91.77	-3.25
39	2	817	510	44	9,802	8,309	0	84.54	92.22	-7.68
40	2	817	480	44	9,765	6,199	0	91.35	93.95	-2.60
41	2	817	30	47	613	862	0	68.88	75.51	-6.63

No.	Mill #	Motor hp	Run time (Minutes)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	SEC	Estimated SEC	Error
42	2	817	450	47	8,613	11,556	0	69.25	82.59	-13.33
43	2	817	**105**	47	1,682	1,600	0	107.59	80.07	**27.52**
44	2	817	405	47	6,595	7,461	0	85.95	90.55	-4.60
45	2	817	450	47	6,872	7,177	0	101.26	95.56	5.70
46	2	817	60	35	1,236	891	0	81.96	68.27	13.69
47	2	817	510	35	10,589	6,930	0	87.31	87.10	0.21
48	2	817	255	35	6,155	3,888	0	80.49	74.13	6.36
49	2	817	255	44	5,320	2,990	0	86.72	84.60	2.13
50	2	817	450	44	9,135	6,592	0	81.71	90.87	-9.16
51	2	817	330	44	6,847	5,067	0	88.09	85.31	2.78
52	2	817	180	47	4,361	1,520	0	88.15	83.89	4.26
53	2	817	510	47	10,900	4,348	0	100.14	101.93	-1.79
54	2	817	45	47	735	1,430	0	79.64	75.60	4.04
55	2	817	465	44	2,584	8,378	0	125.07	99.05	**26.02**
56	2	817	**60**	44	1,451	1,459	0	89.72	73.62	**16.09**
57	2	817	450	44	10,119	6,966	0	80.51	88.40	-7.89
58	4	1,534	195	44	8,791	4,264	0	115.22	128.20	-12.98
59	4	1,534	405	24	25,259	4,138	0	108.23	108.40	-0.17
60	4	1,534	600	24	43,156	6,370	0	99.65	94.82	4.83
61	4	1,534	600	24	38,884	7,182	0	103.05	99.93	3.12
62	4	1,534	555	24	34,213	5,548	0	109.70	106.54	3.17
63	4	1,534	45	26	1,678	1,744	0	100.94	115.58	-14.64
64	4	1,534	300	26	6,296	13,659	0	116.97	107.73	9.23
65	4	1,534	300	47	19,689	5,040	0	98.44	122.15	**-23.72**
66	4	1,534	600	47	27,905	6,674	0	137.93	137.00	0.93
67	4	1,534	180	47	7,188	1,852	0	147.41	137.14	10.27
68	4	1,534	420	64	15,478	3,748	0	169.34	158.11	11.23
69	4	1,534	330	64	15,437	4,070	0	154.92	147.82	7.10
70	4	1,534	**120**	26	4,915	5,948	0	78.61	108.58	**-29.98**
71	4	1,534	465	35	23,908	11,956	0	105.08	107.53	-2.45
72	4	1,534	330	35	15,917	12,216	0	90.29	105.57	**-15.28**
73	4	1,534	270	44	12,724	3,244	0	140.53	132.14	8.39
74	4	1,534	600	44	27,184	6,783	0	144.54	135.59	8.95
75	4	1,534	525	44	21,340	5,565	0	156.76	139.94	**16.82**
76	4	1,534	355.2	24	21,700	3,052	0	111.76	111.41	0.35
77	4	1,534	600	24	33,112	5,922	0	120.46	112.28	8.18
78	4	1,534	195	24	10,144	2,149	0	120.26	115.27	4.99
79	4	1,534	394.8	40	21,944	4,512	0	117.52	124.35	-6.84
80	4	1,534	600	40	23,151	4,739	0	159.87	143.78	**16.09**
81	4	1,534	330	40	16,449	3,752	0	129.35	128.17	1.18
82	4	1,534	270	47	12,199	2,902	0	146.91	136.13	10.78
83	4	1,534	600	47	28,046	6,643	0	138.38	136.84	1.54

No.	Mill #	Motor hp	Run time (Minutes)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	SEC	Estimated SEC	Error
84	5,1#	1,686	266	44	21,909	-	1	106.13	125.66	**-19.53**
85	5,1	1,686	342	47	26,052	-	1	113.76	129.35	**-15.59**
86	5,2	1,686	582	47	32,150	-	1	153.86	145.02	8.83
87	5,1	1,686	130	47	8,160	-	1	137.55	135.94	1.60
88	5,1	1,686	482	24	50,813	9,975	1	67.71	62.82	4.89
89	5,2	1,686	598	24	50,448	10,698	1	84.87	74.14	10.73
90	5,1	1,686	584	24	63,128	11,645	1	67.73*	49.73	**18.00**
91	5,2	1,686	647	44	43,450	-	1	129.64	131.16	-1.52
92	5,1	1,686	627	44	55,938	-	1	98.24	108.60	-10.37
93	5,2	1,686	604	44	37,107	-	1	139.94	136.93	3.01
94	5,1	1,686	608	44	46,659	-	1	113.82	121.74	-7.92
95	5,2	1,686	592	44	36,535	-	1	137.99	136.58	1.40
96	5,1	1,686	**117**	44	8,813	-	1	113.90	131.15	**-17.25**
97	5,1	1,686	427	40	36,489	-	1	102.01	115.91	-13.90
98	5,2	1,686	601	35	33,653	10,096	1	117.99	111.89	6.10
99	5,1	1,686	611	35	43,846	11,156	1	96.29	93.85	2.44
100	5,2	1,686	410	35	24,196	7,068	1	112.49	113.94	-1.45
101	5,1	1,686	625	47	39,585	6,796	1	115.82	121.75	-5.93
102	5,2	1,686	596	47	32,131	4,912	1	138.43	135.20	3.24
103	5,1	1,686	614	47	40,343	4,147	1	119.39	125.46	-6.07
104	5,2	1,686	562	47	23,758	7,228	1	151.36	139.90	11.47
105	5,1	1,686	523	44	38,448	1,834	1	115.25	121.84	-6.59
106	5,1	1,686	90	44	6,000	-	1	126.86	132.86	-6.00
107	5,1	1,686	534	47	36,454	-	1	128.95	132.86	-3.91
108	5,2	1,686	565	47	23,203	4,326	1	171.11	147.83	**23.28**
Average of Absolute Error Value										**7.71**

* denotes an observation whose X value gives it large leverage
#Sawmill 5 data is shown with both 1st and 2nd shifts.

There are totally 16 data points out of 108 with error of greater than ±15 kwh/MBF and the average of absolute error value was 7.71 kWh/MBF from the estimation results of Model 1 for sawmill 1, 2, 4 and 5. Error of ±15 kwh/MBF was considered since the average SEC for all the sawmills was around 100 kWh/MBF and the R^2 was around 85%. The data points 2, 17, 43, 56, 70, and 96 have shift run times less than 2.75 hours and hence have resulted in higher error levels. As discussed in data collection plan, to keep the error rate at ± 10%, at least 2.75 hours data is required for each data set.

Data point 55 seems to have an error in the reported data or the sawmill 2 has poor yield in that shift. Compare data points 50 and 55 from the same sawmill sawing same species as is Table 5.3. Data point 50 had production time of 450 minutes and produced 15,727 (9,135 of 4/4 to 8/4 + Pallet, 6,592 Cant + Tim) board feet, where as data point 55 had production time of 465 minutes and produced 10,962 (2,584 of 4/4 to 8/4 + Pallet, 8,378 Cant + Tim) board feet resulting in 30% lower yield and hence its SEC has gone up compared to other SEC's from sawmill 2 and hence cannot be estimated accurately.

Sawmill 5 had 2 shifts working during the data collection period and there was clear difference in the SEC between 1st and 2nd shift. 2nd shift SEC was always higher than 1st shift since it was sawing lumber during night and productivity of the workers was low. Data point 90 seems to have an error in the reported data as per Minitab analysis, or the sawmill 5 had very high yield in that shift. Compare data points 89 and 90 from the same sawmill sawing same species as is Table 5.3. Data point 89 had production time of 598 minutes and produced 61,146 (50,448 of 4/4 to 8/4 + Pallet, 10,698 Cant + Tim) board feet, where as data point 90 had production time of 584 minutes and produced 74,773 (63,128 of 4/4 to 8/4 + Pallet, 11,645 Cant + Tim) board feet resulting in 22% higher yield and hence its SEC has gone down compared to data point 89's SEC and hence cannot be estimated accurately.

Still there are 7 data points (15, 65, 72, 75, 80, 84, 85, 108) with error of more than ±15 kwh/MBF and must be reduced by improving the model 1.

Table 5.4 shows the data from sawmill 3 and the estimated SEC values using the developed regression model 1. The developed model 1 has failed to estimate the SEC of sawmill 3. There are only 2 data points out of 25 that have error value less than ±15 kwh/MBF and the average of absolute error value is 41.24 kWh/MBF.

Table 5.4: Data of Sawmill 3 and estimated SEC using Model 1

No.	Mill #	Motor hp	Run time (Minutes)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board	Cant + Tim (Board	Resaw	SEC	Estimated SEC	Error
1	3	2630.5	480	44	70,762	9,645	1	105.28	123.60	-18.33
2	3	2630.5	120	44	15,476	2,717	1	124.48	191.53	-67.06
3	3	2630.5	360	47	52,297	10,694	1	104.00	140.88	-36.88
4	3	2630.5	390	47	53,822	8,726	1	111.63	146.14	-34.52
5	3	2630.5	90	47	14,251	-	1	111.68	198.95	-87.27
6	3	2630.5	120	47	25,722	1,272	1	85.78	180.46	-94.69
7	3	2630.5	360	35	54,330	7,372	1	104.21	135.88	-31.66
8	3	2630.5	240	35	36,481	4,917	1	103.86	157.91	-54.05
9	3	2630.5	210	64	24,743	15,166	1	111.65	172.82	-61.18
10	3	2630.5	480	56	82,405	-	1	105.06	136.23	-31.17
11	3	2630.5	480	44	77,793	3,172	1	108.29	127.07	-18.78
12	3	2630.5	480	24	84,341	-	1	86.33	108.10	-21.77
13	3	2630.5	480	24	80,230	-	1	89.69	114.82	-25.13
14	3	2630.5	480	24	82,402	-	1	81.33	111.27	-29.94
15	3	2630.5	480	24	83,415	-	1	84.82	109.61	-24.79
16	3	2630.5	480	44	76,564	3,388	1	108.37	128.58	-20.21
17	3	2630.5	315	44	28,493	15,223	1	124.17	162.18	-38.01
18	3	2630.5	165	24	34,619	-	1	82.45	155.72	-73.27
19	3	2630.5	300	47	38,783	-	1	140.73	181.29	-40.56
20	3	2630.5	180	35	25,114	4,076	1	105.32	172.02	-66.71
21	3	2630.5	480	35	63,695	11,321	1	110.70	124.26	-13.56
22	3	2630.5	480	35	65,815	12,566	1	108.55	117.91	-9.36
23	3	2630.5	90	35	12,258	3,681	1	103.72	184.34	-80.62
24	3	2630.5	390	44	49,854	2,217	1	130.79	165.34	-34.55
25	3	2630.5	480	44	75,778	5,791	1	107.44	124.31	-16.87
Average of Absolute Error Value										**41.24**

Estimation model 1 can be improved by adding the left over variables or considering interactions between the variables. Simply adding the left over variables will not improve the estimation model since those variables are not significant in the current model. Hence different combinations were tried and a multiple linear regression model (Model 2) with variable ‘horsepower x minutes’ along with ‘level of maintenance’ and ‘Double line’ variables was developed. Maintenance is a key for the performance of any machine and ‘Double line’ represents the line configuration and also some machines are shared in both the sawmills with double line.

The results of the stepwise regression with are shown in Appendix Table A.23. 7 variables were selected out of 9 in the stepwise regression. The variables which were added to the model are ‘Level of Maintenance’ and ‘Double Line’ along with the variable ‘hp x Min’ and the ones left out are Debarker and Temperature. Again, Mallows' Cp is not displayed in the stepwise regression output since some estimators were highly correlated with each other. Mallows’ Cp for the model with only the selected variables in stepwise regression is 8 which tell that the model fits the data well. The results of the developed model (Model 2) are shown below. Residual plots (Figure 5.2) show that there are some outliers in the data and the histogram in Figure 5.2 is better than 5.1 since most of the residuals are distributed within ±10 kwh/MBF.

R^2 adjusted of the developed model 2 was 87.95%, the R^2 predicted was 85.88% and MSE was 82.9. Model 2 is totally different from Model 1 and signs of the regression coefficients no longer make much sense. The most precise variable and the variable that is explaining maximum variance is the variable ‘hp x min’. All the variables are significant in both T and F Tests and have variance inflation factor less than 10. The SEC values estimated from the fitted model 2 are shown in Table 5.5.

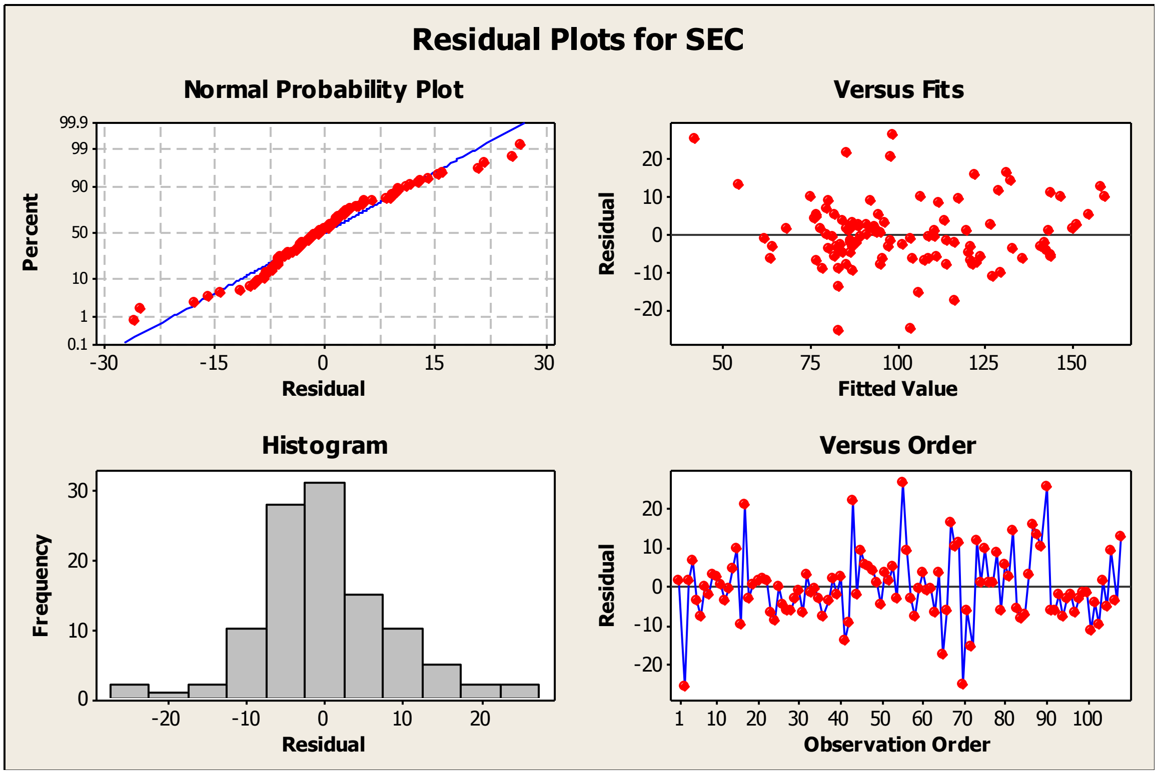


Figure 5.2: Residual Plots of Regression Model 2

Regression Equation

```
SEC  =  93.3125 + 0.637153 Density - 0.00222009 4 to 8 Qtr + Pallet -
        0.00222773 Cant + Tim + 19.4592 Resaw + 24.5632 Double Line - 13.2011
        Maint + 0.000108154 hp x Min
```

Coefficients

Term	Coef	SE Coef	T	P	VIF
Constant	93.3125	7.31446	12.7573	0.000	
Density	0.6372	0.11512	5.5345	0.000	1.58698
4 to 8 Qtr + Pallet	-0.0022	0.00019	-11.6167	0.000	9.54291
Cant + Tim	-0.0022	0.00033	-6.6620	0.000	1.80449
Resaw	19.4592	3.21508	6.0525	0.000	3.31003
Double Line	24.5632	2.87997	8.5290	0.000	1.97507
Maint	-13.2011	1.59812	-8.2604	0.000	2.00908
hp x Min	0.0001	0.00001	12.5772	0.000	9.14510

Summary of Model

```
S = 9.10496       R-Sq = 88.74%          R-Sq(adj) = 87.95%
PRESS = 10398.0   R-Sq(pred) = 85.88%
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	65330.5	65330.5	9332.9	112.580	0.0000000
Density	1	4137.4	2539.3	2539.3	30.631	0.0000003
4 to 8 Qtr + Pallet	1	6249.8	11187.3	11187.3	134.949	0.0000000
Cant + Tim	1	170.9	3679.3	3679.3	44.383	0.0000000
Resaw	1	4170.8	3036.8	3036.8	36.632	0.0000000
Double Line	1	21878.8	6030.5	6030.5	72.743	0.0000000
Maint	1	15609.2	5656.6	5656.6	68.234	0.0000000
hp x Min	1	13113.6	13113.6	13113.6	158.185	0.0000000
Error	100	8290.0	8290.0	82.9		
Total	107	73620.5				

Table 5.5: Estimated SEC values from Regression Model 2

No.	Mill #	Runtime (Mins)	hp x mins	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error	% Error
1	1	555	537,240	35	29,726	2,648	1	0	4	70.05	68.48	1.57	2.25
2	1	**75**	72,600	44	5,656	0	1	0	4	57.49	83.30	**-25.80**	-44.88
3	1	630	609,840	44	33,160	984	1	0	4	79.48	78.15	1.33	1.68
4	1	630	609,840	44	32,004	1,416	1	0	4	86.37	79.75	6.61	7.66
5	1	235	227,480	44	12,188	1,187	1	0	4	79.31	82.90	-3.60	-4.53
6	1	395	382,360	47	19,329	1,294	1	0	4	77.59	85.47	-7.88	-10.16
7	1	240	232,320	40	12,954	832	1	0	4	79.62	79.97	-0.34	-0.43
8	1	390	377,520	44	17,708	816	1	0	4	85.66	87.70	-2.04	-2.38
9	1	120	116,160	47	6,765	0	1	0	4	90.42	87.46	2.96	3.28
10	1	510	493,680	47	22,100	240	1	0	4	95.95	93.71	2.24	2.33
11	1	570	551,760	47	24,663	312	1	0	4	94.75	94.14	0.61	0.65
12	1	630	609,840	47	29,521	1,320	1	0	4	83.83	87.39	-3.56	-4.25
13	1	630	609,840	47	28,348	1,640	1	0	4	88.84	89.28	-0.45	-0.50
14	1	630	609,840	35	31,129	1,056	1	0	4	81.51	76.76	4.75	5.83
15	1	240	232,320	64	8,489	192	1	0	4	116.38	106.60	9.79	8.41
16	1	285	275,880	47	12,093	2,613	1	0	4	77.42	87.08	-9.66	-12.48
17	1	**105**	101,640	56	3,337	435	1	0	4	119.23	98.26	**20.97**	17.59
18	1	630	609,840	56	19,746	7,241	1	0	4	98.66	101.64	-2.98	-3.02
19	1	195	188,760	56	8,815	676	1	0	4	95.50	94.99	0.51	0.54
20	1	435	421,080	44	17,670	552	1	0	4	94.74	93.08	1.66	1.75
21	1	630	609,840	44	28,526	744	1	0	4	90.76	88.97	1.79	1.97
22	1	630	609,840	44	29,629	1,240	1	0	4	86.94	85.42	1.52	1.75
23	2	270	220,590	64	4,904	5,237	0	0	3	89.13	95.79	-6.66	-7.48
24	2	240	196,080	47	5,863	3,925	0	0	3	73.99	83.10	-9.11	-12.31
25	2	510	416,670	47	10,301	6,540	0	0	3	91.16	91.28	-0.13	-0.14
26	2	510	416,670	47	11,034	8,891	0	0	3	79.47	84.42	-4.95	-6.22
27	2	180	147,060	47	3,975	3,867	0	0	3	76.00	82.12	-6.12	-8.05
28	2	270	220,590	24	5,858	7,166	0	0	3	57.54	63.89	-6.35	-11.03

No.	Mill #	Runtime (Mins)	hp x mins	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error	% Error
29	2	120	98,040	24	2,598	4,194	0	0	3	61.25	64.49	-3.25	-5.30
30	2	390	318,630	24	7,967	10,652	0	0	3	60.79	62.04	-1.25	-2.06
31	2	510	416,670	44	13,481	8,950	0	0	3	70.04	76.94	-6.90	-9.85
32	2	510	416,670	44	8,162	7,840	0	0	3	94.01	91.22	2.79	2.96
33	2	510	416,670	44	10,465	7,593	0	0	3	85.15	86.66	-1.51	-1.77
34	2	300	245,100	44	7,211	4,914	0	0	3	80.82	81.30	-0.48	-0.59
35	2	150	122,550	64	1,852	2,775	0	0	3	94.05	97.45	-3.40	-3.61
36	2	330	269,610	64	5,706	7,104	0	0	3	87.07	95.15	-8.08	-9.28
37	2	150	122,550	44	3,231	3,307	0	0	3	76.63	80.46	-3.82	-4.99
38	2	510	416,670	44	9,196	8,931	0	0	3	88.53	86.50	2.03	2.29
39	2	510	416,670	44	9,802	8,309	0	0	3	84.54	86.54	-2.00	-2.37
40	2	480	392,160	44	9,765	6,199	0	0	3	91.35	88.67	2.68	2.93
41	2	30	24,510	47	613	862	0	0	3	68.88	83.03	-14.15	-20.54
42	2	450	367,650	47	8,613	11,556	0	0	3	69.25	78.55	-9.30	-13.43
43	2	**105**	85,785	47	1,682	1,600	0	0	3	107.59	85.63	**21.95**	20.40
44	2	405	330,885	47	6,595	7,461	0	0	3	85.95	88.18	-2.23	-2.60
45	2	450	367,650	47	6,872	7,177	0	0	3	101.26	92.17	9.09	8.97
46	2	60	49,020	35	1,236	891	0	0	3	81.96	76.58	5.38	6.56
47	2	510	416,670	35	10,589	6,930	0	0	3	87.31	82.13	5.18	5.93
48	2	255	208,335	35	6,155	3,888	0	0	3	80.49	76.22	4.28	5.31
49	2	255	208,335	44	5,320	2,990	0	0	3	86.72	85.80	0.92	1.06
50	2	450	367,650	44	9,135	6,592	0	0	3	81.71	86.54	-4.83	-5.91
51	2	330	269,610	44	6,847	5,067	0	0	3	88.09	84.41	3.67	4.17
52	2	180	147,060	47	4,361	1,520	0	0	3	88.15	86.49	1.65	1.88
53	2	510	416,670	47	10,900	4,348	0	0	3	100.14	94.83	5.30	5.30
54	2	45	36,765	47	735	1,430	0	0	3	79.64	82.81	-3.18	-3.99
55	2	465	379,905	44	2,584	8,378	0	0	3	125.07	98.43	**26.64**	21.30
56	2	60	49,020	44	1,451	1,459	0	0	3	89.72	80.57	9.14	10.19
57	2	450	367,650	44	10,119	6,966	0	0	3	80.51	83.52	-3.01	-3.74
58	4	195	299,130	44	8,791	4,264	0	1	2	115.22	122.84	-7.62	-6.61

No.	Mill #	Runtime (Mins)	hp x mins	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error	% Error
59	4	405	621,270	24	25,259	4,138	0	1	2	108.23	108.66	-0.43	-0.40
60	4	600	920,400	24	43,156	6,370	0	1	2	99.65	96.31	3.34	3.35
61	4	600	920,400	24	38,884	7,182	0	1	2	103.05	103.98	-0.93	-0.91
62	4	555	851,370	24	34,213	5,548	0	1	2	109.70	110.53	-0.83	-0.75
63	4	45	69,030	26	1,678	1,744	0	1	2	100.94	107.89	-6.96	-6.89
64	4	300	460,200	26	6,296	13,659	0	1	2	116.97	113.41	3.56	3.05
65	4	300	460,200	**47**	19,689	5,040	0	1	2	98.44	116.25	**-17.82**	-18.10
66	4	600	920,400	47	27,905	6,674	0	1	2	137.93	144.15	-6.21	-4.50
67	4	180	276,120	**47**	7,188	1,852	0	1	2	147.41	131.20	**16.21**	11.00
68	4	420	644,280	64	15,478	3,748	0	1	2	169.34	159.22	10.12	5.98
69	4	330	506,220	64	15,437	4,070	0	1	2	154.92	143.66	11.26	7.27
70	4	**120**	184,080	**26**	4,915	5,948	0	1	2	78.61	103.79	**-25.18**	-32.03
71	4	465	713,310	35	23,908	11,956	0	1	2	105.08	111.21	-6.13	-5.83
72	4	330	506,220	**35**	15,917	12,216	0	1	2	90.29	105.97	**-15.68**	-17.37
73	4	270	414,180	44	12,724	3,244	0	1	2	140.53	128.83	11.70	8.33
74	4	600	920,400	44	27,184	6,783	0	1	2	144.54	143.59	0.95	0.65
75	4	525	805,350	44	21,340	5,565	0	1	2	156.76	146.84	9.93	6.33
76	4	355.2	544,876.8	24	21,700	3,052	0	1	2	111.76	110.72	1.04	0.93
77	4	600	920,400	24	33,112	5,922	0	1	2	120.46	119.61	0.86	0.71
78	4	195	299,130	24	10,144	2,149	0	1	2	120.26	111.81	8.45	7.03
79	4	394.8	605,623.2	40	21,944	4,512	0	1	2	117.52	123.69	-6.17	-5.25
80	4	600	920,400	40	23,151	4,739	0	1	2	159.87	154.55	5.32	3.33
81	4	330	506,220	40	16,449	3,752	0	1	2	129.35	126.83	2.51	1.94
82	4	270	414,180	47	12,199	2,902	0	1	2	146.91	132.67	14.25	9.70
83	4	600	920,400	47	28,046	6,643	0	1	2	138.38	143.90	-5.52	-3.99
84	5,1#	266	448,476	44	21,909	-	1	0	2	106.13	114.27	-8.14	-7.67
85	5,1	342	576,612	47	26,052	-	1	0	2	113.76	120.84	-7.08	-6.23
86	5,2	582	981,252	47	32,150	-	1	0	2	153.86	151.07	2.79	1.81
87	5,1	**130**	219,180	47	8,160	-	1	0	2	137.55	121.90	**15.64**	11.37
88	5,1	482	812,652	24	50,813	9,975	1	0	2	67.71	54.52	13.18	19.47

No.	Mill #	Runtime (Mins)	hp x mins	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error	% Error
89	5,2	598	1,008,228	24	50,448	10,698	1	0	2	84.87	74.87	10.00	11.78
90	5,1	584	984,624	24	63,128	11,645	1	0	2	67.73*	42.06	**25.67**	37.90
91	5,2	647	1,090,842	44	43,450	-	1	0	2	129.64	135.92	-6.28	-4.84
92	5,1	627	1,057,122	44	55,938	-	1	0	2	98.24	104.55	-6.31	-6.43
93	5,2	604	1,018,344	44	37,107	-	1	0	2	139.94	142.16	-2.22	-1.58
94	5,1	608	1,025,088	44	46,659	-	1	0	2	113.82	121.68	-7.86	-6.91
95	5,2	592	998,112	44	36,535	-	1	0	2	137.99	141.24	-3.26	-2.36
96	5,1	117	197,262	44	8,813	-	1	0	2	113.90	116.17	-2.28	-2.00
97	5,1	427	719,922	40	36,489	-	1	0	2	102.01	108.71	-6.70	-6.57
98	5,2	601	1,013,286	35	33,653	10,096	1	0	2	117.99	121.06	-3.06	-2.60
99	5,1	611	1,030,146	35	43,846	11,156	1	0	2	96.29	97.89	-1.60	-1.66
100	5,2	410	691,260	35	24,196	7,068	1	0	2	112.49	113.97	-1.47	-1.31
101	5,1	625	1,053,750	47	39,585	6,796	1	0	2	115.82	127.26	-11.44	-9.88
102	5,2	596	1,004,856	47	32,131	4,912	1	0	2	138.43	142.72	-4.29	-3.10
103	5,1	614	1,035,204	47	40,343	4,147	1	0	2	119.39	129.47	-10.08	-8.44
104	5,2	562	947,532	47	23,758	7,228	1	0	2	151.36	149.95	1.41	0.93
105	5,1	523	881,778	44	38,448	1,834	1	0	2	115.25	120.33	-5.08	-4.41
106	5,1	90	151,740	44	6,000	-	1	0	2	126.86	117.49	9.37	7.38
107	5,1	534	900,324	47	36,454	-	1	0	2	128.95	132.76	-3.81	-2.96
108	5,2	565	952,590	47	23,203	4,326	1	0	2	171.11	158.19	12.92	7.55
Average of Absolute Error Value												**6.44**	**6.69**

* denotes an observation whose X value gives it large leverage, #Sawmill 5 data is shown with both 1st and 2nd shifts.

There are totally 10 data points out of 108 with error of greater than ±15 kwh/MBF and the average of absolute error value was 6.44 kWh/MBF and the average of absolute percentage error value was 6.69 kWh/MBF from the estimation results of Model 2 for sawmill 1, 2, 4 and 5. The data points 2, 17, 43, 70, and 87 have shift run times less than 2.75 hours and hence have resulted in higher error levels.

Data points 56 and 96 which had higher error values in Model 1 due to shorter run times have been estimated accurately by Model 2. Data points 55 and 90 still has higher error value and the explanation given before still applies here. Data points 15, 75, 80, 84, 85, and 108 which had higher error values in Model 1 have been estimated accurately by Model 2. There are still 3 data points (65, 67, 72) with error of more than ±15 kwh/MBF in sawmill 4. The point to be noted is whenever there is a change in the species, there are chances of two species getting mixed up in the same shift.

Data points 65, 67 and 72 have change in species and there are chances of mixing up of species and resulting in higher error in estimated value. Also, data points 15, 16, 24, 36, 68, 69, 73, 75, 78 and 82 have higher error but within ±15 kwh/MBF due to change in species. Error due to change is species is not mentioned for sawmill 5 since sawmill 5 has error from change in shift also. Also, error due to change in species is not happening every time.

Data points 2, 17, 43, 55, 65, 70, and 90 are identified as outliers from Minitab. After removing these points from the data, R^2 adjusted and R^2 predicted of model 2 becomes 93.69% and 92.51% respectively. After removing these 7 data points, data point 88 and 89 are identified as outliers from Minitab. If all the 9 data points were removed for developing the model, then the R^2 adjusted and R^2 predicted of model 2 becomes 95.06% and 94.40% respectively with error of all the data points remaining within ±15 kwh/MBF. Another point to be noted is the data points (67, 72) which had error of more than ±15 kwh/MBF due to change in species automatically gets reduced once these 9 data points were removed. The obtained regression model looks like,

```
SEC  =  93.0248 + 0.547198 Density - 0.00288141 4 to 8 Qtr + Pallet -
        0.00311373 Cant + Tim + 21.0113 Resaw + 29.5344 Double Line - 11.3222
        Maint + 0.000132491 hp x Min
```

The regression coefficients of the model 2 with and without outliers are listed in Table 5.6. The main differences between the model with outliers and without outliers is increase in value of density variable coefficient by 0.09, 'double line' variable coefficient by 4.97, 'hp x min' variable coefficient by 0.000024 and decrease in value of '4 to 8 Qtr + Pallet' variable coefficient by 0.0006, and decrease in value of 'Cant + Tim' variable coefficient by 0.0009. Even though the change in coefficients of variables 'hp x min', '4 to 8 Qtr + Pallet' and 'Cant + Tim' is small, its effect is significant since the magnitude of these variables is very high. Coefficients of other variables didn't change significantly.

Table 5.6: Comparison of Model 2 Regression Coefficients with and without Outliers

Variable	Regression coefficient value with outliers	Regression coefficient value without outliers
Constant	93.3125	93.0248
Density	0.637153	0.547198
4 to 8 Qtr + Pallet	- 0.00222009	- 0.00288141
Cant + Tim	- 0.00222773	- 0.00311373
Resaw	19.4592	21.0113
Double Line	24.5632	29.5344
Maint	- 13.2011	- 11.3222
hp x Min	0.000108154	0.000132491

Estimated values of Model 2 were converted into 'Total kWh' and are plotted with the actual 'Total kWh' values (Figure 5.3). Estimated values follow actual values very closely.

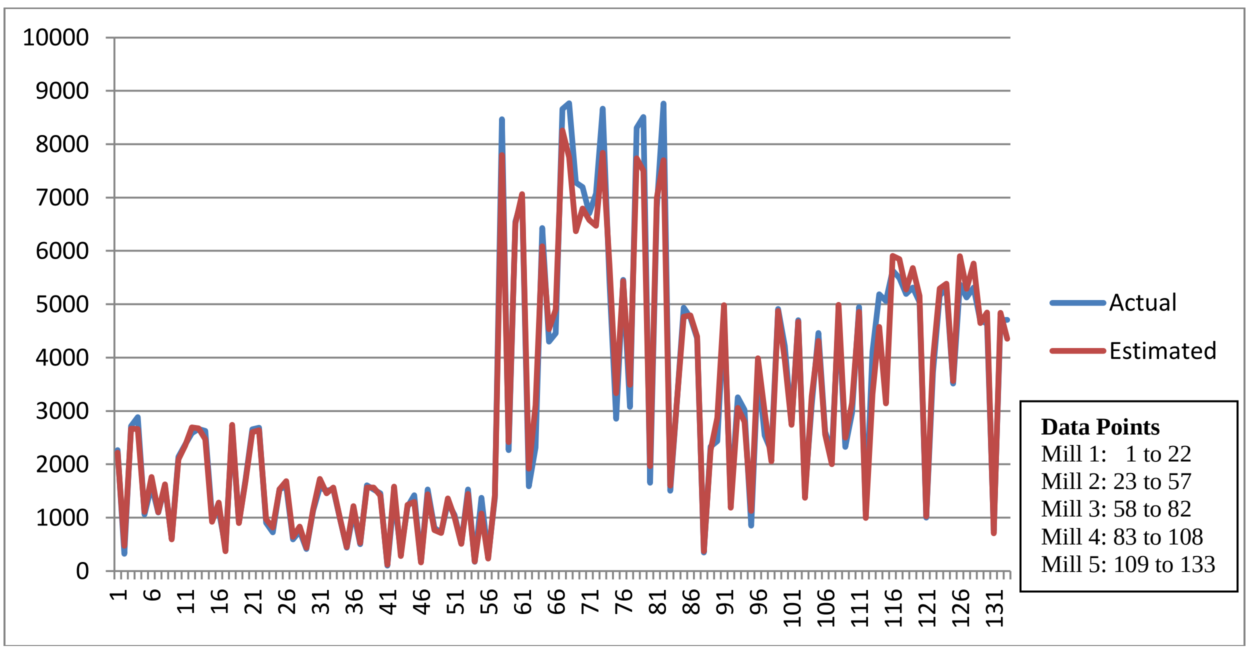


Figure 5.3: Model 2 Estimated Values converted to 'Total kWh' with Actual Values

Table 5.7 shows the data from sawmill 3 and the estimated SEC values using the developed regression model 2.

Table 5.7: Data of Sawmill 3 and estimated SEC using Model 2

No.	**Run time (Mins)**	**hp x mins**	**Density** (lb/ft^3)	**4/4 to 8/4 + Pallet** (Board ft.)	**Cant + Tim** (Board ft.)	**Resaw**	**Double Line**	**Maint Level**	**SEC**	**Estimated SEC**	**Error by Model 2**	**Error by Model 1**
1	480	1,262,640	44	70,762	9,645	1	1	2	105.28	96.94	8.33	-18.33
2	120	315,660	44	15,476	2,717	1	1	2	124.48	132.70	-8.22	-67.06
3	360	946,980	47	52,297	10,694	1	1	2	104.00	103.37	0.63	-36.88
4	390	1,025,895	47	53,822	8,726	1	1	2	111.63	112.90	-1.28	-34.52
5	**90**	236,745	47	14,251	-	1	1	2	111.68	134.85	**-23.17**	-87.27
6	**120**	315,660	47	25,722	1,272	1	1	2	85.78	115.08	**-29.30**	-94.69
7	360	946,980	35	54,330	7,372	1	1	2	104.21	98.61	5.60	-31.66
8	240	631,320	35	36,481	4,917	1	1	2	103.86	109.57	-5.71	-54.05
9	210	552,405	64	24,743	15,166	1	1	2	111.65	122.74	-11.09	-61.18
10	480	1,262,640	56	82,405	-	1	1	2	105.06	100.23	4.84	-31.17
11	480	1,262,640	44	77,793	3,172	1	1	2	108.29	95.75	12.54	-18.78
12	480	1,262,640	24	84,341	-	1	1	2	86.33	75.54	10.79	-21.77
13	480	1,262,640	24	80,230	-	1	1	2	89.69	84.67	5.02	-25.13
14	480	1,262,640	24	82,402	-	1	1	2	81.33	79.84	1.49	-29.94
15	480	1,262,640	24	83,415	-	1	1	2	84.82	77.60	7.22	-24.79
16	480	1,262,640	44	76,564	3,388	1	1	2	108.37	98.00	10.37	-20.21
17	315	828,607.5	44	28,493	15,223	1	1	2	124.17	131.41	-7.25	-38.01
18	165	4,340,325	24	34,619	-	1	1	2	82.45	96.31	-13.86	-73.27
19	300	789,150	47	38,783	-	1	1	2	140.73	140.13	0.60	-40.56
20	180	473,490	35	25,114	4,076	1	1	2	105.32	119.61	-14.29	-66.71
21	480	1,262,640	35	63,695	11,321	1	1	2	110.70	103.16	7.54	-13.56
22	480	1,262,640	35	65,815	12,566	1	1	2	108.55	95.68	12.87	-9.36
23	**90**	236,745	35	12,258	3,681	1	1	2	103.72	123.42	**-19.70**	-80.62
24	390	1,025,895	44	49,854	2,217	1	1	2	130.79	134.30	-3.51	-34.55
25	480	1,262,640	44	75,778	5,791	1	1	2	107.44	94.39	13.05	-16.87
Average of Absolute Error Value											**9.53**	**41.24**

Model 2 has estimated the SEC of sawmill 3 way better than Model 1. The average of absolute error value is 9.53 kWh/MBF where as the average of absolute error value of Model 1 was 41.24 kWh/MBF. Error was very high for shift run times (data points 5, 6 and 23 in Table 5.7) of less than 2.75 hours similar to other sawmills used for developing the model. The other data points were estimated with error of ±15 kwh/MBF.

An estimation model without horse power was developed to check whether the energy consumption can be estimated without using horsepower as an estimator variable. Results of the stepwise regression done to select the variables are shown in Appendix Table A.24.

7 variables were selected out of 9 in the stepwise regression. The variables which were left out are Debarker and Temperature. Mallow's Cp for the model is 8.7 which is greater than 8 (7 variables + 1 Constant) and hence the model fits the data well. Mallow's Cp with only the selected variables in stepwise regression is 8 which again tell that the model fits the data well. The results of the developed model (Model 3) are shown below. Residual plots (Figure 5.4) show that there are some outliers in the data and the histogram in Figure 5.4 is similar to the one in Figure 5.1 since most of the residuals are distributed within ±15 kwh/MBF. R^2 adjusted of the developed model 3 was 83.66%, the R^2 predicted was 81.64% and MSE was 112.4. Model 2 was better than model 3 since its R^2 adjusted was 87.95% and Model 1 had slightly better R^2 adjusted of 83.72% than Model 3. Model 3 is totally different from Model 1 since it has 'Level of Maintenance' and 'Double Line' estimator variables in place of 'Motor hp'.

The most precise variable and the variable that is explaining maximum variance are the '4 to 8 Qtr + Pallet' and 'Level of Maintenance' respectively. All the variables are significant in both T and F Tests and have variance inflation factor of less than 10. The SEC values estimated from the fitted model 3 are shown in Table 5.8.

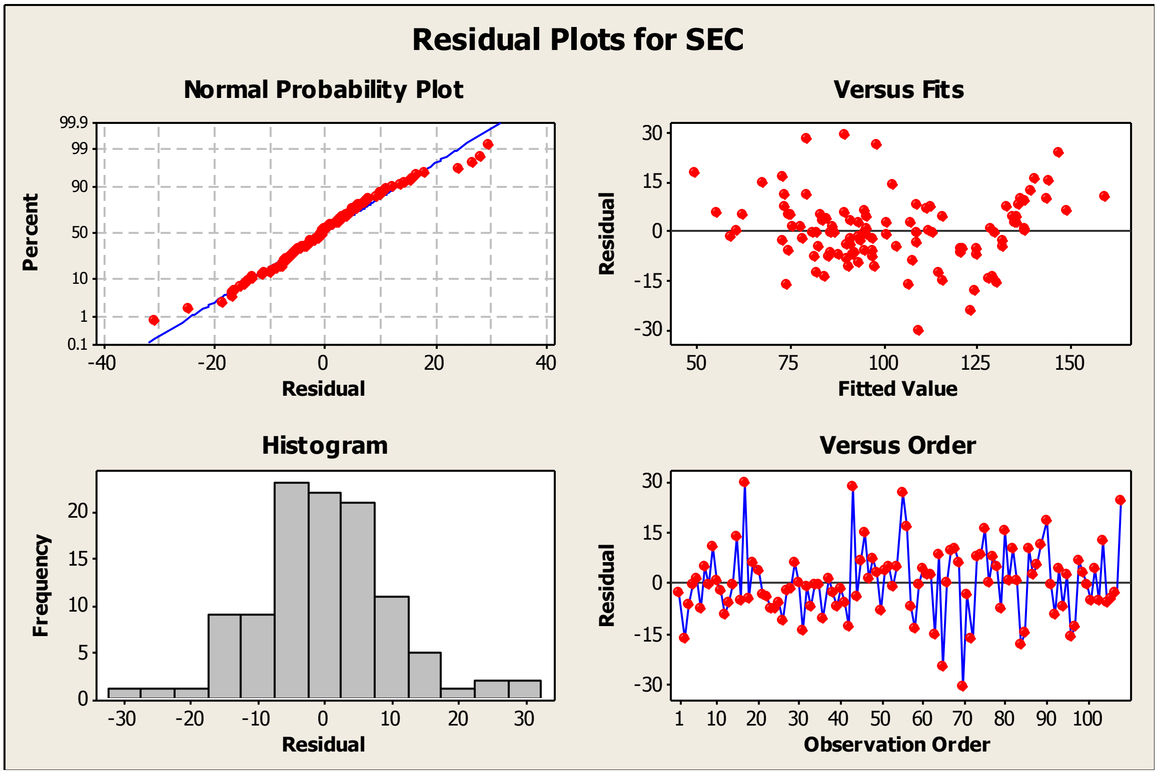


Figure 5.4: Residual Plots of Regression Model 3

```
Regression Equation

SEC      =  122.201 + 0.105517 Min + 0.795616 Density - 0.00161754 4 to 8 Qtr +
            Pallet - 0.00223285 Cant + Tim + 31.4713 Resaw + 31.6876 Double
            Line - 28.3233 Maint
```

Coefficients

Term	Coef	SE Coef	T	P	VIF
Constant	122.201	9.00174	13.5753	0.000	
Min	0.106	0.01110	9.5055	0.000	4.03589
Density	0.796	0.13053	6.0952	0.000	1.50420
4 to 8 Qtr + Pallet	-0.002	0.00019	-8.4478	0.000	7.06257
Cant + Tim	-0.002	0.00040	-5.6152	0.000	1.88133
Resaw	31.471	3.91284	8.0431	0.000	3.61464
Maint	-28.323	1.92324	-14.7269	0.000	2.14526
Double Line	31.688	3.32150	9.5402	0.000	1.93691

Summary of Model

```
S = 10.6038       R-Sq = 84.73%         R-Sq(adj) = 83.66%
PRESS = 13515.4   R-Sq(pred) = 81.64%
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	62376.5	62376.5	8910.9	79.250	0.0000000
Min	1	3198.6	10159.6	10159.6	90.355	0.0000000
Density	1	4878.8	4177.3	4177.3	37.151	0.0000000
4 to 8 Qtr + Pallet	1	2324.5	8024.3	8024.3	71.365	0.0000000
Cant + Tim	1	288.0	3545.3	3545.3	31.530	0.0000002
Resaw	1	4073.9	7273.9	7273.9	64.691	0.0000000
Double Line	1	23226.5	10233.7	10233.7	91.015	0.0000000
Maint	1	24386.1	24386.1	24386.1	216.880	0.0000000
Error	100	11244.0	11244.0	112.4		
Total	107	73620.5				

Table 5.8: Estimated SEC values from Regression Model 3

No.	Mill #	Runtime (Mins)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error
1	1	555	35	29,726	2,648	1	0	4	70.05	72.79	-2.74
2	1	**75**	44	5,656	0	1	0	4	57.49	74.15	**-16.66**
3	1	630	44	33,160	984	1	0	4	79.48	86.03	-6.54
4	1	630	44	32,004	1,416	1	0	4	86.37	86.93	-0.57
5	1	235	44	12,188	1,187	1	0	4	79.31	77.82	1.49
6	1	395	47	19,329	1,294	1	0	4	77.59	85.30	-7.71
7	1	240	40	12,954	832	1	0	4	79.62	74.72	4.91
8	1	390	44	17,708	816	1	0	4	85.66	86.07	-0.41
9	1	120	47	6,765	0	1	0	4	90.42	79.49	10.93
10	1	510	47	22,100	240	1	0	4	95.95	95.30	0.64
11	1	570	47	24,663	312	1	0	4	94.75	97.33	-2.58
12	1	630	47	29,521	1,320	1	0	4	83.83	93.55	-9.72
13	1	630	47	28,348	1,640	1	0	4	88.84	94.73	-5.90
14	1	630	35	31,129	1,056	1	0	4	81.51	81.99	-0.48
15	1	240	64	8,489	192	1	0	4	116.38	102.46	13.92
16	1	285	47	12,093	2,613	1	0	4	77.42	82.45	-5.03
17	1	**105**	56	3,337	435	1	0	4	119.23	89.64	**29.59**
18	1	630	56	19,746	7,241	1	0	4	98.66	103.30	-4.64
19	1	195	56	8,815	676	1	0	4	95.50	89.74	5.76
20	1	435	44	17,670	552	1	0	4	94.74	91.47	3.27
21	1	630	44	28,526	744	1	0	4	90.76	94.06	-3.30
22	1	630	44	29,629	1,240	1	0	4	86.94	91.17	-4.23
23	2	270	64	4,904	5,237	0	0	3	89.13	97.01	-7.89
24	2	240	47	5,863	3,925	0	0	3	73.99	81.70	-7.71
25	2	510	47	10,301	6,540	0	0	3	91.16	97.17	-6.02
26	2	510	47	11,034	8,891	0	0	3	79.47	90.74	-11.27
27	2	180	47	3,975	3,867	0	0	3	76.00	78.55	-2.55
28	2	270	24	5,858	7,166	0	0	3	57.54	59.34	-1.80
29	2	120	24	2,598	4,194	0	0	3	61.25	55.42	5.82
30	2	390	24	7,967	10,652	0	0	3	60.79	60.81	-0.02
31	2	510	44	13,481	8,950	0	0	3	70.04	84.26	-14.22
32	2	510	44	8,162	7,840	0	0	3	94.01	95.34	-1.33
33	2	510	44	10,465	7,593	0	0	3	85.15	92.17	-7.02
34	2	300	44	7,211	4,914	0	0	3	80.82	81.26	-0.44
35	2	150	64	1,852	2,775	0	0	3	94.05	94.79	-0.74
36	2	330	64	5,706	7,104	0	0	3	87.07	97.88	-10.81
37	2	150	44	3,231	3,307	0	0	3	76.63	75.46	1.18
38	2	510	44	9,196	8,931	0	0	3	88.53	91.24	-2.71
39	2	510	44	9,802	8,309	0	0	3	84.54	91.64	-7.11
40	2	480	44	9,765	6,199	0	0	3	91.35	93.25	-1.90
41	2	30	47	613	862	0	0	3	68.88	74.87	-5.99

No.	**Mill #**	**Runtime** (Mins)	**Density** (lb/ft^3)	**4/4 to 8/4 + Pallet** (Board ft.)	**Cant + Tim** (Board ft.)	**Resaw**	**Double Line**	**Maint Level**	**SEC**	**Estimated SEC**	**Error**
42	2	450	47	8,613	11,556	0	0	3	69.25	82.37	-13.12
43	2	**105**	47	1,682	1,600	0	0	3	107.59	79.41	**28.18**
44	2	405	47	6,595	7,461	0	0	3	85.95	90.03	-4.09
45	2	450	47	6,872	7,177	0	0	3	101.26	94.97	6.29
46	2	60	35	1,236	891	0	0	3	81.96	67.42	14.54
47	2	510	35	10,589	6,930	0	0	3	87.31	86.29	1.02
48	2	255	35	6,155	3,888	0	0	3	80.49	73.35	7.15
49	2	255	44	5,320	2,990	0	0	3	86.72	83.86	2.86
50	2	450	44	9,135	6,592	0	0	3	81.71	90.23	-8.51
51	2	330	44	6,847	5,067	0	0	3	88.09	84.67	3.42
52	2	180	47	4,361	1,520	0	0	3	88.15	83.17	4.98
53	2	510	47	10,900	4,348	0	0	3	100.14	101.10	-0.96
54	2	45	47	735	1,430	0	0	3	79.64	74.99	4.64
55	2	**465**	44	2,584	8,378	0	0	3	125.07	98.42	**26.66**
56	2	**60**	44	1,451	1,459	0	0	3	89.72	72.96	**16.75**
57	2	450	44	10,119	6,966	0	0	3	80.51	87.80	-7.29
58	4	195	44	8,791	4,264	0	1	2	115.22	129.08	-13.86
59	4	405	24	25,259	4,138	0	1	2	108.23	108.97	-0.74
60	4	600	24	43,156	6,370	0	1	2	99.65	95.62	4.03
61	4	600	24	38,884	7,182	0	1	2	103.05	100.71	2.34
62	4	555	24	34,213	5,548	0	1	2	109.70	107.17	2.53
63	4	**45**	26	1,678	1,744	0	1	2	100.94	116.07	**-15.13**
64	4	300	26	6,296	13,659	0	1	2	116.97	108.90	8.07
65	4	300	**47**	19,689	5,040	0	1	2	98.44	123.19	**-24.75**
66	4	600	47	27,905	6,674	0	1	2	137.93	137.91	0.03
67	4	180	47	7,188	1,852	0	1	2	147.41	137.87	9.54
68	4	420	64	15,478	3,748	0	1	2	169.34	159.07	10.27
69	4	330	64	15,437	4,070	0	1	2	154.92	148.92	6.00
70	4	**120**	**26**	4,915	5,948	0	1	2	78.61	109.36	**-30.75**
71	4	465	35	23,908	11,956	0	1	2	105.08	108.79	-3.71
72	4	330	**35**	15,917	12,216	0	1	2	90.29	106.89	**-16.60**
73	4	270	44	12,724	3,244	0	1	2	140.53	132.91	7.62
74	4	600	44	27,184	6,783	0	1	2	144.54	136.44	8.09
75	4	525	**44**	21,340	5,565	0	1	2	156.76	140.70	**16.06**
76	4	355.2	24	21,700	3,052	0	1	2	111.76	111.90	-0.14
77	4	600	24	33,112	5,922	0	1	2	120.46	112.86	7.60
78	4	195	24	10,144	2,149	0	1	2	120.26	115.71	4.55
79	4	394.8	40	21,944	4,512	0	1	2	117.52	125.15	-7.64
80	4	600	40	23,151	4,739	0	1	2	159.87	144.35	**15.52**
81	4	330	40	16,449	3,752	0	1	2	129.35	128.90	0.44
82	4	270	47	12,199	2,902	0	1	2	146.91	136.91	10.00
83	4	600	47	28,046	6,643	0	1	2	138.38	137.75	0.63

No.	Mill #	Runtime (Mins)	Density (lb/ft^3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Resaw	Double Line	Maint Level	SEC	Estimated SEC	Error
84	5,1#	266	44	21,909	-	1	0	2	106.13	124.66	**-18.53**
85	5,1	342	47	26,052	-	1	0	2	113.76	128.37	-14.61
86	5,2	582	47	32,150	-	1	0	2	153.86	143.83	10.03
87	5,1	130	47	8,160	-	1	0	2	137.55	134.94	2.61
88	5,1	482	24	50,813	9,975	1	0	2	67.71	62.51	5.19
89	5,2	598	24	50,448	10,698	1	0	2	84.87	73.73	11.14
90	5,1	584	24	63,128	11,645	1	0	2	67.73*	49.63	**18.10**
91	5,2	647	44	43,450	-	1	0	2	129.64	130.02	-0.38
92	5,1	627	44	55,938	-	1	0	2	98.24	107.71	-9.47
93	5,2	604	44	37,107	-	1	0	2	139.94	135.74	4.20
94	5,1	608	44	46,659	-	1	0	2	113.82	120.71	-6.89
95	5,2	592	44	36,535	-	1	0	2	137.99	135.40	2.59
96	5,1	**117**	44	8,813	-	1	0	2	113.90	130.12	**-16.23**
97	5,1	427	40	36,489	-	1	0	2	102.01	114.88	-12.88
98	5,2	601	35	33,653	10,096	1	0	2	117.99	111.31	6.68
99	5,1	611	35	43,846	11,156	1	0	2	96.29	93.51	2.78
100	5,2	410	35	24,196	7,068	1	0	2	112.49	113.21	-0.72
101	5,1	625	47	39,585	6,796	1	0	2	115.82	121.16	-5.34
102	5,2	596	47	32,131	4,912	1	0	2	138.43	134.37	4.06
103	5,1	614	47	40,343	4,147	1	0	2	119.39	124.69	-5.30
104	5,2	562	47	23,758	7,228	1	0	2	151.36	139.15	12.21
105	5,1	523	44	38,448	1,834	1	0	2	115.25	120.93	-5.68
106	5,1	90	44	6,000	-	1	0	2	126.86	131.82	-4.96
107	5,1	534	47	36,454	-	1	0	2	128.95	131.80	-2.85
108	5,2	565	47	23,203	4,326	1	0	2	171.11	146.85	**24.26**
Average of Absolute Error Value											**7.61**

* denotes an observation whose X value gives it large leverage, #Sawmill 5 data is shown with both 1st & 2nd shifts.

There are totally 15 data points out of 108 with error of ±15 kwh/MBF or more and the average of absolute error value was 7.61 kWh/MBF from the estimation results of Model 3 for sawmill 1, 2, 4 and 5. Average of absolute error value of Model 3 is slightly lower than Model 1. The data points 2, 17, 43, 56, 63, 70, and 96 have shift run times less than 2.75 hours and hence have resulted in higher error levels. Data points 55 and 90 still has higher error value and the explanation given before still applies here. There are 3 data points (65, 72, 75) with error of more than ±15 kwh/MBF in sawmill 4 where change of species is happening resulting in higher error value. Inefficiency of Model 3 has resulted in higher error values for data points 80, 84 and 108.

Table 5.9 shows the data from sawmill 3 and the estimated SEC values using the developed regression model 3.

Table 5.9: Data of Sawmill 3 and estimated SEC using Model 3

No.	**Run time** (Mins)	**Density** (lb/ft^3)	**4/4 to 8/4 + Pallet** (Board ft.)	**Cant + Tim** (Board ft.)	**Resaw**	**Double Line**	**Maint Level**	**SEC**	**Estimated SEC**	**Error by Model 3**	**Error by Model 2**	**Error by Model 1**
1	480	44	70,762	9,645	1	1	2	105.28	78.37	26.90	8.33	-18.33
2	120	44	15,476	2,717	1	1	2	124.48	145.28	-20.81	-8.22	-67.06
3	360	47	52,297	10,694	1	1	2	104.00	95.62	8.38	0.63	-36.88
4	390	47	53,822	8,726	1	1	2	111.63	100.72	10.91	-1.28	-34.52
5	**90**	47	14,251	-	1	1	2	111.68	152.55	**-40.87**	-23.17	-87.27
6	**120**	47	25,722	1,272	1	1	2	85.78	134.32	**-48.54**	-29.30	-94.69
7	360	35	54,330	7,372	1	1	2	104.21	90.20	14.01	5.60	-31.66
8	240	35	36,481	4,917	1	1	2	103.86	111.90	-8.04	-5.71	-54.05
9	210	64	24,743	15,166	1	1	2	111.65	127.91	-16.26	-11.09	-61.18
10	480	56	82,405	-	1	1	2	105.06	90.62	14.44	4.84	-31.17
11	480	44	77,793	3,172	1	1	2	108.29	81.45	26.84	12.54	-18.78
12	480	24	84,341	-	1	1	2	86.33	62.03	24.30	10.79	-21.77
13	480	24	80,230	-	1	1	2	89.69	68.68	21.01	5.02	-25.13
14	480	24	82,402	-	1	1	2	81.33	65.17	16.16	1.49	-29.94
15	480	24	83,415	-	1	1	2	84.82	63.53	21.29	7.22	-24.79
16	480	44	76,564	3,388	1	1	2	108.37	82.96	25.41	10.37	-20.21
17	315	44	28,493	15,223	1	1	2	124.17	116.88	7.29	-7.25	-38.01
18	165	24	34,619	-	1	1	2	82.45	109.22	-26.77	-13.86	-73.27
19	300	47	38,783	-	1	1	2	140.73	135.03	5.70	0.60	-40.56
20	180	35	25,114	4,076	1	1	2	105.32	125.83	-20.51	-14.29	-66.71
21	480	35	63,695	11,321	1	1	2	110.70	78.90	31.80	7.54	-13.56
22	480	35	65,815	12,566	1	1	2	108.55	72.69	35.86	12.87	-9.36
23	**90**	35	12,258	3,681	1	1	2	103.72	138.01	**-34.29**	-19.70	-80.62
24	390	44	49,854	2,217	1	1	2	130.79	119.28	11.51	-3.51	-34.55
25	480	44	75,778	5,791	1	1	2	107.44	78.86	28.58	13.05	-16.87
Average of Absolute Error Value										**21.86**	**9.53**	**41.24**

Even without the horsepower estimator variable, Model 3 has estimated the SEC of sawmill 3 better than Model 1. There are 8 data points out of 25 that have error value less than ±15 kwh/MBF. The average of absolute error value of Model 3 is 21.86 kWh/MBF, where as the average of absolute error value of Model 1 was 41.24 kWh/MBF. Error was very high for shift run times (data points 5, 6 and 23 in Table 5.9) of less than 2.75 hours similar to other sawmills used for developing the model. Overall, Model 2 is better than the other two models (Table 5.9).

Estimated SEC of sawmill 3 from models 1, 2 and 3 are plotted in Figure 5.5. From the figure it can be clearly seen that the estimated SEC values of model 1 are away from the actual SEC values. Estimated SEC values of model 2 are closely following the actual SEC values except for data point 5, 6 and 23. Estimated SEC values from model 3 are closer to the actual SEC values than model 1 but are not as close as the estimated SEC values from model 2.

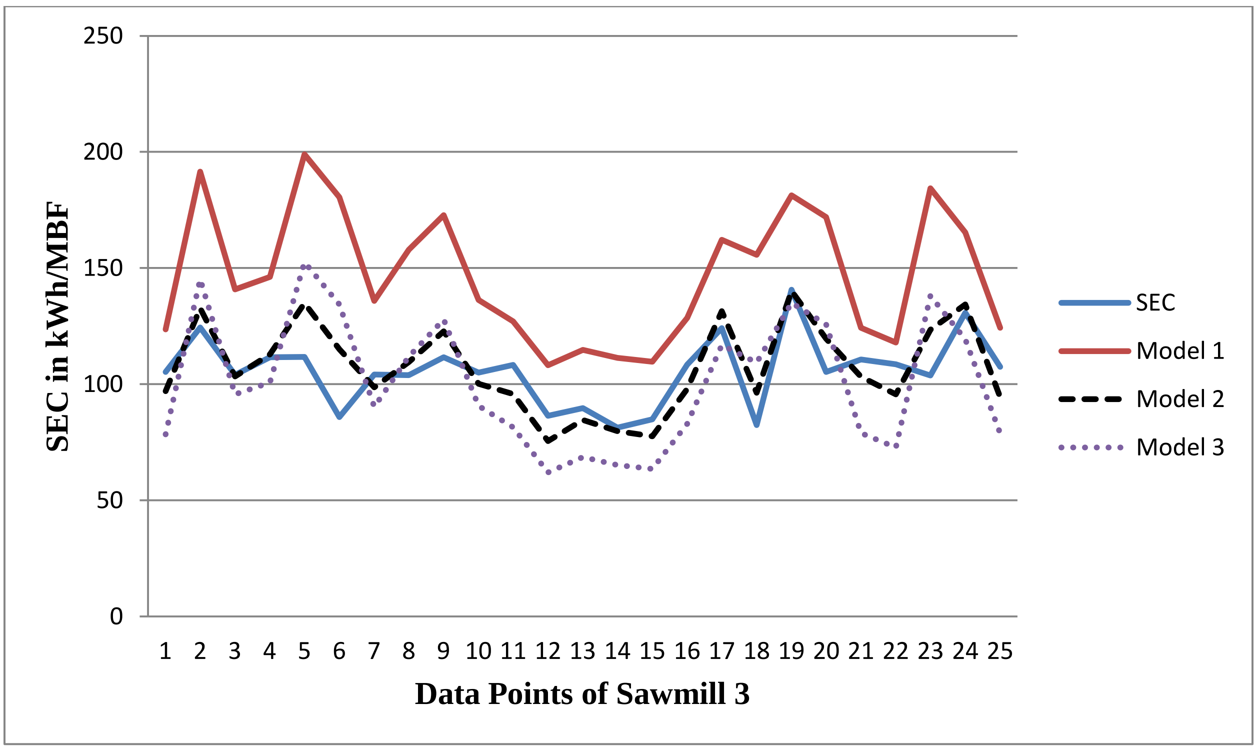


Figure 5.5: Estimated SEC values from Model 1, 2 and 3 plotted with Actual SEC Values

5.3 Limitations of the Model

- Even though there are some data points with less than 2.75 hours that were estimated accurately, in general model cannot estimate energy consumption of a short production run of 2.75 hours or less accurately.
- Model cannot estimate accurately if there is a mix up of two or more species in the same production run.
- Model cannot estimate correctly if the data provided is not accurate or sawmill is performing differently from its normal operation.
- Model cannot estimate accurately if there is too much inconsistency (variance) in the maintenance schedule.
- Model has predicted R^2 of 0.85 and hence can have error of around 15% in the estimated value.

5.4 Estimation Model to estimate Total kWh

Estimation Models developed so far were estimating SEC, total energy consumption in kWh per total board feet sawn in thousands. Estimation model can also be developed to estimate only total energy consumption in kWh. The same 9 predictor variables were used for step-wise regression with one of the variable being interaction between ‘motor horsepower and minutes’. The results of the step-wise regression are shown in Appendix Table A.25.

Interestingly, this time new variable temperature was selected and variable ‘Cant + Timber’ was dropped compared to Model 2. Even though the data of sawmill 2 and 4 had high percentage of cants and timbers, it should be noted that variable ‘Cant + Timber’ was not selected in step-wise regression since it didn’t had any significance in estimating total energy consumption and the correlation results obtained in data analysis chapter makes sense with this outcome. The Mallow’s Cp was 8 when only the variables selected were used to run the step-wise regression and hence the model fits the data well.

The results of the developed model (Model 4) are shown below. Residual plots (Figure 5.6) show that there are some outliers in the data and the histogram in Figure 5.6 is different from other models since total kWh is estimated in this model. R^2 adjusted of the developed model 4 was 99.38%, the R^2 predicted was 99.32% and MSE was 17,376. Model 4 is better than other models developed so far since its R^2 is the highest of all. The most precise variable and the variable that is explaining maximum variance is the variable ‘hp x min’. The variable that is explaining least variance is the temperature and the percentage of adjusted MS it represents is only 0.2%. All the variables are significant in both T and F Tests and have variance inflation factor of less than 10 which indicates that they are not correlated.

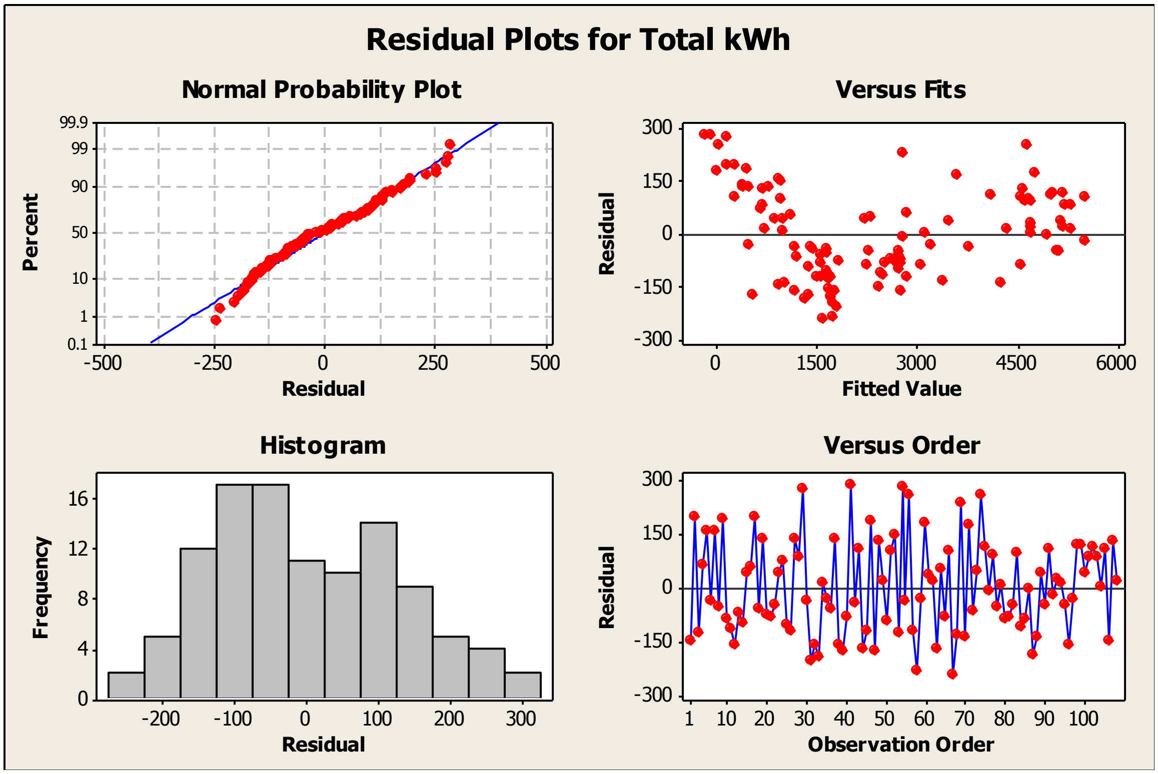


Figure 5.6: Residual Plots of Regression Model 4

```
Regression Equation

Total kWh  =  345.187 - 3.97857 Temp + 5.59643 Density + 0.00997374 4 to 8 Qtr
              + Pallet + 314.926 Resaw + 395.453 Double Line - 236.374 Maint +
              0.00448982 hp x Min
```

Coefficients

Term	Coef	SE Coef	T	P	VIF
Constant	345.187	109.529	3.1516	0.002	
Temp	-3.979	1.273	-3.1252	0.002	2.48785
Density	5.596	1.578	3.5470	0.001	1.42215
4 to 8 Qtr + Pallet	0.010	0.003	3.6538	0.000	9.28846
Resaw	314.926	49.841	6.3186	0.000	3.79517
Double Line	395.453	53.079	7.4503	0.000	3.20076
Maint	-236.374	23.259	-10.1628	0.000	2.03028
hp x Min	0.004	0.000	38.6648	0.000	7.95604

Summary of Model

```
S = 131.818       R-Sq = 99.42%         R-Sq(adj) = 99.38%
PRESS = 2027969  R-Sq(pred) = 99.32%
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	296751334	296751334	42393048	2439.74	0.0000000
Temp	1	73746050	169715	169715	9.77	0.0023255
Density	1	7433715	218612	218612	12.58	0.0005949
4 to 8 Qtr + Pallet	1	167139625	231973	231973	13.35	0.0004137
Resaw	1	10225313	693731	693731	39.92	0.0000000
Double Line	1	1571979	964498	964498	55.51	0.0000000
Maint	1	10658000	1794647	1794647	103.28	0.0000000
hp x Min	1	25976651	25976651	25976651	1494.97	0.0000000
Error	100	1737605	1737605	17376		
Total	107	298488940				

The total kWh and SEC values estimated from the fitted model 4 are shown in Table 5.10. SEC shown was calculated the same way as total energy consumed by total board feet sawn in thousands using equation 4.4 (page 67) for a particular shift.

Table 5.10: Estimated SEC values from Regression Model 4

No.	**Mill #**	**Runtime** (Mins)	**Density** (lb/ft^3)	**Temp** (^{o}F)	**hp x mins**	**4/4 to 8/4 + Pallet**	**Double Line**	**Resaw**	**Maint Level**	**Total kWh**	**Estimated Total kWh**	**Error**	**Estimated SEC**	**SEC**	**Error**
1	1	555	35	50	537,240	29,726	0	1	4	2,267.90	2,420.15	-152.25	74.76	70.05	-4.70
2	1	**75**	44	54	72,600	5,656	0	1	4	325.19	128.39	196.80	22.70	57.49	**34.79**
3	1	630	44	48	609,840	33,160	0	1	4	2,713.87	2,838.69	-124.82	83.14	79.48	-3.66
4	1	630	44	48	609,840	32,004	0	1	4	2,886.32	2,827.16	59.16	84.59	86.37	1.77
5	1	235	44	50	227,480	12,188	0	1	4	1,060.73	904.84	155.89	67.65	79.31	11.66
6	1	395	47	62	382,360	19,329	0	1	4	1,600.11	1,640.49	-40.38	79.55	77.59	-1.96
7	1	240	40	42	232,320	12,954	0	1	4	1,097.69	943.65	154.04	68.45	79.62	11.17
8	1	390	44	48	377,520	17,708	0	1	4	1,586.78	1,641.50	-54.72	88.61	85.66	-2.95
9	1	**120**	47	36	116,160	6,765	0	1	4	611.69	423.43	188.26	62.59	90.42	**27.83**
10	1	510	47	46	493,680	22,100	0	1	4	2,143.47	2,231.59	-88.12	99.89	95.95	-3.94
11	1	570	47	55	551,760	24,663	0	1	4	2,366.43	2,482.11	-115.68	99.38	94.75	-4.63
12	1	630	47	66	609,840	29,521	0	1	4	2,585.31	2,747.57	-162.26	89.09	83.83	-5.26
13	1	630	47	66	609,840	28,348	0	1	4	2,664.01	2,735.87	-71.86	91.23	88.84	-2.40
14	1	630	35	60	609,840	31,129	0	1	4	2,623.49	2,720.32	-96.83	84.52	81.51	-3.01
15	1	240	64	58	232,320	8,489	0	1	4	1,010.33	969.77	40.56	111.71	116.38	4.67
16	1	285	47	64	275,880	12,093	0	1	4	1,138.54	1,082.28	56.25	73.59	77.42	3.83
17	1	**105**	56	66	101,640	3,337	0	1	4	449.74	255.06	194.68	67.62	119.23	**51.61**
18	1	630	56	60	609,840	19,746	0	1	4	2,662.48	2,724.32	-61.83	100.95	98.66	-2.29
19	1	195	56	48	188,760	8,815	0	1	4	906.37	772.46	133.91	81.39	95.50	14.11
20	1	435	44	56	421,080	17,670	0	1	4	1,726.44	1,804.87	-78.43	99.05	94.74	-4.30
21	1	630	44	61	609,840	28,526	0	1	4	2,656.64	2,740.75	-84.11	93.64	90.76	-2.87
22	1	630	44	66	609,840	29,629	0	1	4	2,683.63	2,731.86	-48.23	88.50	86.94	-1.56
23	2	270	64	43	220,590	4,904	0	0	3	903.83	862.48	41.35	85.05	89.13	4.08
24	2	240	47	47	196,080	5,863	0	0	3	724.24	650.94	73.29	66.50	73.99	7.49
25	2	510	47	58	416,670	10,301	0	0	3	1,535.14	1,641.85	-106.71	97.49	91.16	-6.34

No.	Mill #	Runtime (Mins)	Density (lb/ft^3)	Temp (^{o}F)	hp x mins	4/4 to 8/4 + Pallet	Double Line	Resaw	Maint Level	Total kWh	Estimated Total kWh	Error	Estimated SEC	SEC	Error
26	2	510	47	44	416,670	11,034	0	0	3	1,583.44	1,704.86	-121.43	85.56	79.47	-6.09
27	2	**180**	47	34	147,060	3,975	0	0	3	596.00	463.74	132.26	59.14	76.00	**16.87**
28	2	270	24	38	220,590	5,858	0	0	3	749.42	668.03	81.39	51.29	57.54	6.25
29	2	**120**	24	24	98,040	2,598	0	0	3	415.98	140.99	274.99	20.76	61.25	**40.49**
30	2	390	24	28	318,630	7,967	0	0	3	1,131.87	1,169.03	-37.16	62.79	60.79	-2.00
31	2	510	44	28	416,670	13,481	0	0	3	1,571.08	1,776.14	-205.06	79.18	70.04	-9.14
32	2	510	44	43	416,670	8,162	0	0	3	1,504.34	1,663.41	-159.07	103.95	94.01	-9.94
33	2	510	44	31	416,670	10,465	0	0	3	1,537.66	1,734.12	-196.46	96.03	85.15	-10.88
34	2	300	44	21	245,100	7,211	0	0	3	979.90	971.13	8.76	80.09	80.82	0.72
35	2	150	64	24	122,550	1,852	0	0	3	435.17	467.45	-32.28	101.03	94.05	-6.98
36	2	330	64	21	269,610	5,706	0	0	3	1,115.42	1,178.10	-62.68	91.97	87.07	-4.89
37	2	**150**	44	24	122,550	3,231	0	0	3	501.04	369.27	131.76	56.48	76.63	**20.15**
38	2	510	44	20	416,670	9,196	0	0	3	1,604.75	1,765.23	-160.48	97.38	88.53	-8.85
39	2	510	44	36	416,670	9,802	0	0	3	1,531.05	1,707.62	-176.56	94.29	84.54	-9.75
40	2	480	44	50	392,160	9,765	0	0	3	1,458.31	1,541.50	-83.19	96.56	91.35	-5.21
41	2	**30**	47	50	24,510	613	0	0	3	101.60	-183.67	285.27	-124.52	68.88	**193.4**
42	2	450	47	49	367,650	8,613	0	0	3	1,396.76	1,440.73	-43.97	71.43	69.25	-2.18
43	2	**105**	47	14	85,785	1,682	0	0	3	353.10	245.33	107.77	74.75	107.59	**32.84**
44	2	405	47	18	330,885	6,595	0	0	3	1,208.05	1,378.87	-170.82	98.10	85.95	-12.15
45	2	450	47	18	367,650	6,872	0	0	3	1,422.61	1,546.70	-124.09	110.09	101.26	-8.83
46	2	**60**	35	18	49,020	1,236	0	0	3	174.33	-7.26	181.58	-3.41	81.96	**85.37**
47	2	510	35	25	416,670	10,589	0	0	3	1,529.56	1,708.86	-179.31	97.54	87.31	-10.23
48	2	255	35	38	208,335	6,155	0	0	3	808.40	677.53	130.87	67.46	80.49	13.03
49	2	255	44	42	208,335	5,320	0	0	3	720.68	703.65	17.02	84.68	86.72	2.05
50	2	450	44	61	367,650	9,135	0	0	3	1,285.07	1,381.41	-96.34	87.84	81.71	-6.13
51	2	330	44	53	269,610	6,847	0	0	3	1,049.50	950.23	99.26	79.76	88.09	8.33
52	2	**180**	47	57	147,060	4,361	0	0	3	518.39	376.09	142.31	63.95	88.15	**24.20**
53	2	510	47	56	416,670	10,900	0	0	3	1,526.90	1,655.78	-128.89	108.59	100.14	-8.45
54	2	**45**	47	45	36,765	735	0	0	3	172.41	-107.54	279.95	-49.67	79.64	**129.3**
55	2	465	44	52	379,905	2,584	0	0	3	1,371.06	1,406.90	-35.84	128.34	125.07	-3.27

No.	Mill #	Runtime (Mins)	Density (lb/ft^3)	Temp (^{o}F)	hp x mins	4/4 to 8/4 + Pallet	Double Line	Resaw	Maint Level	Total kWh	Estimated Total kWh	Error	Estimated SEC	SEC	Error
56	2	**60**	44	28	49,020	1,451	0	0	3	261.08	5.47	255.60	1.88	89.72	**87.84**
57	2	450	44	34	367,650	10,119	0	0	3	1,375.53	1,498.64	-123.11	87.72	80.51	-7.21
58	4	**195**	44	52	299,130	8,791	1	0	2	1,504.23	1,737.97	-233.74	133.13	115.22	**-17.90**
59	4	405	24	58	621,270	25,259	1	0	2	3,181.70	3,212.77	-31.07	109.29	108.23	-1.06
60	4	600	24	52	920,400	43,156	1	0	2	4,935.25	4,758.18	177.07	96.07	99.65	3.58
61	4	600	24	52	920,400	38,884	1	0	2	4,747.09	4,715.57	31.52	102.37	103.05	0.68
62	4	555	24	55	851,370	34,213	1	0	2	4,361.89	4,347.11	14.77	109.33	109.70	0.37
63	4	**45**	26	56	69,030	1,678	1	0	2	345.41	517.27	-171.86	151.16	100.94	**-50.22**
64	4	300	26	65	460,200	6,296	1	0	2	2,334.09	2,283.80	50.29	114.45	116.97	2.52
65	4	300	47	70	460,200	19,689	1	0	2	2,434.23	2,515.01	-80.78	101.70	98.44	-3.27
66	4	600	47	68	920,400	27,905	1	0	2	4,769.64	4,671.13	98.51	135.09	137.93	2.85
67	4	**180**	47	67	276,120	7,188	1	0	2	1,332.59	1,575.78	-243.19	174.31	147.41	**-26.90**
68	4	420	64	72	644,280	15,478	1	0	2	3,255.79	3,386.68	-130.89	176.15	169.34	-6.81
69	4	330	64	66	506,220	15,437	1	0	2	3,022.05	2,790.28	231.77	143.04	154.92	11.88
70	4	120	26	74	184,080	4,915	1	0	2	853.89	994.49	-140.60	91.55	78.61	-12.94
71	4	465	35	77	713,310	23,908	1	0	2	3,768.55	3,598.50	170.05	100.34	105.08	4.74
72	4	330	35	72	506,220	15,917	1	0	2	2,540.12	2,608.90	-68.78	92.73	90.29	-2.44
73	4	270	44	76	414,180	12,724	1	0	2	2,244.00	2,198.26	45.73	137.67	140.53	2.86
74	4	600	44	66	920,400	27,184	1	0	2	4,909.50	4,655.11	254.39	137.05	144.54	7.49
75	4	525	44	60	805,350	21,340	1	0	2	4,217.76	4,104.14	113.62	152.54	156.76	4.22
76	4	355.2	24	73	544,876.	21,700	1	0	2	2,766.36	2,774.60	-8.24	112.10	111.76	-0.33
77	4	600	24	64	920,400	33,112	1	0	2	4,702.11	4,610.26	91.85	118.11	120.46	2.35
78	4	195	24	78	299,130	10,144	1	0	2	1,478.34	1,536.09	-57.76	124.96	120.26	-4.70
79	4	394.8	40	82	605,623.	21,944	1	0	2	3,109.02	3,103.51	5.51	117.31	117.52	0.21
80	4	600	40	78	920,400	23,151	1	0	2	4,458.74	4,544.75	-86.01	162.95	159.87	-3.08
81	4	330	40	59	506,220	16,449	1	0	2	2,612.90	2,693.91	-81.00	133.36	129.35	-4.01
82	4	270	47	62	414,180	12,199	1	0	2	2,218.52	2,265.52	-46.99	150.02	146.91	-3.11
83	4	600	47	60	920,400	28,046	1	0	2	4,800.24	4,704.36	95.88	135.62	138.38	2.76
84	5,1#	266	44	58	448,476	21,909	0	1	2	2,325.14	2,434.94	-109.80	111.14	106.13	-5.01
85	5,1	342	47	62	576,612	26,052	0	1	2	2,963.61	3,052.45	-88.83	117.17	113.76	-3.41

No.	Mill #	Runtime (Mins)	Density (lb/ft^3)	Temp (^{o}F)	hp x mins	4/4 to 8/4 + Pallet	Double Line	Resaw	Maint Level	Total kWh	Estimated Total kWh	Error	Estimated SEC	SEC	Error
86	5,2	582	47	57	981,252	32,150	0	1	2	4,946.48	4,949.92	-3.44	153.96	153.86	-0.11
87	5,1	**130**	47	52	219,180	8,160	0	1	2	1,122.39	1,308.98	-186.58	160.41	137.55	**-22.87**
88	5,1	482	24	56	812,652	50,813	0	1	2	4,115.69	4,254.34	-138.65	69.99	67.71	-2.28
89	5,2	598	24	50	1,008,22	50,448	0	1	2	5,189.42	5,152.67	36.75	84.27	84.87	0.60
90	5,1	584	24	65	984,624	63,128	0	1	2	5,064.19	5,113.48	-49.28	68.39	67.73	-0.66
91	5,2	647	44	60	1,090,84	43,450	0	1	2	5,632.85	5,525.94	106.92	127.18	129.64	2.46
92	5,1	627	44	56	1,057,12	55,938	0	1	2	5,495.17	5,515.01	-19.84	98.59	98.24	-0.35
93	5,2	604	44	51	1,018,34	37,107	0	1	2	5,192.91	5,172.98	19.94	139.41	139.94	0.54
94	5,1	608	44	51	1,025,08	46,659	0	1	2	5,310.84	5,298.53	12.31	113.56	113.82	0.26
95	5,2	592	44	48	998,112	36,535	0	1	2	5,041.39	5,088.37	-46.98	139.27	137.99	-1.29
96	5,1	**117**	44	61	197,262	8,813	0	1	2	1,003.77	1,164.48	-160.71	132.13	113.90	**-18.24**
97	5,1	427	40	63	719,922	36,489	0	1	2	3,722.08	3,756.82	-34.75	102.96	102.01	-0.95
98	5,2	601	35	56	1,013,28	33,653	0	1	2	5,162.08	5,045.56	116.53	115.33	117.99	2.66
99	5,1	611	35	67	1,030,14	43,846	0	1	2	5,296.20	5,179.15	117.05	94.16	96.29	2.13
100	5,2	410	35	63	691,260	24,196	0	1	2	3,517.04	3,477.55	39.49	111.23	112.49	1.26
101	5,1	625	47	72	1,053,75	39,585	0	1	2	5,371.99	5,289.90	82.09	114.05	115.82	1.77
102	5,2	596	47	67	1,004,85	32,131	0	1	2	5,127.90	5,015.92	111.98	135.41	138.43	3.02
103	5,1	614	47	69	1,035,20	40,343	0	1	2	5,311.83	5,226.13	85.70	117.47	119.39	1.93
104	5,2	562	47	64	947,532	23,758	0	1	2	4,690.13	4,686.97	3.15	151.26	151.36	0.10
105	5,1	523	44	60	881,778	38,448	0	1	2	4,642.43	4,537.39	105.04	112.64	115.25	2.61
106	5,1	**90**	44	67	151,740	6,000	0	1	2	761.18	908.17	-147.00	151.36	126.86	**-24.50**
107	5,1	534	47	72	900,324	36,454	0	1	2	4,700.60	4,569.82	130.78	125.36	128.95	3.59
108	5,2	565	47	67	952,590	23,203	0	1	2	4,710.43	4,692.21	18.22	170.45	171.11	0.66
Average of Absolute Error Value															**12.06**

* denotes an observation whose X value gives it large leverage, #Sawmill 5 data is shown with both 1st and 2nd shifts.

There are totally 18 data points out of 108 with error of ±15 kwh/MBF or more and the average of absolute error value was 12.06 kWh/MBF from the estimation results of Model 4 for sawmill 1, 2, 4 and 5. Average of absolute error value of Model 4 is greater than all the other Models developed so far. The data points with error of ±15 kwh/MBF or more have shift run times less than

3 hours except for one data point with shift run time of 3.25 hours. Also, the error value increased rapidly as the shift run time decreased.

Table 5.11: Data of Sawmill 3 and estimated SEC using Model 4

No.	**Runtime** (Mins)	**Density** (lb/ft^3)	**Temp** (^{o}F)	**hp x mins**	**4/4 to 8/4 + Pallet**	**Double Line**	**Resaw**	**Maint Level**	**Total kWh**	**Estimated Total kWh**	**Error**	**Estimated SEC**	**SEC**	**Error**
1	480	44	52	1,262,640	70,762	1	1	2	8,464.90	6,996.96	1,467.94	87.02	105.28	18.26
2	120	44	32	315,660	15,476	1	1	2	2,264.58	2,273.36	-8.78	124.96	124.48	**-0.48**
3	360	47	39	946,980	52,297	1	1	2	6,551.06	5,464.05	1,087.00	86.74	104.00	17.26
4	390	47	42	1,025,895	53,822	1	1	2	6,981.93	5,821.64	1,160.29	93.07	111.63	18.55
5	**90**	47	44	236,745	14,251	1	1	2	1,591.53	1,875.87	-284.35	131.63	111.68	-19.95
6	**120**	47	34	315,660	25,722	1	1	2	2,315.49	2,384.38	-68.89	88.33	85.78	**-2.55**
7	360	35	39	946,980	54,330	1	1	2	6,430.15	5,417.17	1,012.98	87.80	104.21	16.42
8	240	35	45	631,320	36,481	1	1	2	4,299.55	3,798.02	501.52	91.74	103.86	12.11
9	210	64	47	552,405	24,743	1	1	2	4,455.75	3,480.98	974.78	87.22	111.65	24.43
10	480	56	62	1,262,640	82,405	1	1	2	8,657.71	7,140.46	1,517.25	86.65	105.06	18.41
11	480	44	70	1,262,640	77,793	1	1	2	8,767.84	6,995.47	1,772.36	86.40	108.29	21.89
12	480	24	61	1,262,640	84,341	1	1	2	7,281.16	6,984.66	296.50	82.81	86.33	3.52
13	480	24	66	1,262,640	80,230	1	1	2	7,195.51	6,923.77	271.74	86.30	89.69	3.39
14	480	24	71	1,262,640	82,402	1	1	2	6,701.76	6,925.54	-223.78	84.05	81.33	-2.72
15	480	24	61	1,262,640	83,415	1	1	2	7,075.26	6,975.43	99.83	83.62	84.82	1.20
16	480	44	34	1,262,640	76,564	1	1	2	8,664.44	7,126.45	1,538.00	89.13	108.37	19.24
17	315	44	49	828,607.5	28,493	1	1	2	5,428.20	4,638.59	789.61	106.11	124.17	18.06
18	**165**	24	53	4,340,325	34,619	1	1	2	2,854.32	2,800.28	54.04	80.89	82.45	**1.56**
19	300	47	42	789,150	38,783	1	1	2	5,457.95	4,608.70	849.25	118.83	140.73	21.90
20	**180**	35	44	473,490	25,114	1	1	2	3,074.22	2,980.00	94.22	102.09	105.32	**3.23**
21	480	35	48	1,262,640	63,695	1	1	2	8,304.22	6,892.03	1,412.20	91.87	110.70	18.83
22	480	35	50	1,262,640	65,815	1	1	2	8,508.43	6,905.21	1,603.21	88.10	108.55	20.45
23	**90**	35	48	236,745	12,258	1	1	2	1,653.18	1,772.92	-119.74	111.23	103.72	**-7.51**
24	390	44	54	1,025,895	49,854	1	1	2	6,810.27	5,717.53	1,092.74	109.80	130.79	20.99
25	480	44	51	1,262,640	75,778	1	1	2	8,764.15	7,050.97	1,713.18	86.44	107.44	21.00
Average of Absolute Error Value														**13.36**

Data points 55 and 90 which had higher error values in other models were estimated accurately from Model 4. But the Minitab still identifies data point 90 as the observation with large leverage from its X value. Other 3 data points (65, 72, 75) which had error of more than ±15 kwh/MBF in the estimation results of Model 2 were estimated accurately from Model 4. Table 5.11 shows the data from sawmill 3 and the estimated SEC values using the developed regression model 4.

Even though Model 4 had very high R^2 predicted of 99.38% it has not estimated the SEC of sawmill 3 that well. There are only 10 data points that were estimated with error of less than 15 kWh/MBF. Another thing to notice is that the shifts with shorter run times have less error compared to other shifts which is opposite to how Model 4 estimated shorter shift run times for sawmill 1, 2, 4 and 5. The average of absolute error value of Model 4 for sawmill 3 is 13.36 kWh/MBF, where as the average of absolute error value of Model 2 was 9.53 kWh/MBF. Model 4 was good in estimating SEC of shift run times of more than 3 hours for sawmill 1, 2, 4 and 5 but was not good for sawmill 3. Model 4 was developed to illustrate, estimation of SEC can also be done by estimating total energy consumption of each shift. Same estimator variables used in Model 2 were used in Model 4, but still, it didn’t estimate sawmill 3 as good as Model 2. Estimated SEC values from model 4 and model 2 are plotted along with the actual SEC values for comparison (Figure 5.7). From the figure, it can be seen that estimated values from Model 4 are not following the actual SEC values as good as Model 2.

5.5 Discussion

Even though the R^2 predicted of Model 4 is 99.38%, it didn’t estimate the SEC values as good as Model 2. The reason is too much variability in the distribution of Total kWh (total kWh range is 100 kWh to 8,700 kWh, SD 2,292) as seen in normal probability plot (Figure 5.8) and hence the categorical variables cannot handle a large range of total kWh efficiently. Once the Total kWh values are converted into SEC, the variability gets reduced (SEC range is 60 to 170, SD 24.49) as seen in normal probability plot (Figure 5.9) due to normalization. Hence Model 2 predicts SEC better than Model 4 since categorical variables can handle a small range efficiently.

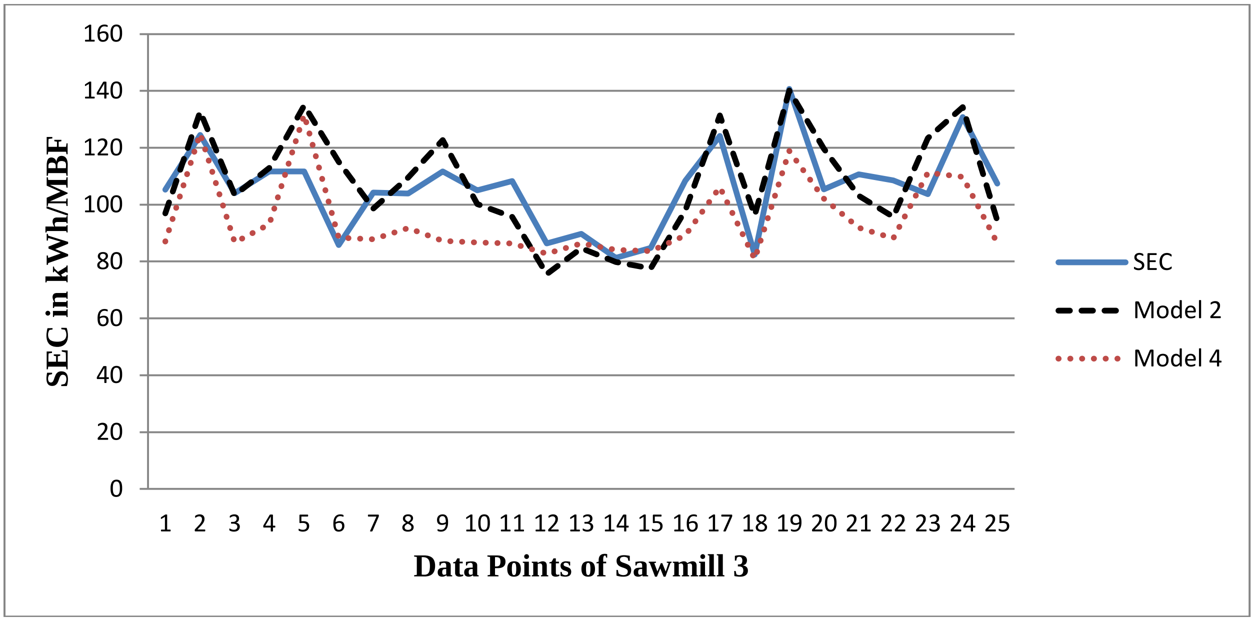


Figure 5.7: Estimated SEC Values from Model 2 and 4 plotted with Actual SEC Values

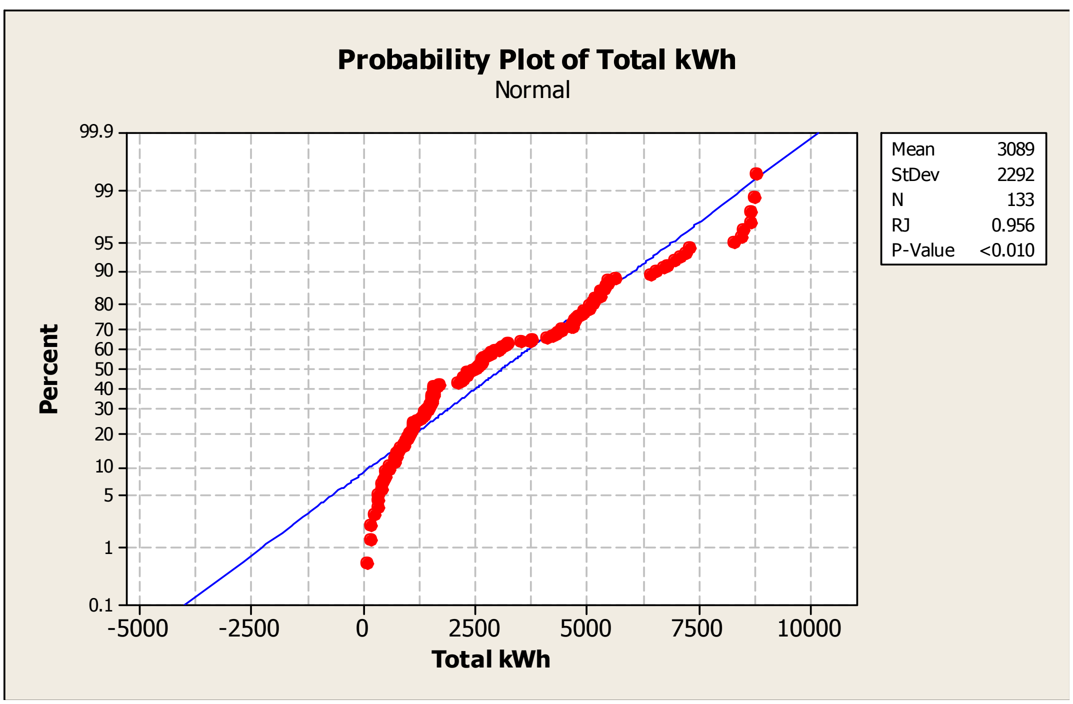


Figure 5.8: Normality Test for Total kWh of Sawmill 1, 2, 3, 4, and 5

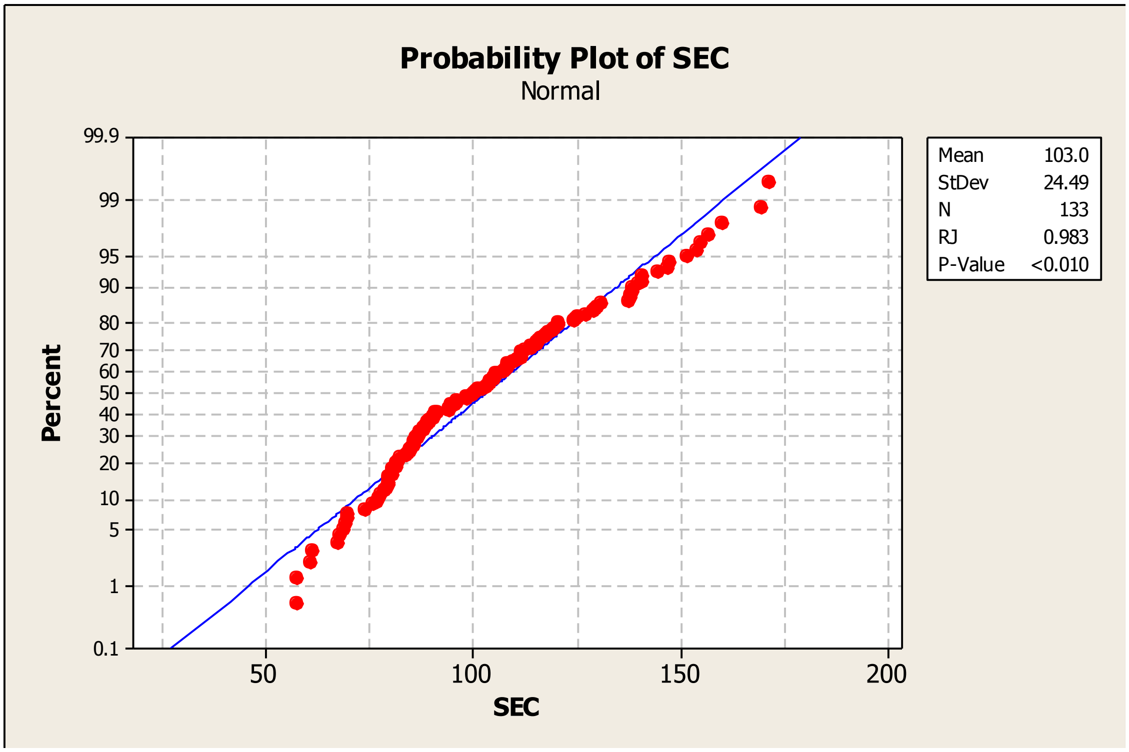


Figure 5.9: Normality Test for SEC of Sawmill 1, 2, 3, 4, and 5

Another interesting thing noticed from Model 4 is very high correlation of estimator variable 'hp x minutes' with predictor variable 'Total kWh' (Figure 5.10). The R^2 of the estimation models with only 'hp x min' variable was more than 0.99 (Table 5.12) for individual sawmills. Even though, the R^2 was very high at individual sawmill levels, at more than one sawmill level the estimation model with only 'hp x min' variable didn't perform well since the regression coefficients and constants were different in model of each sawmill due to different motor load factors of each sawmill (Table 5.12).

Table 5.12 : Summary of 'hp x min' Model to estimate 'Total kWh'

Model for Sawmill	Motor Horse Power	Model	R^2	Motor Load Factor
1	968	29.1406 + 0.00430452 hp x min	99.22	0.307
2	817	34.2681 + 0.0036265 hp x Min	99.19	0.265
4	1,534	-15.5785 + 0.00520418 hp x Min	99.18	0.358
5	1,686	-0.101295 + 0.00511631 hp x Min	99.79	0.362
1, 2, 4 & 5	-	-287.293 + 0.00534421 hp x min	98.10	-

In equation 4.3 (page 65) which calculates total kWh, only minutes is the variable and the rest are constants. Horse power and minutes are known, efficiency will be almost same for every sawmill (Table 4.2) and the thing that is different for each sawmill is load factor. Motor load factor is the percent of total motor capacity used to do a particular work. Lumber sawing takes place intermittently, what it means is either the motor will be sawing or it will be idling. When idling it may consume around 15% of motor capacity and while sawing it may consume around 60% of motor capacity or more depending on what species and size it is sawing. Also, the frequency of cutting matters a lot for getting a particular load factor. If one sawmill's cutting frequency is high then it will have more load factor and it is indicated in terms of board feet, not in terms of 'hp x min'. Sawmill will be fast if it has a resaw or a gang saw. Sawmill 3 has a high load factor compared to other sawmills since it has very high board feet production per hour per hp (Table 6.22).

Correlation between 'hp x min' and 'Total kWh' is shown in Figure 5.10. Variable 'hp x min' was divided by 1,000 and 'Total kWh' was divided by 10 for comparison. Even though hp x min has similar pattern as the total kWh (hence it has $R^2 > 0.99$), there is a gap between hp x min and kWh and that gap is different for each sawmill (Figure 5.11).

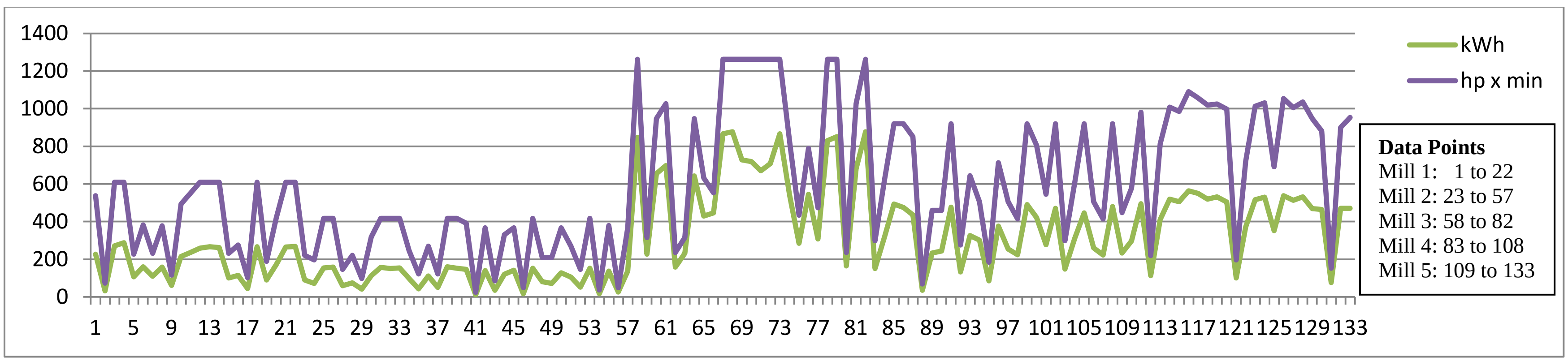


Figure 5.10: Correlation between 'hp x min' and 'Total kWh'

Relationship between 'hp x min' and 'Total kWh' is plotted in Figure 5.11. From Figure 5.11, Sawmill 2 has least gap with the x-axis and then Sawmill 1. Sawmill 4 and 5 have same gap and Sawmill 3 has the biggest gap. This gap is nothing but the motor load factor. This gap cannot be estimated just by the constant in the regression equation keeping the same regression coefficient for the 'hp x min' variable in the regression model since both the constants and regression coefficients are different in the regression models of each sawmill. Hence additional variables that represent motor load factor are required along with 'hp x min' to estimate 'Total kWh'.

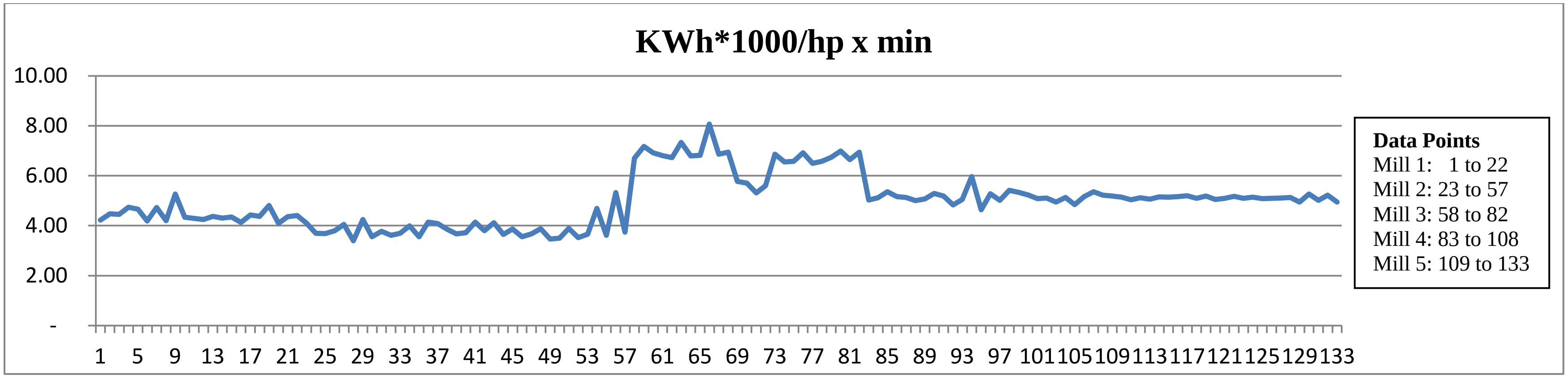


Figure 5.11: Relationship between 'hp x min' and 'Total kWh'

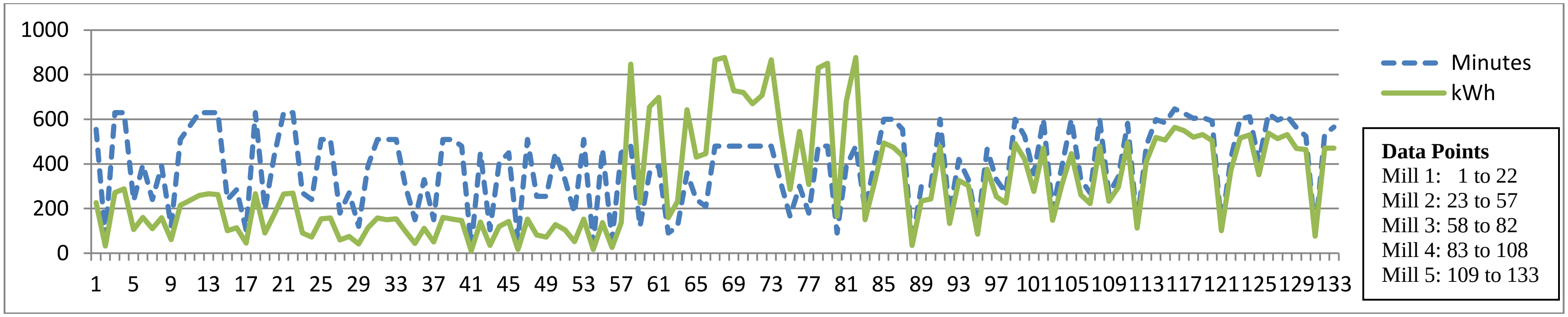


Figure 5.12: Correlation between 'min' and 'Total kWh'

Since horse power was a constant, the actual correlation was between variable 'minutes' and 'Total kWh' (Figure 5.12). Variable 'Minutes' is in actual value and variable 'Total kWh' is divided by 10 for comparison. Again the gap between 'minutes' and 'Total kWh' is totally different for different sawmills.

Also, total board feet sawn is correlated to 'Total kWh' (Pearson Correlation Coefficient = 0.949) as shown in Figure 5.13. Total board feet is divided by 100 and 'Total kWh' by 10 for comparison. Interesting thing is the gap between Board Feet and kWh is really narrow. The reason is average kWh/MBF is 100 for all the sawmills. Board feet is above kWh for sawmill 1 and 2 since the average SEC of sawmill 1 and 2 are 88 and 84 kWh/MBF (Table 4.6) respectively. For sawmill 3 the board feet is aligning with the kWh since the average SEC of sawmill 3 is 106 kWh/MBF. For sawmill 4 and 5 the board feet is below kWh since the average SEC of sawmill 4 and 5 are 124 and 118 kWh/MBF respectively. Also there are places where board feet is off from the kWh due to sawing a very low or high density wood, for example: Poplar a very low density wood species is sawn in sawmill 3 between points 66 and 73.

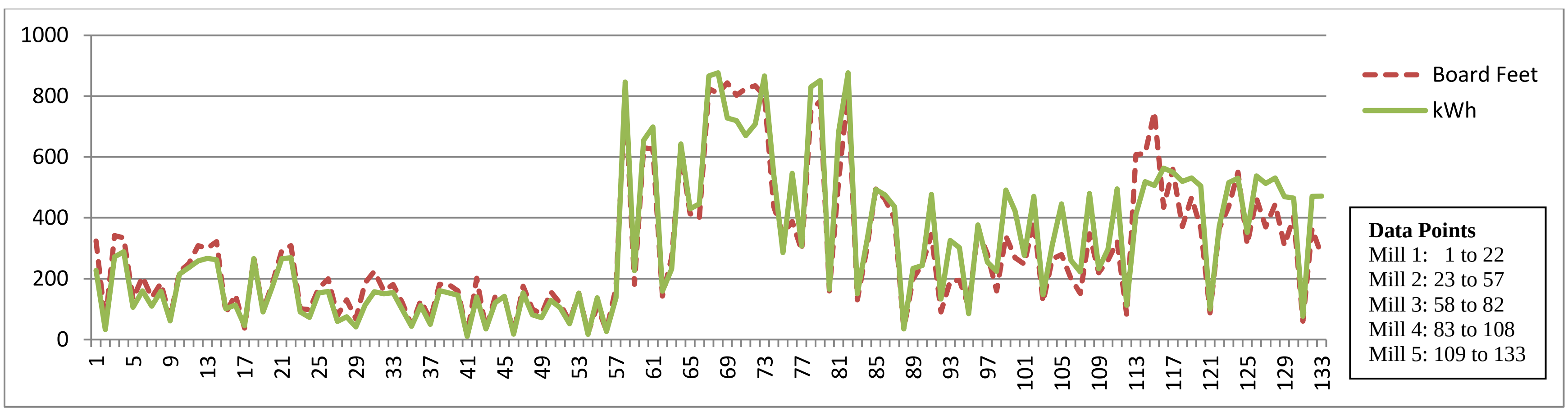


Figure 5.13: Correlation between 'Board Feet' and 'Total kWh'

Another interesting thing to notice is the wider gap between board feet and kWh for sawmill 5. This is happening due to poor production during shift 2 and more production in shift 1 to compensate for that. So, without board feet, total kWh cannot be predicted properly. So, board feet, density and minutes dictate the energy consumption and all the other variables are constants.

The relationship between total board feet sawn and total kWh is shown in Figure 5.14. The value shown are nothing but SEC values. Model 1, 2 and 3 are estimating SEC. SEC is highest for sawmill 4 and 5 and lowest for sawmill 1and 2 and sawmill 3 is in the middle (Figure 5.14). Model 4 is estimating 'Total kWh' and the 'Total kWh' is highest for sawmill 3, then sawmill 4 and 5 and lowest for sawmill 2 and then 1. So, the signs of the regression coefficients of the variables representing board feet are negative in SEC models (i.e., higher the board feet production, lower will be the SEC) and are positive in 'Total kWh' models (i.e., higher the board feet production, higher will be the Total kWh).

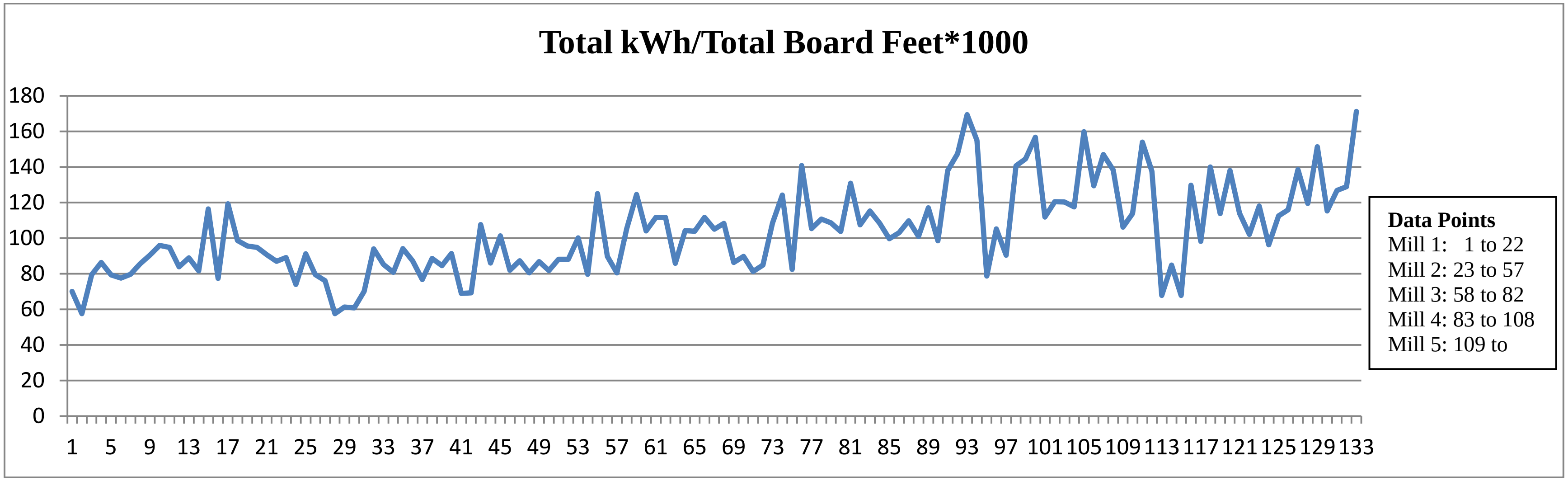


Figure 5.14: Relationship between 'Board Feet' and 'Total kWh'

5.6 Sawmill Energy Estimation Program (SMEEP) Development

Sawmill energy estimation program was developed to make the estimation and analysis easy for a sawmill owner. 'VisualBasic® for Applications in Excel' was thought to be the right tool to develop the program since the program involves lot of calculations like estimation of energy consumption, allocation of energy consumption based on sizes sawn, analysis to find out the reasons for inefficiency of a sawmill and suggesting solutions with estimated savings to overcome those inefficiencies and robust Microsoft Excel® can easily support these calculations.

The system diagram of SMEEP is shown in Figure 1.14. The inputs to the SMEEP are the wood species and board feet of different sizes lumber sawn as product parameters, sawing time and level of maintenance (saw blade usage time) as process parameters, and motor horsepower of equipment, usage of resaw or gangsaw and line configuration of single or double line as system parameters. Also, average electricity rate in \$/kWh and sawing cost/MBF of grade lumber will be the inputs. The outputs from the SMEEP are estimated kWh/MBF, total energy consumption for the shift data entered, motor load factor, SEC for different lumber sizes, best achieved SEC for different lumber sizes, details of energy savings and productivity savings and suggestions to improve efficiency.

1st shift data of Hickory species from sawmill 2 used in data analysis chapter (Table 4.13) was used to test the developed SMEEP. Input sheet with inputs are shown in Figure 5.15. There is an option to either enter the horsepower or not to enter it to run the program. Estimation Model 2 will be used for calculation if horse power of the motors were entered; otherwise estimation Model 3 will be used for calculation. There are ten species in the pull down menu and if the program has to be tested for new species, there is an option to enter density value in lb/ft^3. For the new species whose density value is entered, best achieved SEC values of species closest to its density value is used for calculating savings and is also displayed in the output.

Figure 5.16 shows the output for the entered data. The estimated SEC (kWh/MBF) is the one obtained by Model 2. The estimated SEC, estimated total kWh (energy consumption), the calculated SEC for individual sizes, best achieved SEC values for individual sizes and motor load factor along with the species and its density value are shown in the output.

Calculations of SMEEP Test Data

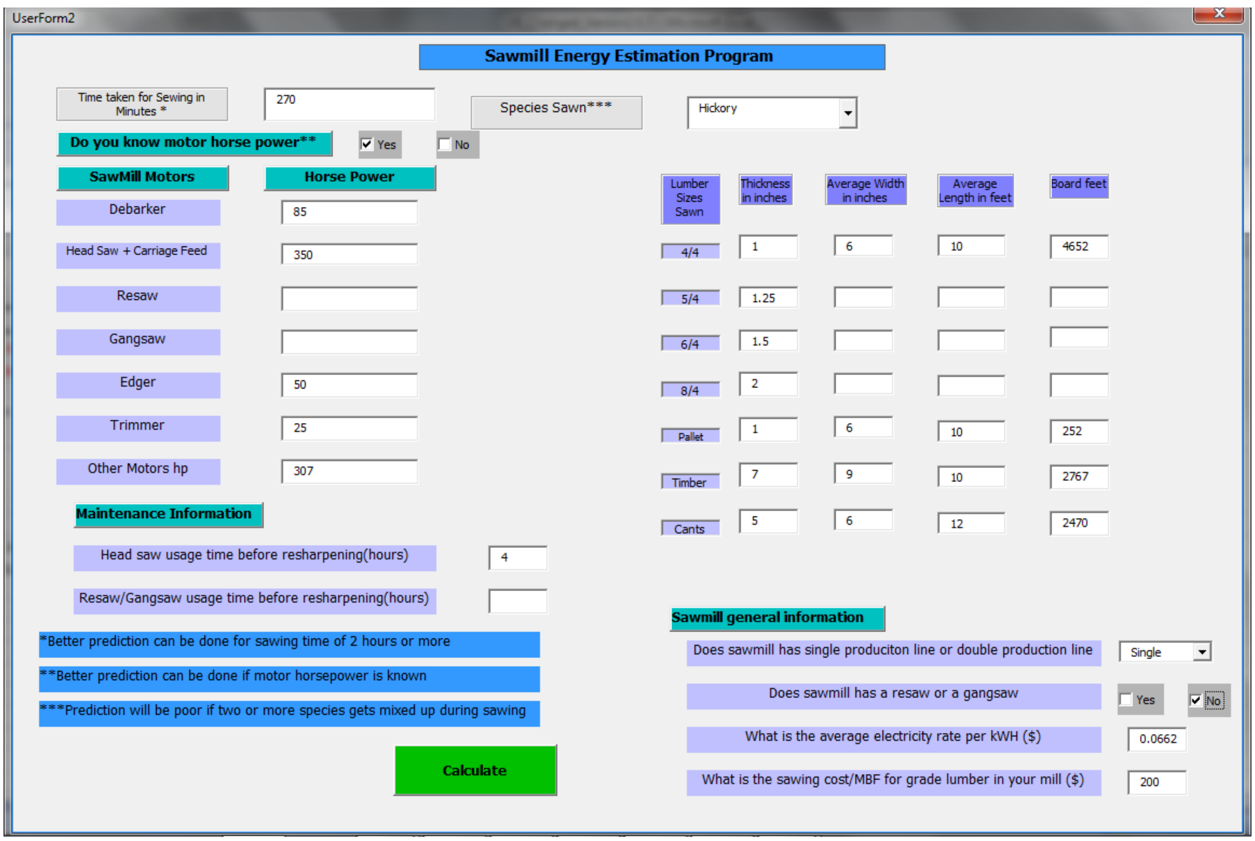


Figure 5.15: Input Sheet of the SMEEP

Some of the input values were converted or calculated into the following values before entering them into the regression model.

Species = Hickory ⟶ Density = 64 lb/ft^3

Head saw usage time before resharpening = 4 hours ⟶ Maintenance Index: 3

Total hp = 85 + 350 + 50 + 25 + 307 = 817

4 to 8 Qtr + Pallet = 4,652 + 252 = 4,904 Board Feet

Cant + Tim = 2,767 + 2,470 = 5,237 Board Feet

hp x min = 817 x 270 = 220,590

The estimated SEC was calculated using the following regression equation of model 2.

```
SEC  =  93.3125 + 0.637153 Density - 0.00222009 4 to 8 Qtr + Pallet -
        0.00222773 Cant + Tim + 19.4592 Resaw + 24.5632 Double Line - 13.2011
        Maint + 0.000108154 hp x Min
```

The regression equation with the input values looks like.

```
SEC  =  93.3125 + 0.637153 x 64 - 0.00222009 x 4,904 - 0.00222773 x 5,237 + 19.4592 x
         0 + 24.5632 x 0 - 13.2011 x 3 + 0.000108154 x 220,590
```

SEC = 95.79 kWh / MBF

Estimated total kWh = SEC x Total Board Feet / 1,000

= 95.79 x (4,904 + 5,237)

= 971.41 kWh

Load Factor is calculated as,

$$\text{Load Factor} = \frac{\text{Total kWh x Efficiency}}{\text{Motor hp x Hours x 0.746}}$$

$$\text{Load Factor} = \frac{971.41 \text{ x } 0.9}{817 \text{ x } (270/60) \text{ x } 0.746} = 31.88\ \%$$

Calculation of SEC for individual sizes need calculation of surface area cut on Main saw, Edger and Trimmer for all the sizes sawn in the given shift. Calculation for 4/4 size is shown as an example.

Total board feet of 4/4 cut = 4,652 Bft

Total length cut = Total board feet cut / (Width x Thickness)

= 4,652 Bft / (0.5 feet x 1 inch) (1 bft = 1 ft x 1 ft x 1 inch)

= 9,304 ft

Surface area cut by head saw	= Total length cut x Width
	= 9,304 ft x 0.5 ft
	= 4,652 sq. ft
Surface area cut by Edger	= Total length cut x Thickness
	= 9,304 ft x (1/12) ft
	= 775 sq. ft
No. of pieces cut	= (Total length cut/Average piece length)
	= 9,304 ft / 10 ft
	= 930 pieces
Surface area cut by Trimmer	= Width x thickness x No. of pieces cut
	= 0.5 ft x (1/12) ft x 930 pieces
	= 39 sq. ft
Total surface area cut for 4/4	= Surface area cut by (head saw + Edger + Trimmer)
	= 4,652 + 775 + 39
	= 5,466 sq. ft.

Energy was allocated to individual size of lumber by a factor that was calculated as the ratio of the total surface area cut for that particular size to the total surface area cut for all the sizes in that shift. For example for 4/4 size, the factors are allocated as follows:

Factor for 4/4 = Total Surface area cut for 4/4 size / Total Surface area cut for all the sizes

= 5,466 / 6,651

= 0.8218

Similarly factors for other sizes are calculated and are shown in Table 5.13.

Table 5.13: Surface Area Cut and Factors allocation for the SMEEP Test Data

Size Type	Size	Board Feet	Surface Area Head saw	Surface Area Edger	Surface Area Trimmer	Surface Area Total	Factor
Four Quarter	4/4	4,652	4,652	775	39	5,466	0.8218
Pallet	1”x 6”x10’	252	252	42	2	296	0.0445
Timber	7”x 9”x10”	2,767	395	0	0	395	0.0594
Cant	5” x 6” x 12’	2,470	494	0	0	494	0.0743
	Total	**10,141**	**5,793**	**817**	**41**	**6,651**	**1**

Energy consumed by particular size lumber was allocated based on the factors calculated by multiplying the total energy consumption by the factor for that particular size. The energy consumed by main saw, edger and trimmer were not allocated individually like the way done in energy allocation methodology since the energy consumption of individual motors is not known here. SEC was calculated by dividing the total energy allocated for that size by the MBF sawn for that particular size. Table 5.14 shows the energy consumed for sawing different size lumber and the total kWh consumed per thousand board feet of lumber.

Table 5.14: Energy consumed for Sawing different Size Lumber of SMEEP Test Data

Size Type	Size	Board Feet	Total kWh Consumed	kWh/ thousand Board Feet
Four Quarter	4/4	4,652	798.29	171.60
Pallet	1"x 6"x10'	252	43.24	171.60
Timber	7"x 9"x10"	2,767	57.73	20.86
Cant	5" x 6" x 12'	2,470	72.15	29.21
	Total	**10,141**	**971.41**	**-**

The estimated values by the SMEEP and the actual values from Table 4.5 and Table 4.13 for the 1st shift data of Hickory species from sawmill 2 are shown in Table 5.15 for comparison. Since the estimated SEC is greater than actual SEC by 6.7 kWh/MBF, the other values calculated from, it are also higher than actual values. Also, the best achieved values from sawmill 1 are shown in Table 5.15.

Table 5.15: Estimated, Actual and Best Achieved SEC values for the SMEEP Test Data

Sawmill 2 1st Shift Data Results	Estimated	Actual	Best Achieved
SEC	95.79	89.13	Not Applicable
Total kWh	971.41	903.83	Not Applicable
4/4 SEC	171.60	160.17	118.31
Pallet SEC	171.60	160.16	118.31
Timber SEC	20.86	19.01	13.82
Cant SEC	29.21	26.62	24.73

Table 5.16 and Table 5.17 shows the best achieved values from sawmill 1 used in the SMEEP for comparison purpose. Best achieved values for the species and sizes not sawn in sawmill 1 were estimated based on the values of species and sizes sawn in sawmill 1.

Table 5.16: Best Achieved SEC values from Sawmill 1 for different Lumber Sizes

Species	Four Quarter	Five Quarter	Six Quarter	Eight Quarter	Pallet Material	Timber
Yellow Poplar	70.21	55.12	50.34	41.27	70.21	7.43
Sycamore	70.81	56.31	51.78	41.57	70.81	7.69
Soft Maple	79.00	64.55	60.12	45.64	79.00	8.46
Ash	83.36	70.42	66.52	47.81	83.36	9.44
Birch	91.21	77.10	73.30	51.77	91.21	9.89
Red Oak	91.12	77.72	73.30	51.77	91.12	9.89
White Oak	94.01	77.59	73.87	53.21	94.01	10.73
Hard Maple	91.53	76.94	72.66	51.95	91.53	10.09
Cherry	120.29	114.55	106.64	66.14	120.29	14.11
Hickory	118.31	113.69	105.55	65.30	118.31	13.82

Table 5.17: Best Achieved SEC values from Sawmill 1 for different Cant Sizes

Species	Cants (3"x8"x12')	Cants (3.5"x6"x12')	Cants (14”x4”x12’)	Cants (5"x6"x12')	Cants (3"x4"x12')
Yellow Poplar	17.43	20.43	22.06	13.07	21.79
Sycamore	17.61	20.61	22.24	13.21	22.01
Soft Maple	20.61	24.71	26.34	16.28	27.14
Ash	22.02	26.15	27.78	17.36	28.94
Birch	25.52	29.72	31.25	20.24	33.20
Red Oak	24.26	28.52	30.15	19.14	31.90
White Oak	23.82	28.11	29.74	18.83	31.39
Hard Maple	23.85	28.19	29.82	18.89	31.49
Cherry	32.36	37.15	38.78	25.61	42.69
Hickory	31.39	35.97	37.6	24.73	41.21

If the calculated SEC for individual sizes is greater than best achieved values by 20%, then energy savings and productivity savings are calculated for reaching best achieved values along with suggestions to reach best achieved values. Difference of 20% is considered since the predicted R^2 of Model 2 is 85.88% and predicted R^2 of Model 3 is 81.64% and hence it is assumed that there can be a maximum error of 14% to 18.5% and 20% is more than these error values.

For the data entered from sawmill 2, the suggestions given are shown in the output (Figure 5.16). The suggestions are to install a resaw or a gangsaw, increase saw blade re-sharpening frequency, and resizing of motors to improve motor load factor.

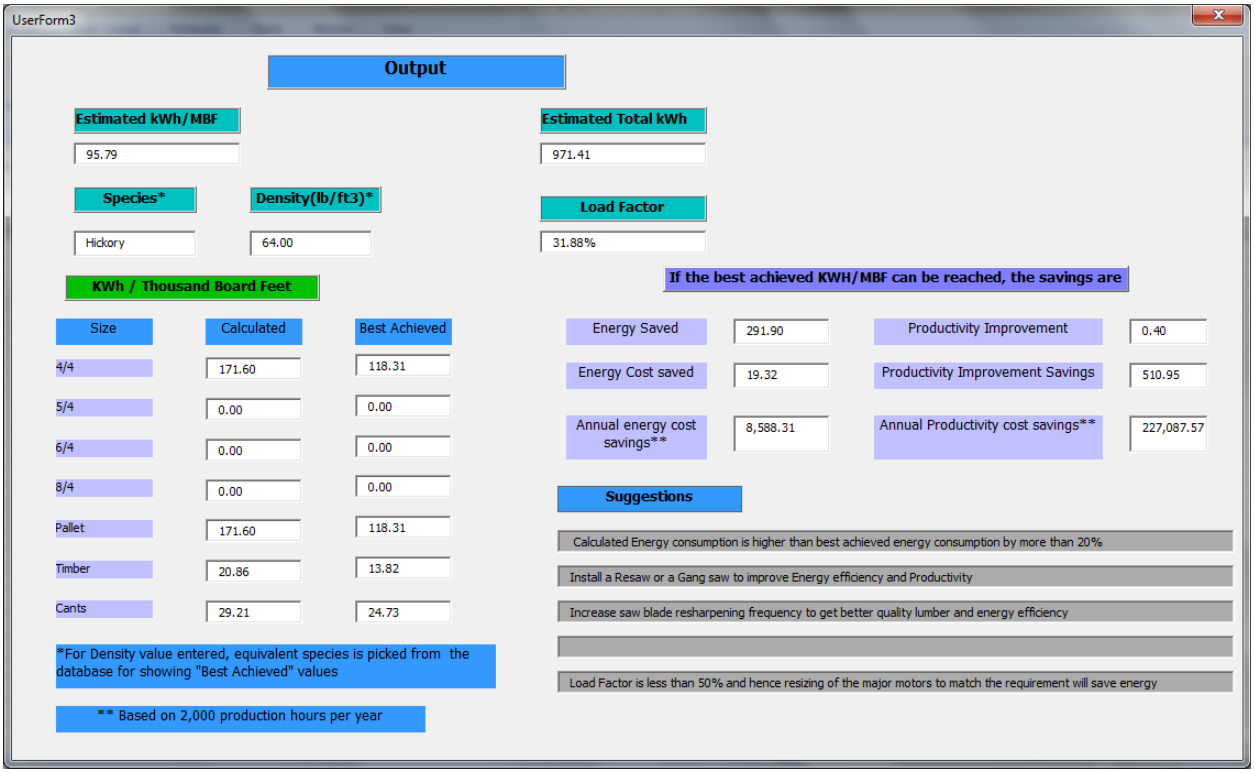


Figure 5.16: Output Sheet of the SMEEP

Table 5.18: Energy Savings and Energy Cost Savings for the SMEEP Test Data

Lumber Size	Calculated SEC (a) kWh/MBF	Best Achieved SEC (b) kWh/MBF	Energy Savings c= (a) - (b) kWh/MBF	Board Feet Sawn (d) MBF	Total Energy Savings per shift (kWh) e = (c) x (d)	Energy Cost Savings per shift ($) f= (e) x 0.0662	Energy Cost Savings per year ($)
4/4	171.60	118.31	53.29	4.652	247.9	16.41	7,293.73
Pallet	171.60	118.31	53.29	0.252	13.4	0.89	394.26
Timber	20.86	13.82	7.04	2.767	19.5	1.29	573.73
Cants	29.21	24.73	4.48	2.470	11.1	0.73	326.59
Total	**-**	**-**	**-**	**10.141**	**291.90**	**19.32**	**8,588.31**

The calculation involved in estimating the energy and energy cost savings are shown in Table 5.18. The energy savings is estimated to be the difference between calculated SEC and best achieved values.

The industrial electricity rate of Appalachian Power Co in West Virginia, the utility provider for sawmill 2 is $0.0662/kWh (US EIA 2013). Energy cost savings are calculated by multiplying average energy rate of $0.0662/kWh with the kWh energy savings. The Energy cost savings per year is calculated as shown below.

$$\text{Energy Cost Savings per year} = \frac{\text{Energy Cost Savings per shift x 2000 production hours / year}}{\text{Test Data Shift time in Minutes / 60}}$$

$$\text{Energy Cost Savings per year} = \frac{\text{19.32 x 2000 production hours / year}}{270 / 60}$$

$$= \$8{,}588.31$$

Also, the estimated energy savings is 10,811 kWh/month or 129,732 kWh/year based on 2,000 production hours per year.

The calculation involved in estimating productivity improvement and productivity improvement cost savings are shown in Table 5.19. As per the discussion with the sawmill owners, the sawing cost per MBF for 4/4 to 8/4 lumber excluding energy cost is around $200. For the cants and timbers, sawing cost per MBF was estimated to be 30% and 15% of 4/4 to 8/4 lumber production cost which becomes $60 and $30 respectively.

Table 5.19: Productivity Savings and Productivity Cost Savings for the SMEEP Test Data

Lumber Size	Calculated SEC (a) kWh/MBF	Best Achieved SEC (b) kWh/MBF	Productivity Savings (c)= (a/b)-1 kWh/MBF	Board Feet Sawn (d) MBF	Productivity Savings per shift (MBF) (e) = (c) x (d)	Production Cost ($) per MBF (f)	Productivity Cost Savings per shift ($) (g) = (e) x (f)
4/4	171.60	118.31	0.45	4.652	2.095	200	419.10
Pallet	171.60	118.31	0.45	0.252	0.114	200	22.70
Timber	20.86	13.82	0.51	2.767	1.411	30	42.31
Cants	29.21	24.73	0.181	2.470	0.447	60	26.84
Total	**-**	**-**	**-**	**10.141**	**4.067**		**510.95**

The productivity savings will be (e)/(d) in the Table 5.19 which turns out to be 0.40 or 40%. The productivity cost savings per year is calculated as shown below.

$$\text{Productivity Cost Savings per year} = \frac{\text{Productivity Cost Savings per shift x 2000 production hours / year}}{\text{Test Data Shift time in Minutes / 60}}$$

$$\text{Productivity Cost Savings per year} = \frac{\text{510.95 x 2000 production hours / year}}{270 \ / \ 60} = \$227{,}087.57$$

Conclusion:

Ten Variables were selected from Product, Process, and System Parameters. Stepwise regression was used to select the variables. Three multiple linear regression models were developed to estimate energy consumption per thousand board feet. Model 1 had 6 estimator variables, Model 2 had 7 estimator variables with ‘hp x min’ variable and Model 3 had 7 estimator variables. The most important variables was ‘Motor hp’ and Minutes in Model 1, ‘Motor hp x Min’ in Model 2 and ‘Level of Maintenance’ in Model 3. Model 2 had the highest R^2 value and estimated sawmill 3 SEC better than the other two models. Although sawmill 5 had data from day and night shifts with significant difference in the SEC’s between them, Model 2 predicted all the SEC values of sawmill 5 within acceptable error level except for one shift. Even though Model 3 didn’t had ‘Motor hp’ variable, it estimated sawmill 3 better than Model 1. One multiple linear regression model was developed to estimate total energy consumption of each shift. It estimated all the data points with shift run times of greater than 3.25 hours in sawmill 1, 2, 4 and 5 accurately, but it didn’t accurately estimate sawmill 3. Overall, Model 2 was better than all the models. SMEEP was developed to help the end user to input sawmill data and estimate energy consumption of sawing and calculate SEC of different lumber sizes and compare it with the best achievable SEC to find out the efficiency of the sawmill. SMEEP also provided methods to improve sawmill efficiency with estimated savings.

6. Sensitivity Analysis and Comparison of Sawmill Motors

6.1 Sensitivity Analysis of Estimator Variables

Sensitivity analysis was done to find out the effect of different variables on energy consumption. The following variables were used for sensitivity analysis.

1. Density
2. Minutes
3. Horsepower
4. 4/4 to 8/4 + Pallet
5. Cant + Timber
6. Level of Maintenance
7. Width of the Lumber Sawn

Model 1 was used to do the sensitivity analysis for the 1st five variables and Model 2 was used for the 6th variable since it was not present in Model 1. The 1st five variables were tested for their sensitivity to energy consumption by varying their values to ±10% and ±20%. The 6th variable was tested for its sensitivity to energy consumption by changing its value by ±1. Estimator variables 'Resaw' and 'Double Line' were not considered for sensitivity analysis since they are binary variables. Width of the lumber sawn in sawmills was considered for sensitivity analysis since the width sawn affected the energy consumption of main saw, resaw and gangsaw.

Table 6.1 shows the sawmill data used for conducting sensitivity analysis. One shift data of 'Red Oak' Species was used from all the 5 sawmills for doing sensitivity analysis.

Table 6.1: Data used for Sensitivity Analysis in Model 1

Mill #	Motor hp	Minutes	Density	4/4 to 8/4 + Pallet	Cant + Timber	Resaw	SEC	Estimated SEC	Error
1	968	630	44	29,629	1,240	1	86.94	90.35	-3.41
2	817	450	44	10,119	6,966	0	80.51	88.40	-7.89
3	2,630.5	480	44	75,778	5,791	1	107.44	124.31	-16.87
4	1,534	600	44	27,184	6,783	0	144.54	139.68	8.95
5	1,686	523	44	38,448	1,834	1	115.25	121.84	-6.59

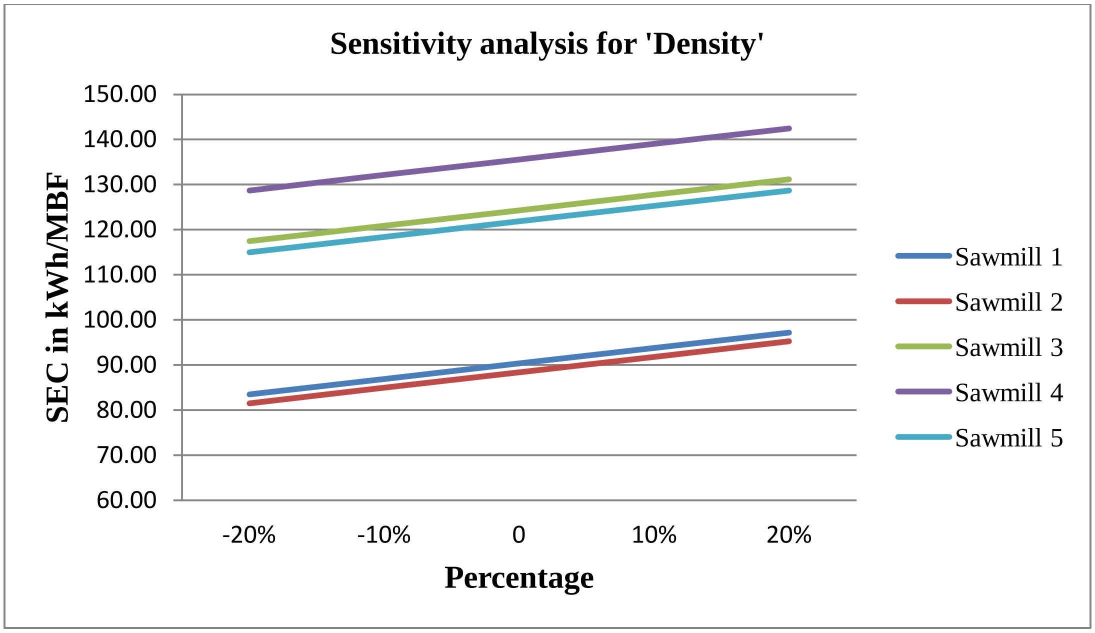


Figure 6.1: Sensitivity Analysis Results for Variable 'Density'

Figure 6.1 shows the sensitivity analysis results of variable 'density'. Since the density chosen for sensitivity analysis was same for all the 5 sawmills, the effect of changing it also remained same for all the five sawmills. As the value of density is increased, the energy consumption also increased.

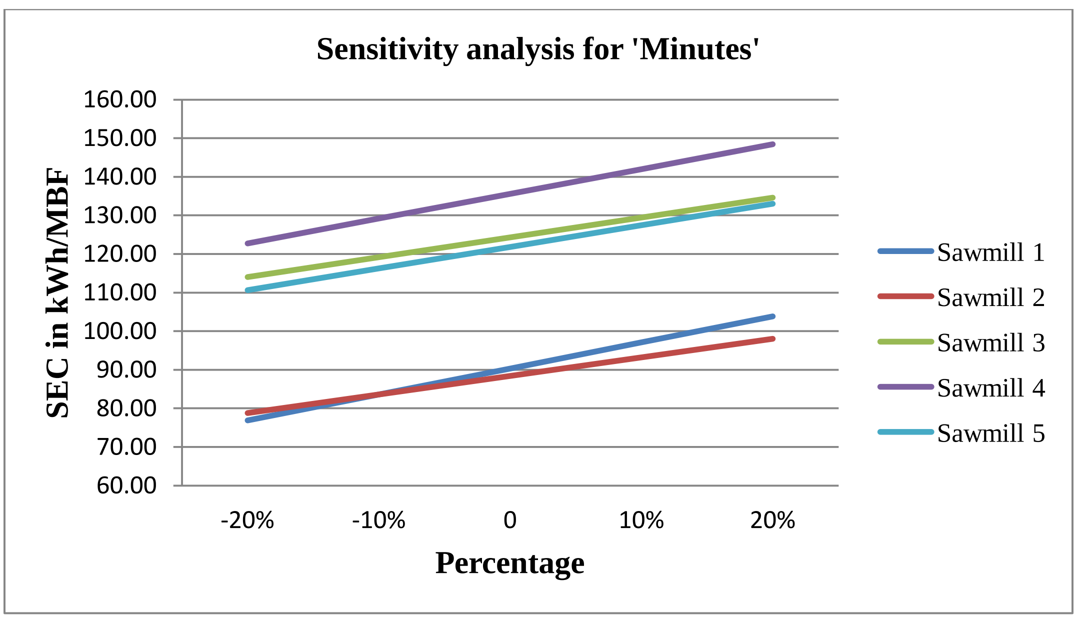


Figure 6.2: Sensitivity Analysis Results for Variable 'Minutes'

Figure 6.2 shows the sensitivity analysis results of variable 'minutes'. The minutes chosen for sensitivity analysis was different for each sawmill, and hence the effect of changing it has resulted in some difference between the sawmills. As the value of minutes is increased, the energy consumption also increased. Change in minutes has shown more effect on the energy consumption of sawmill 1 and 4 since the shift data selected for them had more minutes than the other sawmills.

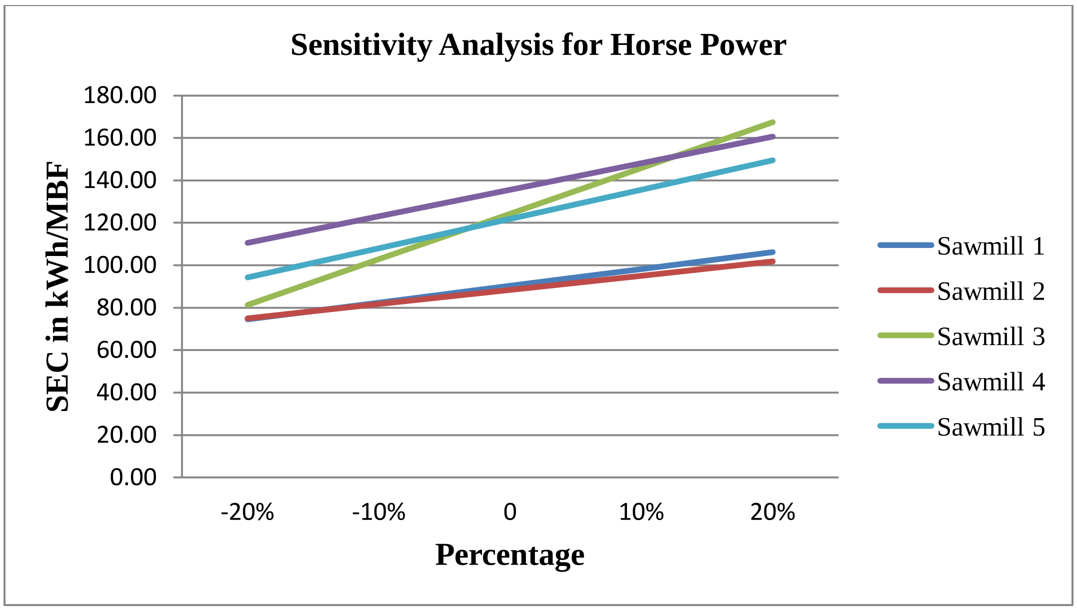


Figure 6.3: Sensitivity Analysis Results for Variable 'Horse Power'

Figure 6.3 shows the sensitivity analysis results of variable 'horsepower'. The horsepower was different for each sawmill, and hence the effect of changing it has resulted in significant difference among sawmills. As the value of horsepower is increased, the energy consumption also increased. Change in horsepower has shown more effect on the energy consumption of sawmill 3 and then sawmill 4 and 5 since the horsepower of sawmill 3 is the highest and then the horsepower of sawmill 5 and 4 comes in 2nd and 3rd highest position among sawmills.

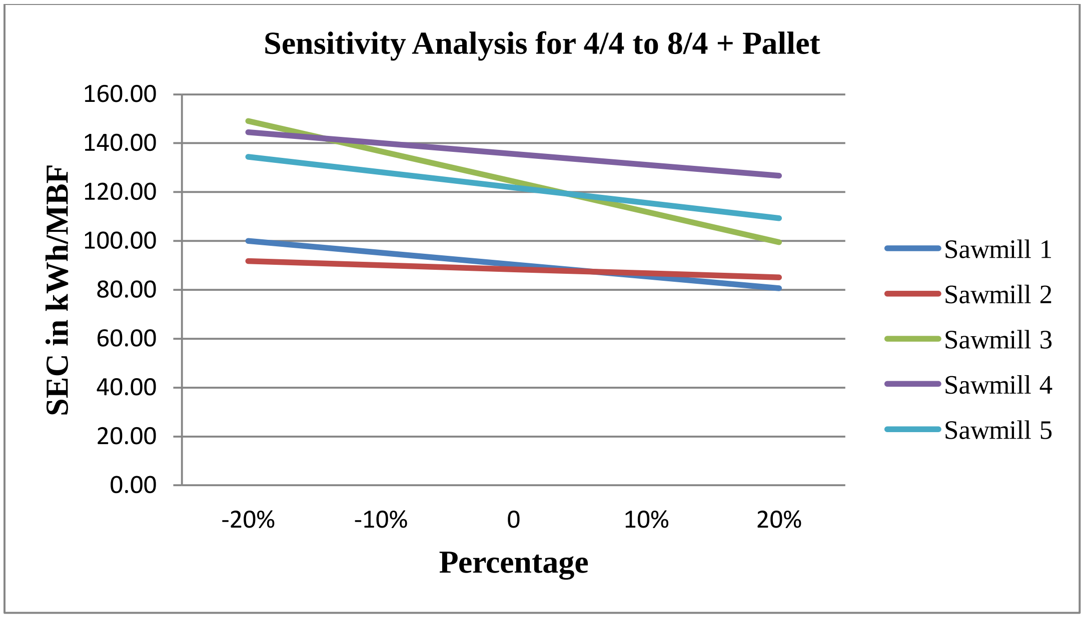


Figure 6.4: Sensitivity Analysis Results for Variable '4/4 to 8/4 + Pallet'

Figure 6.4 shows the sensitivity analysis results of variable '4/4 to 8/4 + Pallet'. The quantity of '4/4 to 8/4 + Pallet' produced in the shift selected from each sawmill was different except for sawmill 1 and 4. The effect of changing it has resulted in significant difference among sawmills. As the value of '4/4 to 8/4 + Pallet' is increased, the energy consumption decreased which suggests that within the same shift if more production of '4/4 to 8/4 + Pallet' is done, it will result in lower energy consumption. Change in '4/4 to 8/4 + Pallet' has shown more effect on the energy consumption of sawmill 3 and then sawmill 5 and then sawmill 1 and 4 and least effect on sawmill 2 since the quantity of '4/4 to 8/4 + Pallet' produced follows that order.

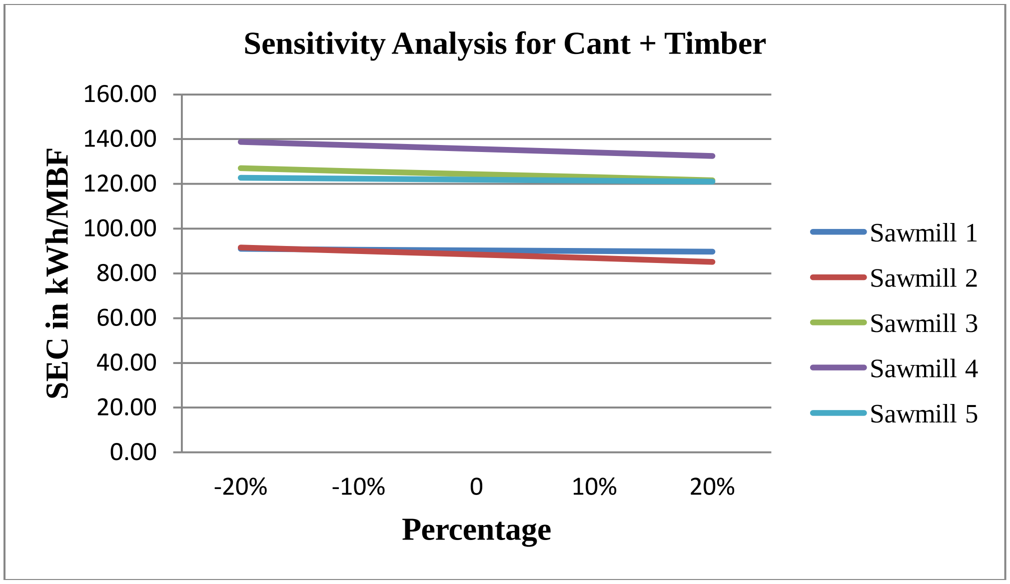


Figure 6.5: Sensitivity Analysis Results for Variable 'Cant + Timber'

Figure 6.5 shows the sensitivity analysis results of variable 'Cant + Timber'. The quantity of 'Cant + Timber' produced in the shift selected from each sawmill was different except for sawmill 2 and 4. The effect of changing it has resulted in some difference among sawmills. As the value of 'Cant + Timber' is increased, the energy consumption decreased which suggests that within the same shift if more production of 'Cant + Timber' is done, it will result in lower energy consumption. Change in 'Cant + Timber' has shown more effect on the energy consumption of sawmill 2 and 4 than sawmill 1, 3 and 5 since sawmill 2 and 4 were producing more percentage of 'Cant + Timber'. Another thing to notice is that effect of changing 'Cant + Timber' variable on energy consumption is way lower than the effect of changing '4/4 to 8/4 + Pallet' variable since for sawing '4/4 to 8/4 + Pallet' lumber more energy is required than 'Cant + Timber'.

Table 6.2: Data used for Sensitivity Analysis in Model 2

Mill #	Hp x Min	Density	4/4 to 8/4 + Pallet	Cant + Timber	Resaw	Double Line	Maint	SEC	Estimated SEC	Error
1	609,840	44	29,629	1,240	1	0	4	86.94	85.42	1.52
2	367,650	44	10,119	6,966	0	0	3	80.51	83.52	-3.01
3	1,262,640	44	75,778	5,791	1	1	2	107.44	94.39	13.05
4	920,400	44	27,184	6,783	0	1	2	144.54	143.59	0.95
5	881,778	44	38,448	1,834	1	0	2	115.25	120.33	-5.08

Same data that was used in Model 1 was used for conducting sensitivity analysis using Model 2 (Table 6.2). The only variable that was tested for sensitivity using Model 2 was 'Level of Maintenance'.

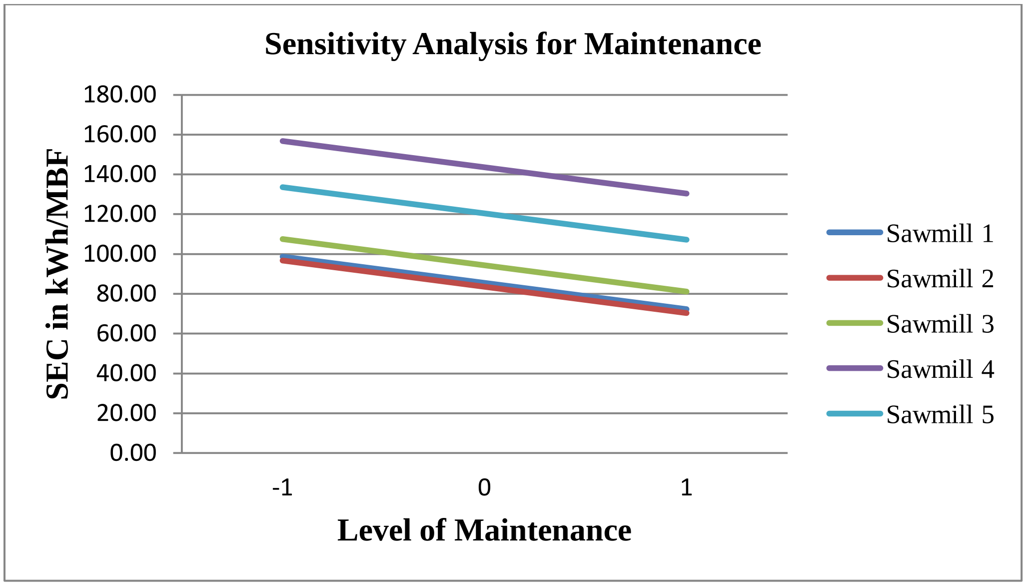


Figure 6.6: Sensitivity Analysis Results for Variable 'Level of Maintenance'

Figure 6.6 shows the sensitivity analysis results of variable 'level of maintenance'. The effect of changing maintenance level has remained same for all the five sawmills. As the level of maintenance went up, the energy consumption decreased. Maintenance level has been decreased and increased only by one level since the frequency of re-sharpening in sawmill 1 is already 3.5 hours and practically it cannot be decreased beyond 2.5 hours and also the SEC values achieved by sawmill 1 and sawmill 2 when the maintenance level is increased by 2 levels is not practically achievable. Increase in two levels of maintenance will result in decrease of SEC by 26.4 kWh/MBF.

6.2 Sensitivity Analysis of different Lumber Widths produced on SEC

As seen, the main sawing operation in sawmills is performed by main saw, re-saw, and gang saw. The energy consumption of these motors were allocated to different size lumber based on surface area cut as length by average width (6”) of lumber. Actually the width of the lumber sawn varies considerably. During the visits to the sawmill 5, it was found that the electricity consumption of these motors did not increase proportionately with the width of the lumber sawn. Data of red oak species was collected in Sawmill 5 to find the variation in electricity consumption of re-saw for different widths of 4/4 size lumber of 10 feet length sawn. As shown in Table 6.3, the electricity consumption is not increasing at the same proportion of the widths.

Table 6.3: Resaw electricity consumption for different widths of Red Oak (Maddula 2014)

Width (Inches)	Electricity Consumption (Amps) ‘X’	Energy Factor (X/105)	Board Feet (Y)	Productivity Factor (5/Y)	Combined Factor (X/105)*(5/Y)
4	89	0.85	3.33	1.5	1.27
5	95	0.90	4.17	1.2	1.09
6	105	1.00	5.00	1	1.00
8	117	1.11	6.67	0.75	0.84
10	121	1.15	8.33	0.6	0.69
12	130	1.24	10.00	0.5	0.62

Main saw, Resaw and gang saw motors must operate more time when sawing 4 inch width boards to produce one MBF of lumber compared to 12 inch width boards because of less volume in them. As explained before, motors energy was allocated based on an average width of 6 inches for grade lumber. The electricity consumption and board feet calculated for 6 inch width lumber is considered as standard electricity consumption and standard board feet for calculating energy and productivity factors. Energy factors for other widths were calculated by dividing the electricity consumption for that width by the standard electricity consumption i.e. 105 amps. Productivity factors were obtained by dividing board feet of that particular size by the standard board feet i.e. 5 board feet. Combined factor was calculated by multiplying energy and productivity factors. Then the energy consumption of main saw, resaw and gang saw motors for other widths (4, 8, 10, 12) were calculated by multiplying the total energy consumption of these motors by the calculated combined factors. The calculated energy consumption of different widths was used to allocate energy to lumber produced during each shift as explained before. Figure 6.7 shows the combined factor obtained for different widths of lumber sawn. From the figure it can be seen that, for sawing unit board feet of 4 inch width lumber, twice the energy required for sawing unit board feet of 12 inch width lumber is needed on resaw.

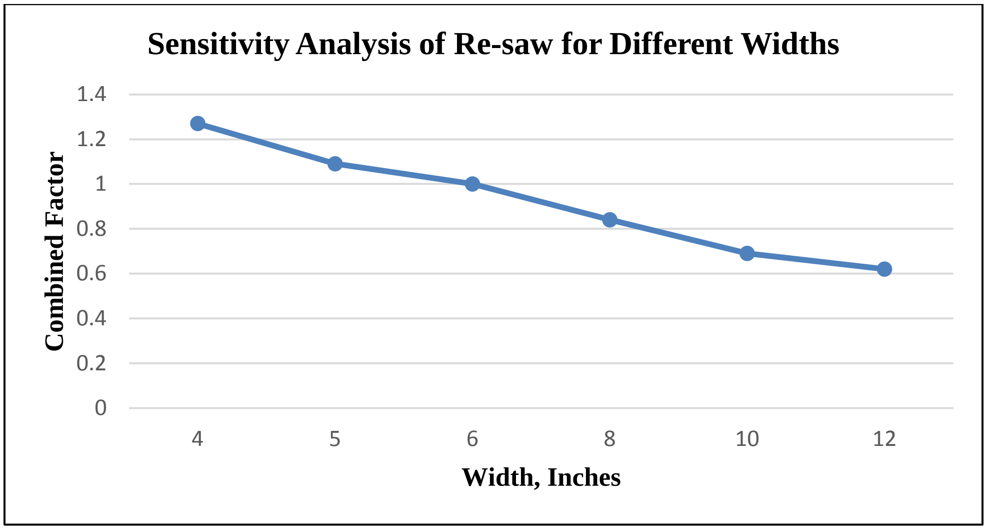


Figure 6.7: Sensitivity Analysis of different widths of Red Oak sawn for Resaw Energy Consumption (Maddula 2014)

Table 6.4 shows the SEC of 4/4 lumber size for widths of 4” to 12” for different species sawn in sawmill 1.

Table 6.4: SEC of 4/4 size Lumber for different Widths and Species sawn in Sawmill 1

Species	4" Width	6" Width	8" Width	10" Width	12" Width
Hickory	124.55	118.31	114.61	107.43	106.19
Hard Maple	98.24	91.53	87.54	79.95	78.60
Cherry	129.32	120.29	114.97	105.62	103.76
Red Oak	97.52	91.12	87.31	80.10	78.80
Soft Maple	84.75	79.00	75.60	69.46	68.28
White Oak	100.85	94.01	89.95	82.52	81.10
ASH	89.69	83.36	79.62	72.54	71.27

Since the thickness of 4/4 lumber and pallet were same, SEC of 4/4 lumber can be considered as the SEC of pallet size also. SEC of Hickory and Cherry species are higher than other species since their densities are higher compared to other species and also more time is spent in sawing them so that less wastage is produced since they are expensive species. Table 6.5 shows the SEC of 5/4, 6/4 and 8/4 lumber sizes for widths of 4” to 12” for different species sawn in sawmill 1.

Table 6.5: SEC for different Widths and Species sawn in Sawmill 1

Species	Thickness	4" Width	6" Width	8" Width	10" Width	12" Width
Hard Maple	5/4	83.41	76.94	73.19	66.59	65.32
Red Oak	5/4	84.00	77.72	74.08	67.70	66.46
White Oak	5/4	83.55	77.59	74.13	68.25	67.06
White Oak	6/4	80.55	73.87	70.06	64.00	62.68
Red Oak	8/4	57.07	51.77	48.79	44.17	43.17

Table 6.6 shows the SEC of cants and timbers for different species sawn in sawmill 1. The point to be noted is the SEC of these will remain the same since their width is fixed.

Table 6.6: SEC for Cants and Timbers sawn in Sawmill 1

Species	Cants (3"x8"x12')	Timbers (7"x9"x10')
Hickory	31.39	-
Hard Maple	23.85	10.09
Cherry	32.36	14.11
Red Oak	24.26	9.89
Soft Maple	20.61	8.46
White Oak	23.82	10.73
ASH	22.02	9.44

Table 6.7 shows the SEC of 4/4 lumber size for widths of 4” to 12” for different species sawn in sawmill 2.

Table 6.7: SEC of 4/4 Lumber for different Widths and Species sawn in Sawmill 2

Species	4" Width	6" Width	8" Width	10" Width	12" Width
Hickory	188.42	169.53	158.53	149.28	145.08
Hard Maple	143.77	129.93	121.83	114.65	111.35
Poplar	137.73	124.43	116.61	109.75	106.58
Red Oak	157.96	142.25	133.09	125.17	121.57
Soft Maple*	179.65	162.78	153.01	144.26	140.41
White Oak	150.59	135.90	127.33	119.86	116.45

*Produced in lesser volume and hence has high SEC

Table 6.8 shows the SEC of 5/4, 6/4 and 8/4 lumber sizes for widths of 4” to 12” for different species sawn in sawmill 2.

Table 6.8: SEC for different Widths and Species sawn in Sawmill 2

Species	Thickness	4" Width	6" Width	8" Width	10" Width	12" Width
Soft Maple	5/4	151.57	137.35	129.02	121.61	118.23
White Oak	5/4	177.16	159.58	149.29	140.57	136.55
Poplar	6/4	102.11	93.15	87.70	82.63	80.09
White Oak	6/4	104.56	95.13	89.45	84.33	81.80
Poplar	8/4	80.51	72.95	68.31	64.23	62.10
Red Oak	8/4	91.58	82.84	77.51	72.82	70.41
Soft Maple	8/4	105.51	95.71	89.78	84.49	81.84

Table 6.9 shows the SEC of cants and timbers for different species sawn in sawmill 2.

Table 6.9: SEC for different Cants and Timbers sawn in Sawmill 2

Species	Cants (5"x6"x12')	Cants (3"x4"x12')	Cants (3.5"x6"x12’)	Timber (7"x9"x10')
Hickory	27.89	-	-	20.35
Hard Maple	-	-	30.77	16.87
Poplar	20.64	36.25	-	14.80
Red Oak	22.85	-	47.68	19.99
Soft Maple	27.63	-	-	20.54
White Oak	25.59	-	-	18.59

Table 6.10 shows the SEC of 4/4 lumber size for widths of 4” to 12” for different species sawn in sawmill 3.

Table 6.10: SEC of 4/4 Lumber for different Widths and Species sawn in Sawmill 3

Species	4" Width	6" Width	8" Width	10" Width	12" Width
Hard Maple	129.62	119.26	113.12	107.36	104.68
Poplar	94.98	87.29	82.72	78.43	76.43
Red Oak	128.84	118.37	112.17	106.37	103.66
Soft Maple	133.19	122.74	116.56	110.78	108.07
White Oak	135.61	124.92	118.58	112.66	109.89
Birch*	193.38	179.73	171.65	164.16	160.62
Black Cherry	114.09	105.06	99.71	94.70	92.36
Hickory*	182.73	168.35	159.84	151.94	148.22

*Produced in lesser volume in only half shift and hence have high SEC

Table 6.11 shows the SEC of 6/4 and 8/4 lumber sizes for widths of 4" to 12" for poplar species sawn in sawmill 3.

Table 6.11: SEC for different Widths of Poplar Species sawn in Sawmill 3

Species	Thickness	4" Width	6" Width	8" Width	10" Width	12" Width
Poplar	6/4	73.31	66.70	62.89	59.53	57.89
Poplar	8/4	58.95	53.72	50.66	48.01	46.66

Table 6.12 shows the SEC of timbers for different species sawn in sawmill 3.

Table 6.12: SEC for Timbers sawn in Sawmill 3

Species	Timber (7"x9"x10')
Hard Maple	10.21
Red Oak	13.84
Soft Maple	14.17
White Oak	14.26
Birch*	20.18
Hickory*	19.15

*Produced in lesser volume in only half shift and hence have high SEC

Table 6.13 shows the SEC of 4/4 lumber size for widths of 4" to 12" for different species sawn in sawmill 4.

Table 6.13: SEC of 4/4 Lumber for different Widths and Species sawn in Sawmill 4

Species	4" Width	6" Width	8" Width	10" Width	12" Width
Hard Maple	194.09	175.28	164.11	153.57	148.65
Poplar	161.71	146.21	137.00	128.24	124.21
Red Oak	193.31	174.38	163.14	152.67	147.68
Ash	237.94	215.66	202.39	189.64	183.81
Hickory	214.85	193.23	180.37	168.39	162.67

Table 6.14 shows the SEC of 6/4 and 8/4 lumber sizes for widths of 4” to 12” for different species sawn in sawmill 4.

Table 6.14: SEC for different Widths and Species sawn in Sawmill 4

Species	Thickness	4" Width	6" Width	8" Width	10" Width	12" Width
Poplar	6/4	123.77	111.20	103.86	97.24	94.06
Ash	6/4	194.71	175.90	164.79	154.59	149.70
Hard Maple	8/4	114.92	103.13	96.20	90.07	87.00
Poplar	8/4	93.65	84.06	78.41	73.37	70.88
Soft Maple	8/4	150.84	136.19	127.53	119.57	115.76
Ash	8/4	136.69	122.95	114.82	107.50	103.89
Sycamore	8/4	218.11	197.25	184.94	173.97	168.52

Table 6.15 shows the SEC of cants and timbers for different species sawn in sawmill 4.

Table 6.15: SEC for Cants and Timbers sawn in Sawmill 4

Species	Cants (14”x4”x12’)	Timber (7"x9"x10')
Hard Maple	34.72	
Poplar	29.46	
Red Oak	34.40	18.20
Soft Maple	47.97	28.43
Ash	42.99	
Sycamore	65.62	43.54
Hickory	38.02	

Table 6.16 shows the SEC of 4/4 lumber size for widths of 4” to 12” for different species sawn in sawmill 5. Point to be noted is some species have higher SEC’s than less denser species since they were produced in 2nd shift which had higher overall SEC.

Table 6.16: SEC of 4/4 Lumber for different Widths and Species sawn in Sawmill 5

Species	4" Width	6" Width	8" Width	10" Width	12" Width
Hard Maple	160.93	144.68	135.06	126.05	121.84
Poplar	100.64	90.00	83.69	77.76	75.00
Red Oak	137.81	123.27	114.65	106.56	102.78
Soft Maple	143.86	128.95	120.12	111.89	108.03
Ash	120.25	107.32	99.66	92.45	89.10

Table 6.17 shows the SEC of 5/4 and 8/4 lumber sizes for widths of 4” to 12” for different species sawn in sawmill 5.

Table 6.17: SEC for different Widths and Species sawn in Sawmill 5

Species	Thickness	4" Width	6" Width	8" Width	10" Width	12" Width
Red Oak	5/4	110.24	98.57	91.68	85.29	82.27
White Oak	5/4	163.75	146.85	136.83	127.47	123.09
Poplar	8/4	58.92	52.69	49.03	45.77	44.16
Ash	8/4	71.77	64.06	59.54	55.49	53.51

Table 6.18 shows the SEC of cants and timbers for different species sawn in sawmill 5.

Table 6.18: SEC for Cants and Timbers sawn in Sawmill 5

Species	Cants (3.5"x6"x12')	Timber (7"x9"x10')
Hard Maple	42.75	-
Poplar	20.56	-
Red Oak	-	13.78
Soft Maple	29.06	-
White Oak	42.83	21.18

SEC of 4/4 size red oak lumber for widths of 4” to 12” is plotted in Figure 6.8. In Figure 6.8, Sawmill 4 and 2 have higher SEC’s than the other sawmills. Other thing to notice is that sawmills (4, 2, 5) with higher SEC’s have more difference between the SEC’s of different widths than sawmills (3, 1) with lower SEC’s.

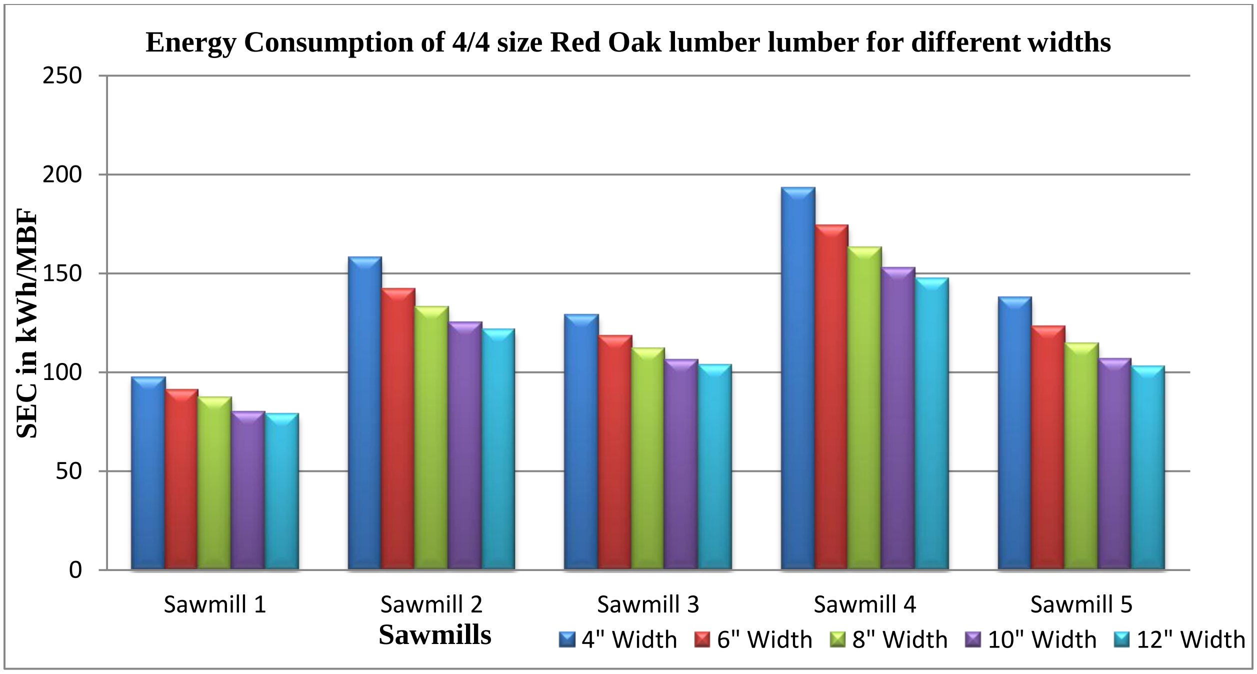


Figure 6.8: SEC's of 4/4 Size Red Oak Lumber for different widths

6.3 Comparison of Sawmill Motors

Sawmill motors energy consumption were compared with in the sawmill and also with other sawmills to see how much energy is consumed in different lumber manufacturing operations. Motor horsepower and Energy consumption of nine major sawmill motors of all the sawmills are shown in Table 6.19 and 6.20. Energy consumption of all the logged and unlogged motors of all the five sawmills is shown in Appendix Table A.16 to A.20.

Table 6.19: Motor Capacities in Horse Power of Major Sawmill Motors

Sawmill	Main Saw + Carriage Feed	Resaw	Gang Saw	Edger	Trimmer	Debarker	Chipper	Compressor	Other Motors	Total kWh
1	300	60	-	50	10	50	150	60	288	968
2	350	-	-	50	25	85	187	40	80	817
3	645	-	418	200	180	210	200	150	627.5	2,630.5
4	600	-	-	175	57.5	80	200	100	321.5	1,534
5	250	150	100	50	100	130	300	300	306	1,686

Even though sawmill 3 and 4 had two lines, horse power capacities and energy consumptions were combined together from both the lines to make the comparison easier with other sawmills. Sawmill 3 had the highest motor capacity and energy consumption and sawmill 2 the lowest.

Table 6.20: Energy Consumption in kWh of Major Sawmill Motors

Sawmill	Main Saw + Carriage Feed	Resaw	Gang Saw	Edger	Trimmer	Debarker	Chipper	Compressor	Other Motors	Total kWh
1	8,351	2,254	-	1,732	1,444	1,231	3,927	7,831	12,997	39,767
2	12,489	-	-	1,338	1,369	5,927	5,856	5,319	2,856	35,154
3	33,211	-	14,351	5,427	10,681	9,220	13,606	20,693	41,364	148,553
4	31,903	-	-	5,694	3,538	3,106	7,358	11,041	18,264	80,904
5	20,523	11,752	4,529	6,083	13,538	4,163	12,249	12,044	21,537	106,418

Even though sawmill 4 produced less than half the quantity of lumber compared to sawmill 3 (Table 6.22) Energy consumption by main saw and carriage feed of sawmill 3 and 4 were almost same. Even though sawmill 2 produced less quantity of lumber compared to sawmill 1, energy consumption of main saw and carriage feed of sawmill 2 was higher than sawmill 1. The reason for higher energy consumption of main saw and carriage feed by sawmill 4 and 2 is that they lack a resaw or a gang saw. Percentage of energy consumed by each motor is shown in Table 6.21.

Table 6.21: Percentage Energy Consumption of Major Sawmill Motors

Sawmill	Main Saw + Carriage Feed (a)	Resaw (b)	Gang Saw (c)	a+b+c	Edger	Trimmer	Debarker	Chipper	Compressor	Other Motors
1	0.21	0.06	-	0.27	0.04	0.04	0.03	0.10	0.20	0.32
2	0.36	-	-	0.36	0.04	0.04	0.17	0.17	0.15	0.07
3	0.22	-	0.10	0.32	0.04	0.07	0.06	0.09	0.14	0.28
4	0.39	-	-	0.39	0.07	0.04	0.04	0.09	0.14	0.23
5	0.19	0.11	0.04	0.34	0.06	0.13	0.04	0.12	0.11	0.20

Percentage of energy used by main saw and carriage feed of sawmill 1 is the lowest and sawmill 4 the highest. Energy consumption of main saw and carriage feed of sawmill 2 and 4 are the highest and also they are almost equal since they use main saw for sawing all the lumber. Energy consumption for the main sawing (breaking down of log into lumber before edging and trimming) was lowest for sawmill 1 and highest for sawmill 4. The reason for the lowest energy consumption by sawmill 1 can be contributed to better maintenance of saw blades and use of small size motor in resaw. Energy consumption of debarker in sawmill 1 is the lowest and in sawmill 2 the highest. This happened since the hydraulic pump used in debarker was not included with the debarker during data collection in sawmill 1, where as it was included in sawmill 2. Another thing to notice in sawmill 2 is energy consumption by other motors is very low compared to other sawmills since those motors energy consumption was merged with the energy consumption of debarker and chipper since they were located in the control panels of debarker and chipper. Trimmer usage is high in sawmill 3 and 5 since they sawed more grade lumber than other sawmills (Table 3.6).

Board feet sawn and surface area sawn in square feet (surface feet) in each sawmill is shown in Table 6.22. Surface feet sawn was calculated using the method explained in energy allocation methodology of Chapter 4. Surface feet sawn of sawmill 2 went down drastically since it sawed more of cants and timbers. Also, board feet sawn per hour per horsepower and surface feet sawn per hour per horsepower were calculated to show how productive is each sawmill since just board feet per hour or surface feet per hour won't give the real picture of productivity of each sawmill. Sawmill 4 had the highest value for both board feet sawn per hour per horsepower and surface feet sawn per hour per horsepower and hence has the highest motor load factor. Sawmill 2 and 4 has very low surface feet sawn per hour per horsepower since they does not have a resaw or a gangsaw. Sawmill 1 has good surface feet sawn per hour per horsepower since it has a resaw and small size motors. Energy consumed by each motor per surface feet sawn was used to compare different motor's energy consumption among sawmills since energy consumed per board feet sawn won't give correct comparison results as discussed in Chapter 4.

Table 6.22: Board Feet sawn and Surface Feet sawn in each Sawmill with Motor Load Factors

Sawmill	Board Feet	Surface Area Sawn in Sq. Ft.	Board feet Per hour	Surface Feet Per hr	Board feet per hour per hp	Surface Feet Per hr per hp	Motor Load Factor
1	460,994	504,433	2,946	3,223	3.04	3.33	0.307
2	420,687	282,329	2,203	1,478	2.70	1.81	0.265
3	1,431,387	1,545,485	9,975	10,770	3.79	4.09	0.485
4	660,379	537,538	3,890	3,167	2.54	2.06	0.358
5	949,149	980,494	4,616	4,769	2.74	2.83	0.362
Total	**3,922,596**	**3,850,279**					

Energy consumption by different motors per 1,000 square feet of surface area sawn is shown in Table 6.23. The average energy consumed is for total lumber sawn in each sawmill and not for individual lumber sizes. Total Energy consumption per 1,000 square feet surface area sawn follows similar pattern as percentage energy consumption of motors.

Table 6.23: Energy Consumption in kWh per 1,000 Square Feet of Surface Area sawn by Major Sawmill Motors

Sawmill	Main Saw + Carriage Feed	Resaw	Gang Saw	Edger	Trimmer	Debarker	Chipper	Compressor	Other Motors	Total kWh/ 1000 Sq. Ft.
1	16.56	4.47	-	3.43	2.86	2.44	7.79	15.52	25.77	78.84
2	44.23	-	-	4.74	4.85	20.99	20.74	18.84	10.12	124.51
3	21.49	-	9.29	3.51	6.91	5.97	8.80	13.39	26.77	96.12
4	59.35	-	-	10.59	6.58	5.78	13.69	20.54	33.98	150.51
5	20.93	11.99	4.62	6.20	13.81	4.25	12.49	12.28	21.97	108.53

Since the percentage energy consumption of motors had only percentage values of energy consumed with in the sawmill, it didn’t give any information about the actual energy consumption values in kWh. Energy consumption per 1,000 square feet of surface area sawn clearly shows how much energy is consumed by each motor. Sawmill 1 had the lowest energy consumed per 1,000 square feet of surface area sawn and sawmill 4 had the highest.

Energy consumption of individual motors per 1,000 square feet of surface area sawn of sawmill 1, 2, 3, 4 and 5 are shown in Figures 6.9 through 6.13.

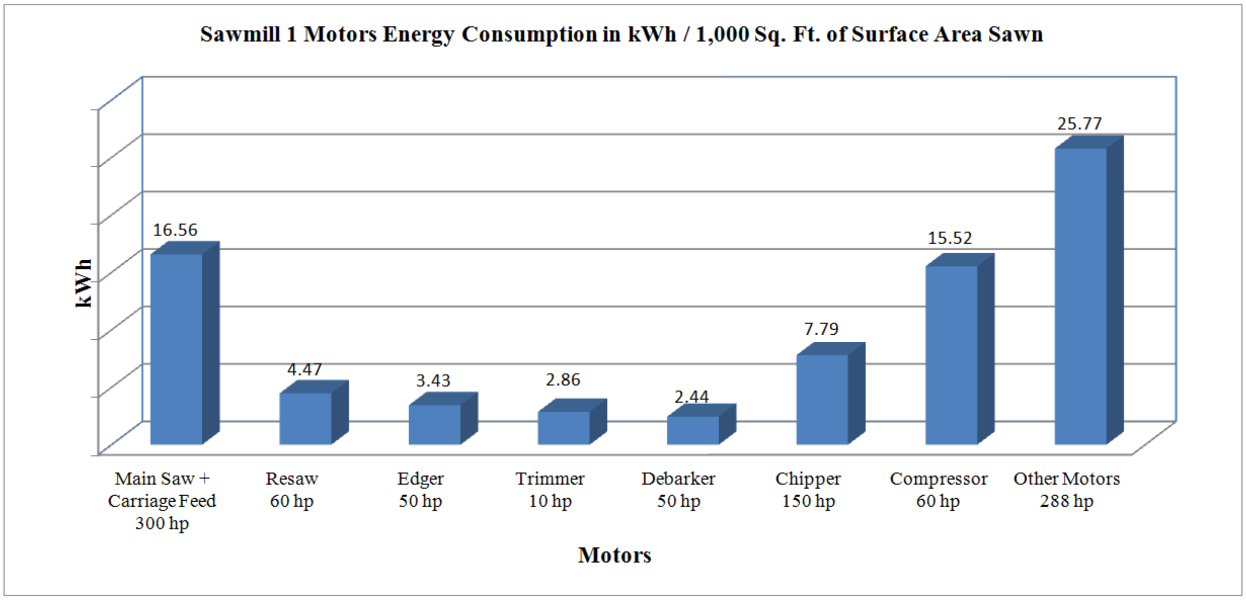


Figure 6.9: Energy Consumption of Sawmill 1 Motors per 1,000 Square Feet of Surface Area sawn

The main consumers of energy in sawmill 1 were main saw and carriage feed, chipper, compressor and other motors. Other motors had motors like dust collector, hydraulic pump of debarker, trim saws and chip blower which consumed considerable amount of energy.

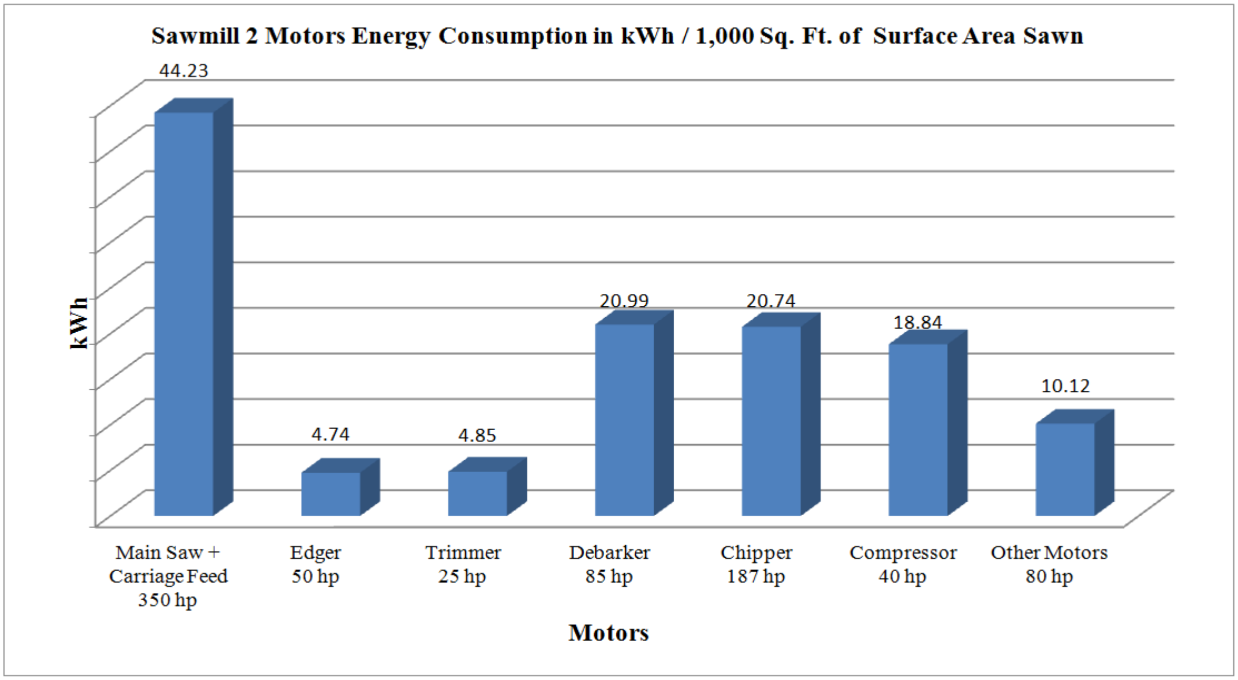


Figure 6.10: Energy Consumption of Sawmill 2 Motors per 1,000 Square Feet of Surface Area sawn

The highest energy consumer of sawmill 2 motors was main saw and carriage feed, since there was no resaw or a gang saw in sawmill 2. Other main energy consumers were debarker, chipper and compressor. Debarker had hydraulic pump and chipper had chip blower and dust collector and hence have higher energy consumption than other sawmills.

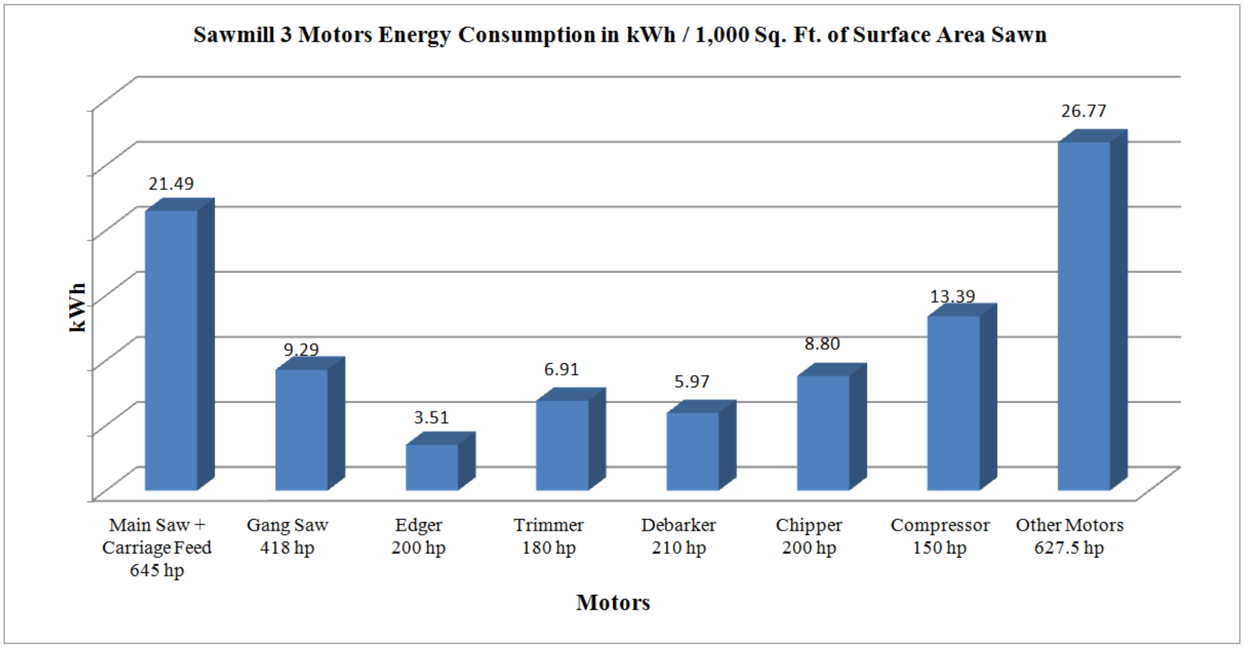


Figure 6.11: Energy Consumption of Sawmill 3 Motors per 1,000 Square Feet of Surface Area sawn

The energy consumption of sawmill 3 motors was similar to sawmill 1. The main consumers of energy in sawmill 3 were main saw and carriage feed, gang saw, chipper, compressor and other motors. Edger consumed less energy than trimmer in sawmill 3 since sawmill 3 had gang saw which was sawing cants and there was not much need of edger to do edging of the lumber coming from gang saw. Since sawmill 3 produced lots of grade lumber and grade lumber needed trimming, trimmer consumed more energy than edger and debarker in sawmill 3. Since sawmill 3 was a large capacity sawmill, there were lot of motors under the other motors category (Appendix Table A.26).

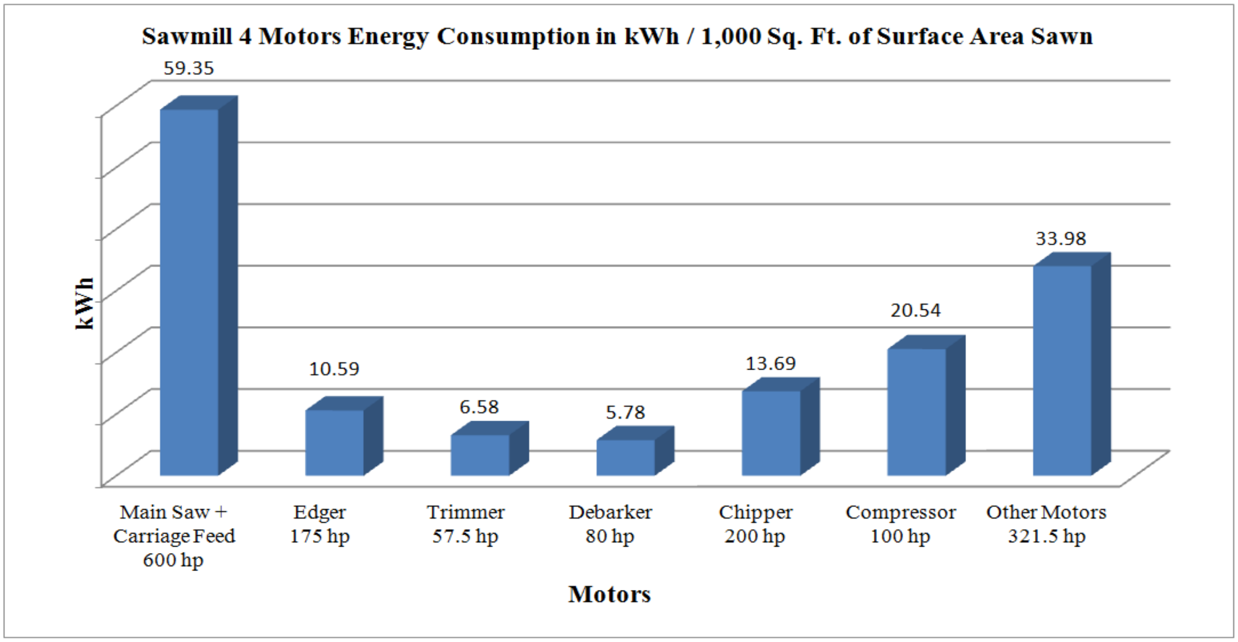


Figure 6.12: Energy Consumption of Sawmill 4 Motors per 1,000 Square Feet of Surface Area sawn

The energy consumption of sawmill 4 motors was similar to sawmill 2. The highest energy consumer of sawmill 4 motors was main saw and carriage feed, since there was no resaw or a gang saw in sawmill 4. Other main energy consumers were chipper, compressor and other motors.

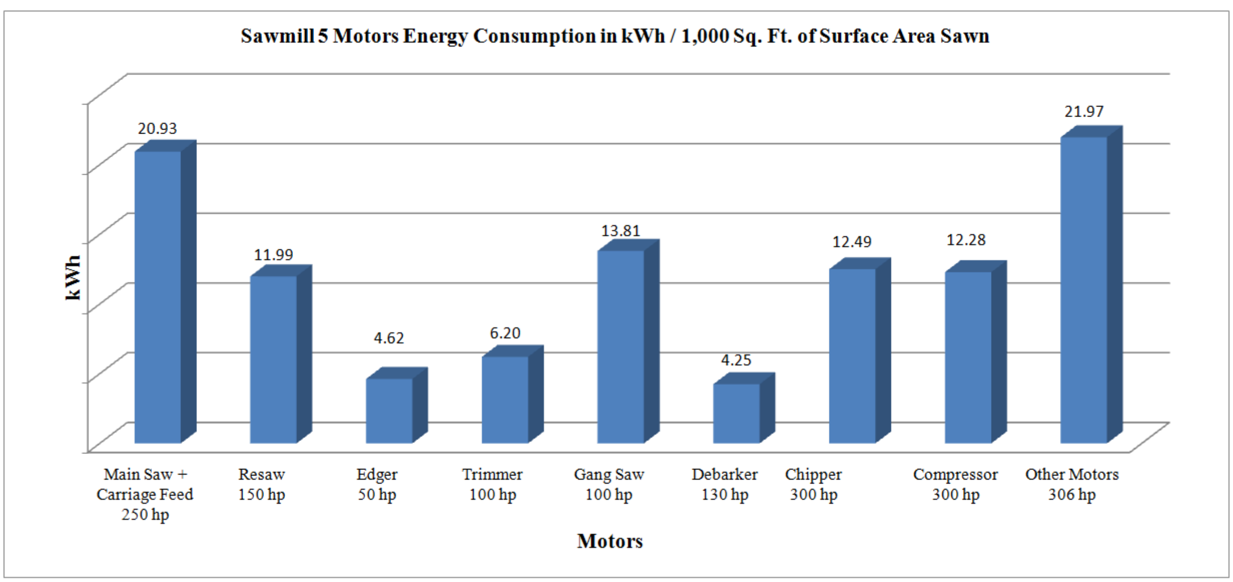


Figure 6.13: Energy Consumption of Sawmill 5 Motors per 1,000 Square Feet of Surface Area sawn

The energy consumption of sawmill 5 was different from rest of the sawmills since it had both a resaw and a gang saw. The main consumers of energy in sawmill 5 were main saw and carriage feed, resaw, gang saw, chipper, compressor and other motors. Since sawmill 5 produced the highest quantity of grade lumber among all the sawmills, and grade lumber needed trimming, trimmer consumed more energy than edger and debarker in sawmill 5.

Conclusion

Estimator variables density, minutes and horsepower were positively correlated to energy consumption where as '4/4 to 8/4 + Pallet', 'Cant + Timber' and 'Level of Maintenance' were negatively correlated in SEC models. Sensitivity analysis conducted on the estimator variables showed that sawmill 3 had the highest effect on its energy consumption from estimator variables 'horsepower' and '4/4 to 8/4 + Pallet'. Sensitivity analysis conducted on width of lumber showed that for sawing one unit board feet of 4 inch width lumber, twice the energy required for sawing one unit board feet of 12 inch width lumber is needed on resaw. In overall SEC, energy consumed for sawing 4 inch width lumber of unit board feet was higher by 24% to 34% than energy required for sawing one unit board feet of 12 inch width lumber depending on the horsepower of the main saw, resaw and gang saw motors used in different sawmills. Sawmill 2 and 4 had higher SEC's as discussed earlier and also didn't follow the order of density correctly. In sawmill 5 also SEC didn't follow the order of density since the lower SEC of 1st shift and higher SEC of 2nd shift were mixed together resulting in higher SEC's for some species. The highest energy consumer of sawmill 2 and 4 motors was main saw and carriage feed, since there was no resaw or a gang saw in them. The energy consumption of sawmill 1 motors was similar to sawmill 3 and energy consumption of sawmill 2 motors was similar to sawmill 4.

7. Conclusion and Future Work

7.1 Contribution of this Research

1. The energy allocation methodology developed based on surface area cut.
2. Analysis of sawmills from productivity view point showing the production bottle necks.
3. Estimation models to estimate energy consumption and identification of important estimator variables.
4. Development of best achievable specific energy consumption values for different sizes and species of lumber.
5. Sawmill Energy Estimation Program that estimates SEC, analyzes the results and gives suggestions with estimated savings.
6. Identification of the correlation between lumber production variables minutes and board feet with total energy consumed.
7. Development of a new method to calculate data collection sample size for data of unknown probability distribution.

7.2 Conclusion

Benchmarking is the best way to know individual sawmill's level of performance in energy consumption and there was a need for developing best achievable energy consumption and a tool to do benchmarking. Previous studies did not consider sawmill manufacturing from the view point of both energy and productivity. Three sawmills with single sawing line and two sawmills with double sawing lines were selected to monitor their electrical energy consumption and production.

Looking at gross energy consumption and calculating overall energy consumption per board feet and using it to estimate the energy efficiency of a sawmill or using it for benchmarking like the authors did in the literature review lead to wrong conclusions. This research analyzed sawmills energy efficiency by taking the sizes and species of lumber sawn into account and allocating the energy consumption based on surface area cut for that particular size which yielded better results. The energy allocation method developed in this research will give a better picture of the sawmill performance in terms of energy efficiency and productivity. Also, the results from the comparison of sawmills concluded that resaw/gangsaw and matching of machine capacities plays major role in achieving energy efficiency and productivity of sawmill.

Ten Variables were selected from Product, Process, and System Parameters. Three multiple linear regression models were developed to estimate energy consumption per thousand board feet. The estimation model with the 'Motor hp x Min' variable was the most promising model developed. As the common sense says, maintenance is the key for the performance of any machine, 'Level of Maintenance' also turned out to be an important estimator variable. SMEEP developed will help the end user to bench mark their sawmill along with knowing methods to improve their sawmill's efficiency with estimated savings.

7.3 Future Work

- Only amperage data was logged for duration of 1 month and voltage and power factor data was collected for only 20 minutes in this research. Better quality data and hence better model can be obtained if energy data can be logged using energy meters.
- There was mix up of species during the data collection of this research and hence some data collected was not accurate. Better data collection can happen if there is no mix up of

species and best data collection can happen if real time tracking of logs using some tracking method can be done.

- Data collection was done for 80% of the motors capacity and remaining 20% was estimated. The estimation accuracy of the model can be improved if 100% of the motor capacity can be logged.
- Five sawmills were studied in this research. Studying more sawmills can help to understand the sawmill manufacturing process better and may help to improve the model by including more estimator variables. For Ex.: New saw blade material like Stellite.
- Estimation Model has not considered the difference in energy efficiency of equipment like using premium efficiency motor vs. standard efficiency motor or compressor with VFD vs. without VFD etc., since the sawmills studied does not have those type of equipment. So, variable for the difference in efficiency of the equipment can be included in the future model or difference in efficiency can be incorporated by multiplying the motor horse power with a factor that represents the motor or equipment efficiency.
- Estimation model grouped board lumber sizes between four quarter to eight quarter and cants and timbers. A future estimation model can split these sizes to obtain better results.
- Production capacities of sawing equipment like head saw, resaw and gang saw were compared by using the amperage data collected every minute. A better comparison of these machine capacities and balancing them can be done by conducting proper time study and assembly line balancing.

Literature Cited

1. Adams, E., 1982 ― *Using a recording watt/varmeter to measure power consumption of sawmill equipment*, Department of Agriculture, Forest Service, Northeastern Forest Experimental Station, Gen. Tech. Rep. NE-71, 1982
2. AFPA 2012 – American Forest and Paper Association Fact Sheet http://www.afandpa.org/our-industry/economic-impact (Accessed Dec 11, 2013)
3. Axelsson, B., Lundberg, Å., and Grönlund, J. (1993). *Studies of the main force at and near cutting edge* Holz als Roh-und Werktoff 51(2), 43-48.
4. AMO 2012 - U.S. Department of Energy : Advanced Manufacturing Office https://www1.eere.energy.gov/manufacturing/pdfs/energy_use_and_loss_and_emissions_forest.pdf (Accessed Dec 15, 2013)
5. Bergman, R., Bowe, S. 2008. *Environmental impact of producing hardwood lumber using life-cycle inventory*. Wood and Fiber Science, 40(3):448 – 458
6. BLS 2013 – United States Department of Labor - Bureau of Labor Statistics, Quarterly Census of Employment and Wages – for NAICS 321 Wood Product Manufacturing and 321113 Sawmills, http://data.bls.gov/cgi-bin/dsrv (Accessed Dec 30, 2013)
7. Bond, B. 2008. *Sawmill and treating insights: Rein in escalating energy costs.* Online: http://www.palletenterprise.com/articledatabase/view.asp?articleID=2648. (Accessed Dec 30, 2013)
8. Carole, T., et.al 2001 ― *Energy Efficiency and Use in the Chemical Industry*, Proceedings ACEEE Summer Study on Energy Efficiency in Industry, Vol. 1, pp 267-275, 2001
9. Cassens, D. L., 2001 "Quality Control in Lumber Purchasing: Hardwood Lumber Grades," Department of Forestry and Natural Resources, Purdue University.
10. CPL 2001 - *Motor Management Success: Crown Pacific Lumber Saves Money with Motor Management Tools* http://www.motorsmatter.org/case_studies/Crown_Pacific.pdf (Accessed Dec 29, 2013)
11. Cristovao 2012 - *Main cutting force models for two species of tropical wood, Wood Material Science & Engineering,* Volume 7, Issue 3, 2012, Special Issue: 20th International Wood Machining Seminar

12. Cristóvão 2013 - Luís Cristóvão, Mats Ekevad, and Anders Grönlund, *Industrial Sawing of Pinus sylvestris L.: Power Consumption*, BioResources 8(4), 6044-6053
13. Dalois C, 1990 - Manuel de sciage et d'affutage. Centre Technique Forestier Tropical, Department du CIRAD
14. Denig, J., 1993 ―*Small Sawmill Handbook - Doing it Right and Making Money*, Chapter 3, Sawmill Equipment – Primary Breakdown, pp 39 – 72, Miller Freeman, Inc., San Francisco, 1993
15. DOE 2004 – US DOE *Best Practices Case Study*, *Weyerhaeuser: Compressed Air System Improvement Saves Energy and Improves Production at a Sawmill* https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/bp_cs_weyerhaeuser.pdf (Accessed on Dec 29, 2013)
16. DOE 2006, U.S. Department of Energy. Forest Products Technologies: Public Private Partnerships Produce R&D Results. Online: http://www1.eere.energy.gov/industry/forest/pdfs/forestsuccesses.pdf (Accessed April 25, 2013)
17. EERE 2012 – US Department of Energy : Office of Energy Efficiency & Renewable Energy http://www1.eere.energy.gov/analysis/eii_efficiency_intensity.html (Accessed Dec 15, 2013)
18. Engineering Toolbox, Wood Densities (Accessed Mar 25, 2015) http://www.engineeringtoolbox.com/weigt-wood-d_821.html http://www.engineeringtoolbox.com/wood-density-d_40.html
19. EPA 2007 - U.S. Environmental Protection Agency : Energy Trends in Selected Manufacturing Sectors http://www.epa.gov/sectors/pdf/energy/report.pdf (Accessed Dec 15, 2013)
20. Espinoza O, Buehlmann U, and Bond B 2011 - *Energy and the US hardwood industry – Part II: Responses to increasing prices.* BioResources 6(4):3899-3914.
21. Fenart 2000 - Fénart, P, Snieg, O. *The frequency variables: a tool to increase the productivity and decrease the energy consumption in sawmills*, CTBA Info 2000 No. 86 pp. 6-9

22. FPI roadmap 2010 - Forest Products Industry Technology Roadmap http://www.twosides.info/Content/rsPDF_101.pdf (Accessed Dec 11, 2013)
23. FPIP 1979 - Forest Products Industry Profile, Website http://www.fpl.fs.fed.us/documnts/fplrp/fplrp310.pdf (Accessed Dec 11, 2013)
24. Garner, J., 2002 - *Energy Conservation in the Pulp, Paper, and Wood Products Industry*, Technical Paper, 2002, http://www.emt-india.net/process/pulp_paper/pdf/garner-paper2002.pdf (Accessed Jan 6, 2014)
25. Gopalakrishnan, B., R. W. Plummer, and W. H. Iskander. 2003. *A comparative study on energy assessment data from manufacturing industry.* ACEEE Summer Study on Energy Efficiency in Industry, July 29–August 1, 2003, Rye Brook, New York; American Council for an Energy-Efficient Economy, Washington, D.C. pp. 86–95.
26. Gopalakrishnan, 2005 - *Energy Efficiency Measures in the Wood Manufacturing Industry*, 2005 ACEEE Summer Study on Energy Efficiency in Industry
27. Iris 2006 - Iris Vazquez-Cooz, Robert W. Meyer. *Cutting Forces for tension and normal wood of Maple.* Forest Products Journal. Apr2006, Vol. 56 Issue 4, p26-34. 9p http://www.fao.org/docrep/ARTICLE/WFC/XII/0886-A2.HTM (Accessed on Dec 23, 2013)
28. ITTO 2012 – International Tropical Timber Organization, Annual Review and Assessment of the World Timber Situation 2012 http://www.itto.int/annual_review/ (Accessed Dec 30, 2013)
29. Koch, P. 1964. *Wood Machining Processes*, Ronald Press, New York, USA.
30. Kivimaa E 1950 - *Cutting force in wood working.* State Institute for Technical Research, Helsinki
31. Li 2006 - Li, Jingge, McCurdy, Murray, Pang, Shusheng. *Energy demand in wood processing plants.* New Zealand Journal of Forestry, 2006:51(2), pp. 13-18. http://ir.canterbury.ac.nz/bitstream/10092/167/1/12603292_Main.pdf (Accessed Jan 6, 2014)
32. Lin, W., J. Wang, S.T. Grushecky and D. Summerfield and B. Gopalakrishnan. 2012. *Energy Consumption and Efficiency of Appalachian Hardwood Sawmills.* Forest Products Journal, 62(1):32-38

33. Maddula - Energy Intensity Determination in Wood Processing Sawmills, M.S. Thesis, West Virginia University, 2014
34. Mardikar, Y. 2007. *Establishing baseline electrical energy consumption in wood processing sawmills: A model based on energy analysis and diagnostics.* Ph.D dissertation. West Virginia University, Morgantown.
35. Matan 2003 - Matan, N. and Kyokong. B, *Effect of moisture content on some physical and mechanical properties of juvenile rubberwood,* Songklanakarin Journal of Science and Technology, 2003, 25(3) : 327-340
36. Mate, A. 2002. *Energy analysis and diagnostics in wood manufacturing industry.* Master's thesis. West Virginia University, Morgantown.
37. McDonald K. A., and Kretschmann, D. E., 1898 "The Encyclopedia of Wood," U.S. Department of Agriculture, pp. 1-2. Chap. 5.
38. Mihai 2008 - *Research concerning the workability by sawing of frozen and unfrozen spruce wood* - PRO LIGNO - Open Access Scientific Journal in the Field of Wood Engineering 2008 Volume 4.
39. Milota, M., West, C., Hartley, I. 2005. *Gate to gate life cycle inventory of softwood lumber production.* Wood and Fiber Science, 37:47-57.
40. Montgomery, D., Runger, G., 2003 - Applied Statistics and Probability for Engineers, Chapter 6, Random Sampling and Data Description, pp 189 – 219, Third Edition John Wiley and Sons, Inc., 2003
41. Montgomery, D., Runger, G., 2003 - Applied Statistics and Probability for Engineers, Chapter 8, Statistical Intervals for a Single Sample, pp 247 – 276, Third Edition John Wiley and Sons, Inc., 2003
42. Mozzo, M., 2000 - *The Importance of Properly Setting the Baseline for Performance Contracts,* Energy Engineering Journal, Vol. 98, # 2, pp 73 – 80, 2000
43. Nadel, S., et.al; 2002 - Energy Efficient Motor Systems: A Handbook on Technology, Program, and Policy Opportunities, Chapter 2, Motor Technologies, pp 13 – 85, Second Edition, American Council for an Energy-Efficient Economy, 2002
44. Normand 2009 – Normand Be´dard, Benoıˆt Laganie`re, *Debarking enhancement of frozen logs, Part II: Infrared system for heating logs prior to debarking,* Forest Products Journal, Jun2009, Vol. 59 Issue 6, p25-30. 6p

45. Onset Data Loggers 2013 - http://www.onsetcomp.com (accessed on Jan 3rd 2013)
46. Orlowski, 2013 - Orlowski K., Ochrymiuk, T., Atkins, A., and Chuchala, D. (2013). *Application of fracture mechanics for energetic effects predictions while wood sawing*, Wood Science and Technology 47(5), 949-963.
47. Pawlik, et.al 2001 - *Analyzing Facility Energy Use: A Balancing Act,* Journal of Strategic Planning for Energy and the Environment, Vol. 21, # 2, pp 8 – 33, 2001
48. Payam 2013 - Payam Moradpour, Kazem Doosthoseini, Frieder Scholz, Asghar Tarmian *Cutting forces in bandsaw processing of oak and beech wood as affected by wood moisture content and cutting directions,* European Journal of Wood and Wood Products, November 2013, Volume 71, Issue 6, pp 747-754
49. Poole, A; Pinheiro, P. 2003. *Developing Energy Profiles for Sawmills in the Amazon Region First Field Visit to Rondolândia and Ji-Paraná.* The National Institute of Energy Efficiency, Brazil. Online: http://www.inee.org.br/down_loads/biomassa/AmazonSawmill.pdf (Accessed April 25, 2013)
50. Ramírez, C., 2006 - *Adding Apples and Oranges: The Monitoring of Energy Efficiency in the Dutch Food Industry* Energy Policy Journal, Vol. 34, Issue 14, pp 1720-1735, 2006
51. Rutgers 2015, Motor Demonstration Lab, https://caes.rutgers.edu/labMotor
52. Sawmill and Woodlot Magazine, 2010, "Understanding Hardwood Lumber Grading,"
53. Spinelli R., Cavallo E., Eliasson L., Facello A. 2013. *Comparing the efficiency of drum and disc chippers.* Silva Fennica vol. 2013 no. 2 article id 930. 11 p.
54. Uppgård, R. 1995 - *Small-scale sawing. Time studies on circular band saw technique,* Swedish University of Agricultural Sciences, Faculty of Forestry, Department of Operational Efficiency, Sweden
55. UN 1983 – Food and agricultural Organization of United Nations, *Energy Utilization in Sawmilling*. http://www.fao.org/docrep/t0269e/t0269e04.htm (Accessed April 25, 2013)
56. USCB 2010 – United States Census Bureau - *Annual Current Industrial Reports of Lumber Production and Mill Stocks.* http://www.census.gov/manufacturing/cir/historical_data/ma321t/index.html (Accessed Dec 11, 2013)

57. USDA 2011 - U.S. Department of Agriculture – *Bulletin of Harwood Market Statistics* http://www.nrs.fs.fed.us/pubs/rn/rn_nrs158.pdf
58. USDOE BP Best Practice Tools - US Department of Energy – Energy Efficiency and Renewable Energy, AMO Energy Resources Center https://ecenter.ee.doe.gov/Pages/default.aspx (Accessed on Dec 23, 2013)
59. USDOE 2015 – MotorMaster+ International - US Department of Energy http://www.energy.gov/eere/amo/articles/motormaster-international
60. US EIA 2010 – US Energy Information Administration Annual Energy Review http://www.eia.gov/consumption/manufacturing/data/2010/pdf/Table1_1.pdf (Accessed Dec 11, 2013)
61. US EIA 2013 – US Energy Information Administration U.S. Energy Prices http://www.eia.gov/electricity/sales_revenue_price/pdf/table8.pdf (Accessed May 23, 2015)
62. Wengert 1992 - Wengert, G. and D. Meyer. 1992. *Energy at the sawmill: Conservation and cost reduction.* Forestry Facts No. 61. Online: http://forest.wisc.edu/sites/default/files/pdfs/publications/61.PDF. (Accessed Dec 23, 2013)
63. Williston, E., 1988 - Lumber Manufacturing, *Chapter 6, Debarking at the Long-Log Deck,* pp 45 – 57, Revised Edition, Miller Freeman Publications, Inc., 1988
64. Williston, E., 1988 - Lumber Manufacturing, *Chapter 9, Principles and Systems for Primary Log Breakdown,* pp 72 – 103, Revised Edition, Miller Freeman Publications, Inc., 1988
65. Williston, E., 1988 - Lumber Manufacturing, *Chapter 11, Edgers,* pp 109 – 121, Revised Edition, Miller Freeman Publications, Inc., 1988
66. Williston, E., 1988 - Lumber Manufacturing, *Chapter 12, Trimming Rough Lumber,* pp 122 – 128, Revised Edition, Miller Freeman Publications, Inc., 1988
67. Williston, E., 1988 - Lumber Manufacturing, *Chapter 20, Chipping and Chip Handling,* pp 216 – 224, Revised Edition, Miller Freeman Publications, Inc., 1988
68. Williston, E., 1988 - Lumber Manufacturing, *Chapter 25, Saw Design and Maintenance,* pp 304 – 345, Revised Edition, Miller Freeman Publications, Inc., 1988

69. WVDOF 2013 - West Virginia Division of Forestry http://www.wvforestry.com/indassistance.cfm?menucall=industry (Accessed Dec 15, 2013)

Appendix

Table A.1: Format for Production Data Collection & Sample Filled by one of the Sawmill

Format for Production Schedule:

(Please provide us the production schedule details for the time loggers are hooked)

Date	Starting time	Ending time	Species	Grade	Size	Board Feet

Required Format for Production Schedule:

(Please provide us the production schedule details for the time loggers are hooked)

Date	Starting time	Ending time	Species	Grade	Size	Board Feet	$/Bdft
4-16-09	5:30Am		Red Oak	Reg FAS-1F	4/4	3,991	600/m
				8½' FAS-1F	4/4	671	600/m
				1C	4/4	4,515	Market
				2A	4/4	6,477	Market
				3A	4/4	4,268	Market
				Fence Boards 1X6-16'	4/4	3,184	540/M
				Pallett Material 1X6, 1X8 RL	4/4	3,116	200/m
				Reg FAS 1F	5/4	5,782	650/m
				Mine Material 3X8-12'	3"	1,416	375/m
4-16-09	4:00pm		Red Oak		Total -	33,420	

✗ R.O. Ave Log Size - 84'

✗ Ø min down time

Ave length of 4/4 size (10'-12')

Ave width of 4/4' Size 8"

Table A.2: Main Saw Amperage Data of Sawmill 1 used for Calculating Duration of Data Logging

57.94	182.30	56.62	58.23	58.37	58.08	57.94	58.52	57.20	56.03	138.94	59.55
60.43	60.28	113.31	133.52	55.74	56.03	69.95	164.72	58.52	58.37	144.21	54.13
62.18	59.84	58.96	57.35	56.47	58.37	55.01	58.67	122.97	57.35	58.37	61.30
59.11	61.16	109.94	56.91	56.91	56.47	66.43	56.32	57.94	114.04	54.42	136.89
197.24	61.16	85.77	57.79	58.81	58.08	56.76	55.15	60.13	55.59	56.03	203.83
57.20	58.37	231.67	58.08	51.78	138.21	199.44	57.50	56.91	56.76	57.06	342.41
59.69	58.23	122.97	56.47	58.52	59.40	59.25	140.11	57.06	59.40	55.44	175.42
152.12	57.79	56.62	58.96	55.30	69.65	58.81	56.76	63.35	210.13	56.47	58.81
58.81	59.11	65.70	59.25	60.28	59.40	64.38	59.11	58.08	56.47	118.87	57.64
57.64	85.03	139.23	58.81	54.13	60.72	58.81	213.21	57.06	53.54	56.62	215.26
109.64	59.25	140.41	120.34	58.81	55.30	56.18	134.69	58.23	249.83	56.32	61.45
57.06	61.45	58.81	168.97	58.37	57.35	60.13	58.08	56.32	56.91	56.32	99.39
56.47	57.35	59.25	60.43	59.84	58.52	57.35	55.44	55.88	55.30	56.18	55.30
59.55	59.84	59.55	58.52	59.99	56.62	58.08	55.74	58.67	111.99	63.94	58.81
59.40	55.88	139.82	56.03	56.76	56.76	56.76	59.25	57.64	140.11	234.89	57.06
57.64	195.04	56.03	56.47	58.81	56.91	122.97	59.25	55.44	55.88	56.62	159.74
58.96	57.50	138.06	57.64	125.17	59.55	58.08	56.18	157.10	123.85	56.76	152.42
133.81	120.63	57.35	133.81	59.55	58.81	56.03	57.20	138.65	56.03	59.25	60.86
78.88	61.74	58.52	59.99	135.13	56.03	58.67	235.33	264.62	219.36	56.62	58.37
59.11	59.11	62.18	54.86	114.48	62.62	58.37	61.16	59.25	58.67	58.81	58.81
191.82	57.20	57.94	58.81	57.79	57.50	56.18	61.30	57.94	124.59	142.31	56.47
58.52	176.88	56.47	57.35	60.28	58.96	57.06	200.02	56.47	160.33	56.32	56.91
57.35	130.15	59.11	59.40	58.37	57.79	56.76	189.33	59.40	162.96	160.91	56.76
150.37	180.25	57.06	58.23	131.03	114.77	59.84	56.62	58.81	58.37	88.40	134.99
59.11	159.16	56.18	58.23	194.02	57.94	56.47	70.53	58.23	58.37	58.23	55.59
62.33	101.59	55.88	56.76	59.40	54.86	56.32	57.06	57.50	56.62	57.64	55.44
160.03	57.35	56.03	56.47	55.15	59.40	56.32	55.15	276.20	136.16	56.47	58.08
58.96	166.48	56.32	60.57	249.54	187.28	197.53	60.13	153.88	57.06	56.18	61.30
196.66	136.30	58.37	232.69	53.98	120.19	58.67	59.69	188.16	56.18	56.62	200.46
123.71	56.62	58.08	56.91	58.52	55.74	110.38	95.44	60.57	58.96	63.50	55.15
59.25	96.75	56.18	54.71	179.08	55.88	57.06	113.75	56.32	77.71	243.09	55.01
57.79	81.08	168.24	59.25	58.96	55.88	57.20	119.46	57.94	165.45	58.37	55.74
60.28	142.02	56.62	54.27	58.96	58.81	56.91	57.64	151.98	53.69	55.74	173.95
59.55	58.67	56.32	59.25	57.06	55.30	122.68	165.60	59.11	57.94	58.81	60.28
137.18	57.35	63.21	59.84	54.57	57.06	55.15	57.35	75.22	57.20	170.44	59.55
60.57	59.11	57.35	181.27	59.55	173.51	57.06	118.14	57.94	58.37	55.59	162.96
57.79	57.20	58.23	55.74	57.20	173.07	58.08	148.90	69.21	161.35	56.18	58.23
153.59	57.79	114.04	56.47	58.67	158.72	56.32	58.52	235.47	57.50	56.32	57.50
58.23	148.76	57.94	56.32	57.79	488.31	61.30	59.55	121.80	249.39	91.19	59.40
60.43	57.64	57.06	288.50	56.76	58.08	53.98	58.23	57.35	56.32	55.74	56.91
58.81	177.91	58.23	58.08	143.92	55.15	57.06	126.34	55.01	59.55	56.62	58.52
109.20	56.91	216.43	59.99	134.25	56.62	56.47	57.35	59.84	57.50	56.47	55.88
57.64	59.40	180.25	57.35	59.84	216.14	57.94	59.11	139.97	57.35	57.20	58.08
57.35	128.25	92.36	144.36	58.52	58.52	57.50	58.81	56.03	159.60	141.14	57.64
62.04	182.59	280.88	62.48	55.88	59.40	57.35	58.96	150.37	57.35	55.15	57.64
61.89	63.35	59.11	58.81	56.32	58.67	56.47	57.20	127.66	57.64	107.15	

Table A.3: Production Data Collected used for Analysis

Shift No.	Mill #	Horse power (hp)	Species*	Density (lb/ft3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Run Time (Mins)	Temp (^oF)	Resaw	Debarker	Double Line	Maint. Level	Total Board Feet	Total kWh	SEC
1	1	968	SM	35	29,726	2,648	555	50	1	0	0	4	32,374	2,267.90	70.05
2	1	968	RO	44	5,656	0	75	54	1	0	0	4	5,656	325.19	57.49
3	1	968	RO	44	33,160	984	630	48	1	0	0	4	34,144	2,713.87	79.48
4	1	968	RO	44	32,004	1,416	630	48	1	0	0	4	33,420	2,886.32	86.37
5	1	968	RO	44	12,188	1,187	235	50	1	0	0	4	13,375	1,060.73	79.31
6	1	968	WO	47	19,329	1,294	395	62	1	0	0	4	20,623	1,600.11	77.59
7	1	968	AS	40	12,954	832	240	42	1	0	0	4	13,786	1,097.69	79.62
8	1	968	RO	44	17,708	816	390	48	1	0	0	4	18,524	1,586.78	85.66
9	1	968	WO	47	6,765	0	120	36	1	0	0	4	6,765	611.69	90.42
10	1	968	WO	47	22,100	240	510	46	1	0	0	4	22,340	2,143.47	95.95
11	1	968	WO	47	24,663	312	570	55	1	0	0	4	24,975	2,366.43	94.75
12	1	968	HM	47	29,521	1,320	630	66	1	0	0	4	30,841	2,585.31	83.83
13	1	968	HM	47	28,348	1,640	630	66	1	0	0	4	29,988	2,664.01	88.84
14	1	968	SM	35	31,129	1,056	630	60	1	0	0	4	32,185	2,623.49	81.51
15	1	968	HK	64	8,489	192	240	58	1	0	0	4	8,681	1,010.33	116.38
16	1	968	WO	47	12,093	2,613	285	64	1	0	0	4	14,706	1,138.54	77.42
17	1	968	CH	56	3,337	435	105	66	1	0	0	4	3,772	449.74	119.23
18	1	968	CH	56	19,746	7,241	630	60	1	0	0	4	26,987	2,662.48	98.66
19	1	968	CH	56	8,815	676	195	48	1	0	0	4	9,491	906.37	95.50
20	1	968	RO	44	17,670	552	435	56	1	0	0	4	18,222	1,726.44	94.74
21	1	968	RO	44	28,526	744	630	61	1	0	0	4	29,270	2,656.64	90.76
22	1	968	RO	44	29,629	1,240	630	66	1	0	0	4	30,869	2,683.63	86.94
23	2	817	HK	64	4,904	5,237	270	43	0	0	0	3	10,141	903.83	89.13
24	2	817	WO	47	5,863	3,925	240	47	0	0	0	3	9,788	724.24	73.99
25	2	817	WO	47	10,301	6,540	510	58	0	0	0	3	16,841	1,535.14	91.16
26	2	817	WO	47	11,034	8,891	510	44	0	0	0	3	19,925	1,583.44	79.47
27	2	817	WO	47	3,975	3,867	180	34	0	0	0	3	7,842	596.00	76.00
28	2	817	YP	24	5,858	7,166	270	38	0	0	0	3	13,024	749.42	57.54
29	2	817	YP	24	2,598	4,194	120	24	0	0	0	3	6,792	415.98	61.25
30	2	817	YP	24	7,967	10,652	390	28	0	0	0	3	18,619	1,131.87	60.79
31	2	817	RO	44	13,481	8,950	510	28	0	0	0	3	22,431	1,571.08	70.04

Shift No.	Mill #	Horse power (hp)	Species*	Density (lb/ft3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Run Time (Mins)	Temp (°F)	Resaw	Debarker	Double Line	Maint. Level	Total Board Feet	Total kWh	SEC
32	2	817	RO	44	8,162	7,840	510	43	0	0	0	3	16,002	1,504.34	94.01
33	2	817	RO	44	10,465	7,593	510	31	0	0	0	3	18,058	1,537.66	85.15
34	2	817	RO	44	7,211	4,914	300	21	0	0	0	3	12,125	979.90	80.82
35	2	817	HK	64	1,852	2,775	150	24	0	0	0	3	4,627	435.17	94.05
36	2	817	HK	64	5,706	7,104	330	21	0	0	0	3	12,810	1,115.42	87.07
37	2	817	RO	44	3,231	3,307	150	24	0	0	0	3	6,538	501.04	76.63
38	2	817	RO	44	9,196	8,931	510	20	0	0	0	3	18,127	1,604.75	88.53
39	2	817	RO	44	9,802	8,309	510	36	0	0	0	3	18,111	1,531.05	84.54
40	2	817	RO	44	9,765	6,199	480	50	0	0	0	3	15,964	1,458.31	91.35
41	2	817	WO	47	613	862	30	50	0	0	0	3	1,475	101.60	68.88
42	2	817	WO	47	8,613	11,556	450	49	0	0	0	3	20,169	1,396.76	69.25
43	2	817	WO	47	1,682	1,600	105	14	0	0	0	3	3,282	353.10	107.59
44	2	817	WO	47	6,595	7,461	405	18	0	0	0	3	14,056	1,208.05	85.95
45	2	817	WO	47	6,872	7,177	450	18	0	0	0	3	14,049	1,422.61	101.26
46	2	817	SM	35	1,236	891	60	18	0	0	0	3	2,127	174.33	81.96
47	2	817	SM	35	10,589	6,930	510	25	0	0	0	3	17,519	1,529.56	87.31
48	2	817	SM	35	6,155	3,888	255	38	0	0	0	3	10,043	808.40	80.49
49	2	817	RO	44	5,320	2,990	255	42	0	0	0	3	8,310	720.68	86.72
50	2	817	RO	44	9,135	6,592	450	61	0	0	0	3	15,727	1,285.07	81.71
51	2	817	RO	44	6,847	5,067	330	53	0	0	0	3	11,914	1,049.50	88.09
52	2	817	HM	47	4,361	1,520	180	57	0	0	0	3	5,881	518.39	88.15
53	2	817	HM	47	10,900	4,348	510	56	0	0	0	3	15,248	1,526.90	100.14
54	2	817	HM	47	735	1,430	45	45	0	0	0	3	2,165	172.41	79.64
55	2	817	RO	44	2,584	8,378	465	52	0	0	0	3	10,962	1,371.06	125.07
56	2	817	RO	44	1,451	1,459	60	28	0	0	0	3	2,910	261.08	89.72
57	2	817	RO	44	10,119	6,966	450	34	0	0	0	3	17,085	1,375.53	80.51
58	3	2,630.5	RO	44	70,762	9,645	480	52	1	1	1	2	80,407	8,464.90	105.28
59	3	2,630.5	RO	44	15,476	2,717	120	32	1	1	1	2	18,193	2,264.58	124.48
60	3	2,630.5	WO	47	52,297	10,694	360	39	1	1	1	2	62,991	6,551.06	104.00
61	3	2,630.5	WO	47	53,822	8,726	390	42	1	1	1	2	62,548	6,981.93	111.63
62	3	2,630.5	HM	47	14,251	-	90	44	1	1	1	2	14,251	1,591.53	111.68
63	3	2,630.5	HM	47	25,722	1,272	120	34	1	1	1	2	26,994	2,315.49	85.78
64	3	2,630.5	SM	35	54,330	7,372	360	39	1	1	1	2	61,702	6,430.15	104.21

Shift No.	Mill #	Horse power (hp)	Species*	Density (lb/ft3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Run Time (Mins)	Temp (°F)	Resaw	Debarker	Double Line	Maint. Level	Total Board Feet	Total kWh	SEC
65	3	2,630.5	SM	35	36,481	4,917	240	45	1	1	1	2	41,398	4,299.55	103.86
66	3	2,630.5	HK	64	24,743	15,166	210	47	1	1	1	2	39,909	4,455.75	111.65
67	3	2,630.5	CH	56	82,405	-	480	62	1	1	1	2	82,405	8,657.71	105.06
68	3	2,630.5	RO	44	77,793	3,172	480	70	1	1	1	2	80,965	8,767.84	108.29
69	3	2,630.5	YP	24	84,341	-	480	61	1	1	1	2	84,341	7,281.16	86.33
70	3	2,630.5	YP	24	80,230	-	480	66	1	1	1	2	80,230	7,195.51	89.69
71	3	2,630.5	YP	24	82,402	-	480	71	1	1	1	2	82,402	6,701.76	81.33
72	3	2,630.5	YP	24	83,415	-	480	61	1	1	1	2	83,415	7,075.26	84.82
73	3	2,630.5	RO	44	76,564	3,388	480	34	1	1	1	2	79,952	8,664.44	108.37
74	3	2,630.5	BR	44	28,493	15,223	315	49	1	1	1	2	43,716	5,428.20	124.17
75	3	2,630.5	YP	24	34,619	-	165	53	1	1	1	2	34,619	2,854.32	82.45
76	3	2,630.5	HM	47	38,783	-	300	42	1	1	1	2	38,783	5,457.95	140.73
77	3	2,630.5	SM	35	25,114	4,076	180	44	1	1	1	2	29,190	3,074.22	105.32
78	3	2,630.5	SM	35	63,695	11,321	480	48	1	1	1	2	75,016	8,304.22	110.70
79	3	2,630.5	SM	35	65,815	12,566	480	50	1	1	1	2	78,381	8,508.43	108.55
80	3	2,630.5	SM	35	12,258	3,681	90	48	1	1	1	2	15,939	1,653.18	103.72
81	3	2,630.5	RO	44	49,854	2,217	390	54	1	1	1	2	52,071	6,810.27	130.79
82	3	2,630.5	RO	44	75,778	5,791	480	51	1	1	1	2	81,569	8,764.15	107.44
83	4	1,534	RO	44	8,791	4,264	195	52	0	0	1	2	13,055	1,504.23	115.22
84	4	1,534	YP	24	25,259	4,138	405	58	0	0	1	2	29,397	3,181.70	108.23
85	4	1,534	YP	24	43,156	6,370	600	52	0	0	1	2	49,526	4,935.25	99.65
86	4	1,534	YP	24	38,884	7,182	600	52	0	0	1	2	46,066	4,747.09	103.05
87	4	1,534	YP	24	34,213	5,548	555	55	0	0	1	2	39,761	4,361.89	109.70
88	4	1,534	SY	26	1,678	1,744	45	56	0	0	1	2	3,422	345.41	100.94
89	4	1,534	SY	26	6,296	13,659	300	65	0	0	1	2	19,955	2,334.09	116.97
90	4	1,534	HM	47	19,689	5,040	300	70	0	0	1	2	24,729	2,434.23	98.44
91	4	1,534	HM	47	27,905	6,674	600	68	0	0	1	2	34,579	4,769.64	137.93
92	4	1,534	HM	47	7,188	1,852	180	67	0	0	1	2	9,040	1,332.59	147.41
93	4	1,534	HK	64	15,478	3,748	420	72	0	0	1	2	19,226	3,255.79	169.34
94	4	1,534	HK	64	15,437	4,070	330	66	0	0	1	2	19,507	3,022.05	154.92
95	4	1,534	SY	26	4,915	5,948	120	74	0	0	1	2	10,863	853.89	78.61
96	4	1,534	SM	35	23,908	11,956	465	77	0	0	1	2	35,864	3,768.55	105.08
97	4	1,534	SM	35	15,917	12,216	330	72	0	0	1	2	28,133	2,540.12	90.29

Shift No.	Mill #	Horse power (hp)	Species*	Density (lb/ft3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Run Time (Mins)	Temp (^{o}F)	Resaw	Debarker	Double Line	Maint. Level	Total Board Feet	Total kWh	SEC
98	4	1,534	RO	44	12,724	3,244	270	76	0	0	1	2	15,968	2,244.00	140.53
99	4	1,534	RO	44	27,184	6,783	600	66	0	0	1	2	33,967	4,909.50	144.54
100	4	1,534	RO	44	21,340	5,565	525	60	0	0	1	2	26,905	4,217.76	156.76
101	4	1,534	YP	24	21,700	3,052	355	73	0	0	1	2	24,752	2,766.36	111.76
102	4	1,534	YP	24	33,112	5,922	600	64	0	0	1	2	39,034	4,702.11	120.46
103	4	1,534	YP	24	10,144	2,149	195	78	0	0	1	2	12,293	1,478.34	120.26
104	4	1,534	AS	40	21,944	4,512	395	82	0	0	1	2	26,456	3,109.02	117.52
105	4	1,534	AS	40	23,151	4,739	600	78	0	0	1	2	27,890	4,458.74	159.87
106	4	1,534	AS	40	16,449	3,752	330	59	0	0	1	2	20,201	2,612.90	129.35
107	4	1,534	HM	47	12,199	2,902	270	62	0	0	1	2	15,101	2,218.52	146.91
108	4	1,534	HM	47	28,046	6,643	600	60	0	0	1	2	34,689	4,800.24	138.38
109	5,1#	1,686	RO	44	21,909	-	266	58	1	1	0	2	21,909	2,325.14	106.13
110	5,1	1,686	HM	47	26,052	-	342	62	1	1	0	2	26,052	2,963.61	113.76
111	5,2	1,686	HM	47	32,150	-	582	57	1	1	0	2	32,150	4,946.48	153.86
112	5,1	1,686	HM	47	8,160	-	130	52	1	1	0	2	8,160	1,122.39	137.55
113	5,1	1,686	YP	24	50,813	9,975	482	56	1	1	0	2	60,788	4,115.69	67.71
114	5,2	1,686	YP	24	50,448	10,698	598	50	1	1	0	2	61,146	5,189.42	84.87
115	5,1	1,686	YP	24	63,128	11,645	584	65	1	1	0	2	74,773	5,064.19	67.73
116	5,2	1,686	RO	44	43,450	-	647	60	1	1	0	2	43,450	5,632.85	129.64
117	5,1	1,686	RO	44	55,938	-	627	56	1	1	0	2	55,938	5,495.17	98.24
118	5,2	1,686	RO	44	37,107	-	604	51	1	1	0	2	37,107	5,192.91	139.94
119	5,1	1,686	RO	44	46,659	-	608	51	1	1	0	2	46,659	5,310.84	113.82
120	5,2	1,686	RO	44	36,535	-	592	48	1	1	0	2	36,535	5,041.39	137.99
121	5,1	1,686	RO	44	8,813	-	117	61	1	1	0	2	8,813	1,003.77	113.90
122	5,1	1,686	AS	40	36,489	-	427	63	1	1	0	2	36,489	3,722.08	102.01
123	5,2	1,686	SM	35	33,653	10,096	601	56	1	1	0	2	43,749	5,162.08	117.99
124	5,1	1,686	SM	35	43,846	11,156	611	67	1	1	0	2	55,002	5,296.20	96.29
125	5,2	1,686	SM	35	24,196	7,068	410	63	1	1	0	2	31,264	3,517.04	112.49
126	5,1	1,686	WO	47	39,585	6,796	625	72	1	1	0	2	46,381	5,371.99	115.82
127	5,2	1,686	WO	47	32,131	4,912	596	67	1	1	0	2	37,043	5,127.90	138.43
128	5,1	1,686	WO	47	40,343	4,147	614	69	1	1	0	2	44,490	5,311.83	119.39
129	5,2	1,686	WO	47	23,758	7,228	562	64	1	1	0	2	30,986	4,690.13	151.36
130	5,1	1,686	RO	44	38,448	1,834	523	60	1	1	0	2	40,282	4,642.43	115.25

Shift No.	Mill #	Horse power (hp)	Species*	Density (lb/ft3)	4/4 to 8/4 + Pallet (Board ft.)	Cant + Tim (Board ft.)	Run Time (Mins)	Temp (^oF)	Resaw	Debarker	Double Line	Maint. Level	Total Board Feet	Total kWh	SEC
131	5,1	1,686	RO	44	6,000	-	90	67	1	1	0	2	6,000	761.18	126.86
132	5,1	1,686	HM	47	36,454	-	534	72	1	1	0	2	36,454	4,700.60	128.95
133	5,2	1,686	HM	47	23,203	4,326	565	67	1	1	0	2	27,529	4,710.43	171.11

* SM – Soft Maple, RO – Red Oak, WO – White Oak, AS – Ash, HM – Hard Maple, HK – Hickory, CH – Cherry, YP – Yellow Poplar, BR – Birch, SY – Sycamore

Table A.4: Lumber Production Data Collected in Board Feet used for Analysis

Shift No.	Mill #	Date	Start time	End time	4/4	5/4	6/4	8/4	Pallet	Cants 3"x8"x12'	Cants 5"x6"x12'	Cants 3"x4"x12'	Cants 3.5"x6"x12'	Cants 14"x4"x12'	Timber 7"x9"x12'
1	1	4/14/09	5:30 AM	2:45 PM	29,726	0	0	0	0	1,728	0	0	0	0	920
2	1	4/14/09	2:45 PM	4:00 PM	2,939	0	0	1,932	785	0	0	0	0	0	0
3	1	4/15/09	5:30 AM	4:00 PM	18,428	2,897	0	7,888	3,947	984	0	0	0	0	0
4	1	4/16/09	5:30 AM	4:00 PM	19,922	5,782	0	0	6,300	1,416	0	0	0	0	0
5	1	4/20/09	5:30 AM	9:25 AM	8,557	1,210	0	0	2,421	312	0	0	0	0	875
6	1	4/20/09	9:25 AM	4:00 PM	13,670	0	0	0	5,659	699	0	0	0	0	595
7	1	4/21/09	5:30 AM	9:30 AM	12,053	0	0	0	901	792	0	0	0	0	40
8	1	4/21/09	9:30 AM	4:00 PM	12,708	2,424	0	0	2,576	816	0	0	0	0	0
9	1	4/22/09	5:30 AM	7:30 AM	4,925	827	0	0	1,013	0	0	0	0	0	0
10	1	4/22/09	7:30 AM	4:00 PM	14,722	0	3,284	0	4,094	240	0	0	0	0	0
11	1	4/23/09	5:30 AM	3:00 PM	16,521	0	4,334	0	3,808	312	0	0	0	0	0
12	1	4/27/09	5:30 AM	4:00 PM	22,509	3,890	0	0	3,122	1,320	0	0	0	0	0
13	1	4/28/09	5:30 AM	4:00 PM	21,655	3,418	0	0	3,275	720	0	0	0	0	920
14	1	4/29/09	5:30 AM	4:00 PM	27,033	0	0	0	4,096	1,056	0	0	0	0	0
15	1	4/30/09	5:30 AM	9:30 AM	7,468	0	0	0	1,021	192	0	0	0	0	0
16	1	4/30/09	9:30 AM	2:15 PM	9,604	0	0	0	2,489	408	0	0	0	0	2,205
17	1	4/30/09	2:15 PM	4:00 PM	2,373	0	0	0	964	120	0	0	0	0	315
18	1	5/4/09	5:30 AM	4:00 PM	14,815	0	0	0	4,931	3,312	0	0	0	0	3,929
19	1	5/5/09	5:30 AM	8:45 AM	6,238	0	0	0	2,577	480	0	0	0	0	196
20	1	5/5/09	8:45 AM	4:00 PM	12,204	2,831	0	0	2,635	552	0	0	0	0	0
21	1	5/6/09	5:30 AM	4:00 PM	23,998	301	0	0	4,227	744	0	0	0	0	0
22	1	5/7/09	5:30 AM	4:00 PM	25,295	325	0	0	4,009	1,200	0	0	0	0	40
23	2	2/10/2009	6:00 AM	10:30 AM	4,652	0	0	0	252	0	2,470	0	0	0	2,767
24	2	2/10/2009	10:30 AM	2:30 PM	3,783	0	1,792	0	288	0	2,155	0	0	0	1,770
25	2	2/11/2009	6:00 AM	2:30 PM	7,819	0	1,748	0	734	0	4,070	0	0	0	2,470
26	2	2/12/2009	6:00 AM	2:30 PM	10,190	0	288	0	556	0	5,080	0	0	0	3,811
27	2	2/13/2009	6:00 AM	9:00 AM	3,479	0	0	0	496	0	1,885	0	0	0	1,982
28	2	2/13/2009	9:00 AM	1:30 PM	0	0	5,858	0	0	0	1,520	5,332	0	0	314
29	2	2/16/2009	6:00 AM	8:00 AM	0	0	2,598	0	0	0	0	3,994	0	0	200
30	2	2/16/2009	8:00 AM	2:30 PM	6,689	0	0	1,074	204	0	6,660	0	0	0	3,992
31	2	2/17/2009	6:00 AM	2:30 PM	8,761	0	0	760	3,960	0	5,210	0	0	0	3,740
32	2	2/18/2009	6:00 AM	2:30 PM	7,044	0	0	786	332	0	2,390	0	0	0	5,450

Shift No.	Mill #	Date	Start time	End time	4/4	5/4	6/4	8/4	Pallet	Cants 3"x8"x12'	Cants 5"x6"x12'	Cants 3"x4"x12'	Cants 3.5"x6"x12’	Cants 14”x4”x12’	Timber 7”x9”x12’
33	2	2/19/2009	6:00 AM	2:30 PM	8,979	0	0	1,138	348	0	2,600	0	0	0	4,993
34	2	2/20/2009	6:00 AM	11:00 AM	5,783	0	0	1,144	284	0	1,840	0	0	0	3,074
35	2	2/20/2009	11:00 AM	1:30 PM	1,808	0	0	0	44	0	675	0	0	0	2,100
36	2	2/23/2009	6:00 AM	11:30 AM	5,448	0	0	0	258	0	1,580	0	0	0	5,524
37	2	2/23/2009	12:00 PM	2:30 PM	2,731	0	0	392	108	0	825	0	0	0	2,482
38	2	2/24/2009	6:00 AM	2:30 PM	8,068	0	0	610	518	0	2,515	0	0	0	6,416
39	2	2/25/2009	6:00 AM	2:30 PM	7,882	0	0	1,506	414	0	3,945	0	0	0	4,364
40	2	2/26/2009	6:00 AM	2:00 PM	8,821	0	0	380	564	0	2,945	0	0	0	3,254
41	2	2/26/2009	2:00 PM	2:30 PM	534	69	0	0	10	0	0	0	0	0	862
42	2	2/27/2009	6:00 AM	1:30 PM	6,795	1,488	0	0	330	0	1,140	0	0	0	10,416
43	2	3/2/2009	6:00 AM	7:45 AM	466	1,188	0	0	28	0	185	0	0	0	1,415
44	2	3/2/2009	7:45 AM	2:30 PM	0	6,251	0	0	344	0	2,510	0	0	0	4,951
45	2	3/3/2009	6:00 AM	1:30 PM	0	6,310	0	0	562	0	3,650	0	0	0	3,527
46	2	3/3/2009	1:30 PM	2:30 PM	0	692	0	540	4	0	240	0	0	0	651
47	2	3/4/2009	6:00 AM	2:30 AM	0	6,183	0	3,918	488	0	3,235	0	0	0	3,695
48	2	3/5/2009	6:00 AM	10:15 AM	0	3,685	0	2,014	456	0	3,235	0	0	0	653
49	2	3/5/2009	10:15 AM	2:30 PM	5,142	0	0	0	178	0	1,515	0	0	0	1,475
50	2	3/6/2009	6:00 AM	1:30 PM	8,507	0	0	0	628	0	1,630	0	361	0	4,601
51	2	3/9/2009	6:00 AM	11:30 AM	6,395	0	0	0	452	0	0	0	764	0	4,303
52	2	3/9/2009	11:30 AM	2:30 PM	4,261	0	0	0	100	0	0	0	322	0	1,198
53	2	3/10/2009	6:00 AM	2:30 PM	10,666	0	0	0	234	0	0	0	854	0	3,494
54	2	3/11/2009	6:00 AM	6:45 AM	729	0	0	0	6	0	0	0	39	0	1,391
55	2	3/11/2009	6:45 AM	2:30 PM	1,786	0	0	0	798	0	0	0	1,100	0	7,278
56	2	3/12/2009	6:00 AM	7:00 AM	1,369	0	0	0	82	0	0	0	14	0	1,445
57	2	3/12/2009	7:00 AM	2:30 PM	9,513	0	0	0	606	0	0	0	1,327	0	5,639
58	3	3/25/2010	7:00 AM	3:30 PM	55,362	0	0	0	15,400	0	0	0	0	0	9,645
59	3	3/26/2010	7:00 AM	9:00 AM	12,559	0	0	0	2,917	0	0	0	0	0	2,717
60	3	3/26/2010	9:00 AM	3:30 PM	42,275	0	0	0	10,022	0	0	0	0	0	10,694
61	3	3/29/2010	7:00 AM	2:00 PM	43,531	0	0	0	10,291	0	0	0	0	0	8,726
62	3	3/29/2010	2:00 PM	3:30 PM	11,066	0	0	0	3,185	0	0	0	0	0	0
63	3	3/30/2010	7:00 AM	9:00 AM	20,559	0	0	0	5,163	0	0	0	0	0	1,272
64	3	3/30/2010	9:00 AM	3:30 PM	44,863	0	0	0	9,467	0	0	0	0	0	7,372
65	3	3/31/2010	7:00 AM	11:00 AM	29,375	0	0	0	7,106	0	0	0	0	0	4,917
66	3	3/31/2010	11:30 AM	3:00 PM	14,729	0	0	0	10,014	0	0	0	0	0	15,166

Shift No.	Mill #	Date	Start time	End time	4/4	5/4	6/4	8/4	Pallet	Cants 3"x8"x12'	Cants 5"x6"x12'	Cants 3"x4"x12'	Cants 3.5"x6"x12’	Cants 14”x4”x12’	Timber 7”x9”x12’
67	3	4/1/2010	7:00 AM	3:30 PM	69,023	0	0	0	13,382	0	0	0	0	0	0
68	3	4/2/2010	7:00 AM	3:30 PM	62,390	0	0	0	15,403	0	0	0	0	0	3,172
69	3	4/5/2010	7:00 AM	3:30 PM	67,686	0	0	0	16,655	0	0	0	0	0	0
70	3	4/6/2010	7:00 AM	3:30 PM	63,511	0	0	0	16,719	0	0	0	0	0	0
71	3	4/7/2010	7:00 AM	3:30 PM	62,532	0	0	0	19,870	0	0	0	0	0	0
72	3	4/8/2010	7:00 AM	3:30 PM	63,574	0	19,841	0	0	0	0	0	0	0	0
73	3	4/9/2010	7:00 AM	3:30 PM	62,101	0	0	0	14,463	0	0	0	0	0	3,388
74	3	4/12/2010	7:00 AM	12:45 PM	22,325	0	0	0	6,168	0	0	0	0	0	15,223
75	3	4/12/2010	12:45 PM	3:30 PM	18,201	0	11,179	382	4,857	0	0	0	0	0	0
76	3	4/19/2010	7:00 AM	12:30 PM	32,383	0	0	0	6,400	0	0	0	0	0	0
77	3	4/19/2010	12:30 PM	3:30 PM	19,909	0	0	0	5,205	0	0	0	0	0	4,076
78	3	4/20/2010	7:00 AM	3:30 PM	50,814	0	0	0	12,881	0	0	0	0	0	11,321
79	3	4/21/2010	7:00 AM	3:30 PM	52,128	0	0	0	13,687	0	0	0	0	0	12,566
80	3	4/22/2010	7:00 AM	8:30 AM	9,583	0	0	0	2,675	0	0	0	0	0	3,681
81	3	4/22/2010	8:30 AM	3:30 PM	39,561	0	0	0	10,293	0	0	0	0	0	2,217
82	3	4/23/2010	7:00 AM	3:30 PM	61,593	0	0	0	14,185	0	0	0	0	0	5,791
83	4	5/16/2011	6:00 AM	9:15 AM	8,449	0	0	0	342	0	0	0	0	2,264	2,000
84	4	5/16/2011	9:15 AM	4:30 PM	13,125	0	0	11,938	196	0	0	0	0	4,138	0
85	4	5/17/2011	6:00 AM	4:30 PM	24,247	0	0	18,708	201	0	0	0	0	6,370	0
86	4	5/18/2011	6:00 AM	4:30 PM	20,503	0	0	18,150	231	0	0	0	0	7,182	0
87	4	5/19/2011	6:00 AM	3:45 PM	19,177	0	0	14,962	74	0	0	0	0	5,548	0
88	4	5/19/2011	3:45 PM	4:30 PM	0	0	0	1,678	0	0	0	0	0	970	774
89	4	5/23/2011	6:00 AM	11:00 AM	0	0	0	6,216	80	0	0	0	0	546	13,113
90	4	5/23/2011	11:00 AM	4:30 PM	13,719	0	0	5,688	282	0	0	0	0	5,040	0
91	4	5/24/2011	6:00 AM	4:30 PM	20,158	0	0	7,430	317	0	0	0	0	6,674	0
92	4	5/25/2011	6:00 AM	9:00 AM	5,384	0	0	1,732	72	0	0	0	0	1,852	0
93	4	5/25/2011	9:00 AM	4:30 PM	14,911	0	0	0	567	0	0	0	0	3,748	0
94	4	5/27/2011	6:00 AM	12:00 PM	14,799	0	0	0	638	0	0	0	0	4,070	0
95	4	5/31/2011	6:00 AM	8:00 AM	0	0	0	4,785	130	0	0	0	0	42	5,906
96	4	5/31/2011	8:15 AM	4:30 PM	0	0	0	23,880	28	0	0	0	0	5,159	6,797
97	4	6/1/2011	6:00 AM	11:30 AM	0	0	0	15,914	3	0	0	0	0	3,822	8,394
98	4	6/1/2011	11:30 AM	4:30 PM	12,338	0	0	0	386	0	0	0	0	3,244	0
99	4	6/2/2011	6:00 AM	4:30 PM	26,153	0	0	0	1,031	0	0	0	0	6,783	0
100	4	6/3/2011	6:00 AM	3:15 PM	20,888	0	0	0	452	0	0	0	0	5,565	0

Shift No.	Mill #	Date	Start time	End time	4/4	5/4	6/4	8/4	Pallet	Cants 3"x8"x12'	Cants 5"x6"x12'	Cants 3"x4"x12'	Cants 3.5"x6"x12’	Cants 14”x4”x12’	Timber 7”x9”x12’
101	4	6/6/2011	10:05 AM	4:30 PM	11,378	0	10,258	2	62	0	0	0	0	3,052	0
102	4	6/7/2011	6:00 AM	4:30 PM	17,413	0	15,536	0	163	0	0	0	0	5,922	0
103	4	6/8/2011	6:00 AM	9:15 AM	5,197	0	4,878	0	69	0	0	0	0	2,149	0
104	4	6/8/2011	9:25 AM	4:30 PM	6,120	0	0	15,568	256	0	0	0	0	4,512	0
105	4	6/9/2011	6:00 AM	4:30 PM	8,698	0	398	13,582	473	0	0	0	0	4,739	0
106	4	6/13/2011	6:00 AM	11:30 AM	5,865	0	0	10,294	290	0	0	0	0	3,752	0
107	4	6/13/2011	12:00 PM	4:30 PM	8,718	0	0	3,330	151	0	0	0	0	2,902	0
108	4	6/14/2011	6:00 AM	4:30 PM	19,040	0	0	8,526	480	0	0	0	0	6,643	0
109	5,1#	4/28/2014	6:00 AM	10:00 AM	15,602	4,529	0	0	1,778	0	0	0	0	0	0
110	5,1	4/28/2014	10:00 AM	4:00 PM	23,999	0	0	0	2,053	0	0	0	0	0	0
111	5,2	4/28/2014	5:00 PM	2:30 AM	28,479	0	0	0	3,671	0	0	0	0	0	0
112	5,1	4/29/2014	6:00 AM	7:30 AM	7,017	0	0	0	1,143	0	0	0	0	0	0
113	5,1	4/29/2014	7:30 AM	4:00 PM	37,240	0	0	12,636	937	0	0	0	9,975	0	0
114	5,2	4/29/2014	5:00 PM	2:30 AM	42,719	0	0	5,782	1,947	0	0	0	10,698	0	0
115	5,1	4/30/2014	6:00 AM	3:30 PM	50,940	0	0	11,125	1,063	0	0	0	11,645	0	0
116	5,2	4/30/2014	3:30 PM	2:30 AM	36,660	2,807	0	0	3,983	0	0	0	0	0	0
117	5,1	5/1/2014	6:00 AM	4:00 PM	36,390	12,699	0	0	6,849	0	0	0	0	0	0
118	5,2	5/1/2014	5:00 PM	2:30 AM	27,376	5,048	0	0	4,683	0	0	0	0	0	0
119	5,1	5/2/2014	6:00 AM	4:00 PM	34,148	6,919	0	0	5,592	0	0	0	0	0	0
120	5,2	5/2/2014	5:00 PM	2:30 AM	30,093	2,398	0	0	4,044	0	0	0	0	0	0
121	5,1	5/5/2014	6:00 AM	7:15 AM	6,594	1,471	0	0	748	0	0	0	0	0	0
122	5,1	5/5/2014	7:15 AM	2:45 PM	29,710	0	0	4,486	2,293	0	0	0	0	0	0
123	5,2	5/5/2014	5:00 PM	2:30 AM	31,084	0	0	0	2,569	0	0	0	10,096	0	0
124	5,1	5/6/2014	6:00 AM	4:00 PM	42,391	0	0	0	1,455	0	0	0	11,156	0	0
125	5,2	5/6/2014	4:30 PM	12:00 PM	21,243	0	0	0	2,953	0	0	0	7,068	0	0
126	5,1	5/7/2014	6:00 AM	4:00 PM	0	39,281	0	0	304	0	0	0	0	0	6,796
127	5,2	5/7/2014	5:00 PM	2:30 AM	0	32,087	0	0	44	0	0	0	2,860	0	2,052
128	5,1	5/8/2014	6:00 AM	4:00 PM	0	40,325	0	0	18	0	0	0	0	0	4,147
129	5,2	5/8/2014	5:00 PM	2:30 AM	0	23,751	0	0	7	0	0	0	48	0	7,180
130	5,1	5/10/2014	6:00 AM	2:30 PM	33,057	1,516	0	0	3,875	0	0	0	0	0	1,834
131	5,1	5/12/2014	6:00 AM	6:45 AM	5,014	506	0	0	480	0	0	0	0	0	0
132	5,1	5/12/2014	6:45 AM	4:00 PM	33,810	0	0	0	2,644	0	0	0	0	0	0
133	5,2	5/12/2014	5:00 PM	2:30 AM	21,115	0	0	0	2,088	0	0	0	4,326	0	0

Table A.5: Machines Run Time Data Collected in Minutes used for Correlation Analysis

Shift No.	Mill #	Head Saw Run Time	Resaw Run Time	Edger Run Time	Trimmer Run Time	Chipper Run Time	Debarker Run Time	Compressor Run Time	% 4 to 8 Qtr	% Pallet	% Cant + Tim	Total kWh	SEC
1	1	488.0	487.0	491.0	505.0	556.0	217.0	555.5	0.9182	0.0000	0.0818	2,267.90	70.05
2	1	62.0	75.0	75.0	76.0	82.0	22.0	75.0	0.8612	0.1388	0.0000	325.19	57.50
3	1	556.0	565.0	604.0	580.0	704.0	217.0	665.0	0.8556	0.1156	0.0288	2,713.87	79.48
4	1	567.0	553.0	593.0	580.0	708.0	648.0	667.5	0.7691	0.1885	0.0424	2,886.32	86.37
5	1	223.0	222.0	228.0	226.0	298.0	76.0	265.5	0.7302	0.1810	0.0887	1,060.73	79.31
6	1	347.0	351.0	360.0	356.0	423.0	142.0	370.0	0.6629	0.2744	0.0627	1,600.11	77.59
7	1	225.0	224.0	235.0	228.0	299.0	77.0	273.5	0.8743	0.0654	0.0604	1,097.69	79.62
8	1	338.0	342.0	359.0	349.0	394.0	124.0	390.0	0.8169	0.1391	0.0441	1,586.78	85.66
9	1	119.0	118.0	142.0	123.0	184.0	37.0	154.0	0.8503	0.1497	0.0000	611.69	90.42
10	1	435.0	411.0	462.0	464.0	569.0	167.0	506.5	0.8060	0.1833	0.0107	2,143.47	95.95
11	1	501.0	442.0	514.0	512.0	643.0	166.0	549.0	0.8350	0.1525	0.0125	2,366.43	94.75
12	1	575.0	568.0	605.0	579.0	708.0	220.0	584.0	0.8560	0.1012	0.0428	2,585.31	83.83
13	1	540.0	558.0	579.0	571.0	730.0	231.0	659.0	0.8361	0.1092	0.0547	2,664.01	88.84
14	1	538.0	537.0	562.0	572.0	712.0	233.0	663.5	0.8399	0.1273	0.0328	2,623.49	81.51
15	1	145.0	163.0	185.0	216.0	311.0	66.0	276.5	0.8603	0.1176	0.0221	1,010.33	116.39
16	1	240.0	239.0	254.0	242.0	285.0	109.0	285.0	0.6531	0.1693	0.1777	1,138.54	77.42
17	1	105.0	105.0	105.0	105.0	114.0	27.0	105.0	0.6291	0.2556	0.1153	449.74	119.23
18	1	576.0	554.0	599.0	578.0	716.0	183.0	662.5	0.5490	0.1827	0.2683	2,662.48	98.66
19	1	181.0	192.0	192.0	196.0	258.0	58.0	229.5	0.6573	0.2715	0.0712	906.37	95.50
20	1	362.0	374.0	394.0	380.0	444.0	117.0	435.0	0.8251	0.1446	0.0303	1,726.44	94.75
21	1	558.0	504.0	587.0	574.0	710.0	213.0	662.5	0.8302	0.1444	0.0254	2,656.64	90.76
22	1	554.0	555.0	582.0	571.0	718.0	218.0	666.0	0.8300	0.1299	0.0402	2,683.63	86.94
23	2	278.0	0.0	251.0	255.0	267.0	284.0	286.0	0.4587	0.0249	0.5164	903.83	89.13
24	2	204.0	0.0	199.0	210.0	241.0	219.0	236.0	0.5696	0.0294	0.4010	724.24	73.99
25	2	451.0	0.0	439.0	465.0	510.0	450.0	560.0	0.5681	0.0436	0.3883	1,535.14	91.16
26	2	486.0	0.0	447.0	465.0	498.0	487.0	554.0	0.5259	0.0279	0.4462	1,583.44	79.47
27	2	199.0	0.0	174.0	180.0	181.0	198.0	232.0	0.4436	0.0632	0.4931	596.00	76.00
28	2	228.0	0.0	211.0	225.0	271.0	209.0	274.0	0.4498	0.0000	0.5502	749.42	57.54
29	2	144.0	0.0	118.0	120.0	135.0	142.0	148.0	0.3825	0.0000	0.6175	415.98	61.25
30	2	346.0	0.0	327.0	345.0	393.0	353.0	388.0	0.4169	0.0110	0.5721	1,131.87	60.79

Shift No.	Mill #	Head Saw Run Time	Resaw Run Time	Edger Run Time	Trimmer Run Time	Chipper Run Time	Debarker Run Time	Compressor Run Time	% 4 to 8 Qtr	% Pallet	% Cant + Tim	Total kWh	SEC
31	2	487.0	0.0	446.0	465.0	509.0	510.0	560.0	0.4245	0.1765	0.3990	1,571.08	70.04
32	2	467.0	0.0	424.0	465.0	493.0	433.0	560.0	0.4893	0.0207	0.4899	1,504.34	94.01
33	2	481.0	0.0	445.0	465.0	512.0	493.0	567.0	0.5603	0.0193	0.4205	1,537.66	85.15
34	2	312.0	0.0	278.0	285.0	293.0	300.0	347.0	0.5713	0.0234	0.4053	979.90	80.82
35	2	105.0	0.0	102.0	120.0	157.0	153.0	158.0	0.3908	0.0095	0.5997	435.17	94.05
36	2	346.0	0.0	309.0	315.0	319.0	341.0	375.0	0.4253	0.0201	0.5546	1,115.42	87.07
37	2	143.0	0.0	141.0	150.0	174.0	147.0	189.0	0.4777	0.0165	0.5058	501.04	76.64
38	2	483.0	0.0	435.0	465.0	532.0	504.0	557.0	0.4787	0.0286	0.4927	1,604.75	88.53
39	2	483.0	0.0	446.0	465.0	508.0	434.0	559.0	0.5184	0.0229	0.4588	1,531.05	84.54
40	2	458.0	0.0	423.0	435.0	474.0	455.0	527.0	0.5764	0.0353	0.3883	1,458.31	91.35
41	2	27.0	0.0	26.0	30.0	37.0	30.0	36.0	0.4088	0.0068	0.5844	101.60	68.88
42	2	430.0	0.0	388.0	405.0	447.0	359.0	504.0	0.4107	0.0164	0.5730	1,396.76	69.25
43	2	125.0	0.0	100.0	105.0	98.0	117.0	152.0	0.5040	0.0085	0.4875	353.10	107.59
44	2	356.0	0.0	352.0	360.0	394.0	348.0	405.0	0.4447	0.0245	0.5308	1,208.05	85.95
45	2	421.0	0.0	391.0	405.0	460.0	435.0	476.0	0.4491	0.0400	0.5109	1,422.61	101.26
46	2	49.0	0.0	59.0	60.0	61.0	59.0	60.0	0.5792	0.0019	0.4189	174.33	81.96
47	2	451.0	0.0	436.0	465.0	528.0	450.0	566.0	0.5766	0.0279	0.3956	1,529.56	87.31
48	2	263.0	0.0	233.0	240.0	272.0	255.0	305.0	0.5675	0.0454	0.3871	808.40	80.49
49	2	219.0	0.0	216.0	225.0	255.0	224.0	246.0	0.6188	0.0214	0.3598	720.68	86.72
50	2	386.0	0.0	363.0	405.0	467.0	363.0	505.0	0.5409	0.0399	0.4192	1,285.07	81.71
51	2	343.0	0.0	308.0	315.0	341.0	302.0	379.0	0.5368	0.0379	0.4253	1,049.50	88.09
52	2	142.0	0.0	142.0	150.0	176.0	146.0	184.0	0.7245	0.0170	0.2585	518.39	88.15
53	2	454.0	0.0	455.0	465.0	528.0	472.0	571.0	0.6995	0.0153	0.2852	1,526.90	100.14
54	2	62.0	0.0	44.0	45.0	44.0	51.0	89.0	0.3367	0.0028	0.6605	172.41	79.64
55	2	420.0	0.0	409.0	420.0	469.0	409.0	467.0	0.1629	0.0728	0.7643	1,371.06	125.07
56	2	83.0	0.0	57.0	60.0	71.0	69.0	115.0	0.4705	0.0282	0.5014	261.08	89.72
57	2	401.0	0.0	405.0	405.0	435.0	435.0	456.0	0.5568	0.0355	0.4077	1,375.53	80.51
58	3	478.8	463.2	489.0	525.0	501.0	561.6	571.0	0.6885	0.1915	0.1200	8,464.90	105.28
59	3	115.5	115.2	129.0	151.8	157.8	226.8	120.0	0.6903	0.1603	0.1493	2,264.58	124.48
60	3	351.3	334.2	355.8	433.2	403.8	345.6	390.0	0.6711	0.1591	0.1698	6,551.06	104.00
61	3	396.6	246.0	406.8	430.8	447.0	394.8	420.6	0.6960	0.1645	0.1395	6,981.93	111.63
62	3	82.8	82.8	82.8	88.2	91.8	82.8	90.0	0.7765	0.2235	0.0000	1,591.53	111.68

Shift No.	Mill #	Head Saw Run Time	Resaw Run Time	Edger Run Time	Trimmer Run Time	Chipper Run Time	Debarker Run Time	Compressor Run Time	% 4 to 8 Qtr	% Pallet	% Cant + Tim	Total kWh	SEC
63	3	126.0	109.8	129.0	157.8	162.6	115.8	120.6	0.7616	0.1913	0.0471	2,315.49	85.78
64	3	353.7	343.8	351.6	394.8	384.6	348.0	390.0	0.7271	0.1534	0.1195	6,430.15	104.21
65	3	243.3	214.2	247.2	256.2	280.8	247.8	240.0	0.7096	0.1717	0.1188	4,299.55	103.86
66	3	213.3	192.0	214.8	211.8	240.0	210.6	210.0	0.3691	0.2509	0.3800	4,455.75	111.65
67	3	469.8	447.0	486.0	529.2	537.0	472.8	504.6	0.8376	0.1624	0.0000	8,657.71	105.06
68	3	475.2	457.2	505.2	535.8	561.6	465.6	511.2	0.7706	0.1902	0.0392	8,767.84	108.29
69	3	477.9	456.0	511.8	550.2	538.8	423.0	510.0	0.8025	0.1975	0.0000	7,281.16	86.33
70	3	466.8	469.8	502.8	522.0	535.8	276.0	510.0	0.7916	0.2084	0.0000	7,195.51	89.69
71	3	494.4	456.0	511.2	547.8	540.0	463.8	510.0	0.7589	0.2411	0.0000	6,701.76	81.33
72	3	493.2	439.2	505.2	523.8	484.8	498.6	510.0	1.0000	0.0000	0.0000	7,075.26	84.82
73	3	478.5	448.2	502.2	517.8	522.0	465.6	510.0	0.7767	0.1809	0.0424	8,664.44	108.37
74	3	262.5	255.0	328.2	363.0	387.0	304.8	345.0	0.5107	0.1411	0.3482	5,428.20	124.17
75	3	159.0	151.2	160.8	163.2	160.8	154.8	165.0	0.8597	0.1403	0.0000	2,854.32	82.45
76	3	305.1	265.8	318.0	355.8	346.8	301.2	330.0	0.8350	0.1650	0.0000	5,457.95	140.73
77	3	174.6	171.0	175.2	177.0	177.6	175.2	180.0	0.6821	0.1783	0.1396	3,074.22	105.32
78	3	442.5	399.0	487.8	522.0	537.6	442.2	510.0	0.6774	0.1717	0.1509	8,304.22	110.70
79	3	476.4	436.8	499.2	510.0	540.0	475.2	510.0	0.6651	0.1746	0.1603	8,508.43	108.55
80	3	96.9	70.2	100.2	107.4	133.8	67.2	90.0	0.6012	0.1678	0.2309	1,653.18	103.72
81	3	382.2	373.2	387.0	417.6	412.8	235.2	420.0	0.7598	0.1977	0.0426	6,810.27	130.79
82	3	477.6	454.8	523.8	522.6	552.6	472.8	510.0	0.7551	0.1739	0.0710	8,764.15	107.45
83	4	174.0	0.0	181.5	155.1	195.0	53.5	196.0	0.6524	0.0258	0.3218	1,504.23	113.53
84	4	369.5	0.0	371.0	328.7	411.0	112.5	476.0	0.8546	0.0066	0.1389	3,181.70	106.76
85	4	574.0	0.0	571.5	514.2	661.0	218.5	724.0	0.8689	0.0040	0.1271	4,935.25	98.46
86	4	562.5	0.0	582.0	490.5	646.0	143.0	674.0	0.8412	0.0050	0.1539	4,747.09	101.73
87	4	504.5	0.0	530.5	448.5	605.0	130.5	616.0	0.8606	0.0018	0.1376	4,361.89	108.19
88	4	42.5	0.0	44.0	35.3	51.0	10.5	53.0	0.4970	0.0000	0.5030	345.41	99.63
89	4	265.5	0.0	280.0	242.8	314.0	85.5	347.0	0.3217	0.0040	0.6744	2,334.09	115.24
90	4	276.0	0.0	287.5	254.8	337.0	71.0	420.0	0.7874	0.0113	0.2014	2,434.23	97.26
91	4	553.0	0.0	587.5	492.0	654.0	145.0	688.0	0.8013	0.0090	0.1897	4,769.64	135.58
92	4	146.0	0.0	149.5	133.9	192.0	46.0	201.0	0.7913	0.0078	0.2009	1,332.59	144.53
93	4	384.5	0.0	397.0	328.9	425.0	85.0	486.0	0.7804	0.0289	0.1908	3,255.79	165.72
94	4	365.0	0.0	381.5	315.2	421.0	65.0	554.0	0.7627	0.0322	0.2052	3,022.05	152.34

Shift No.	Mill #	Head Saw Run Time	Resaw Run Time	Edger Run Time	Trimmer Run Time	Chipper Run Time	Debarker Run Time	Compressor Run Time	% 4 to 8 Qtr	% Pallet	% Cant + Tim	Total kWh	SEC
95	4	73.0	0.0	71.0	74.5	136.0	36.0	168.0	0.4466	0.0118	0.5416	853.89	77.75
96	4	443.0	0.0	457.5	397.7	497.0	165.5	555.0	0.6701	0.0008	0.3291	3,768.55	103.73
97	4	296.0	0.0	311.0	259.3	325.0	88.5	348.0	0.5707	0.0001	0.4292	2,540.12	89.24
98	4	256.5	0.0	257.5	235.3	301.0	76.0	390.0	0.7765	0.0238	0.1998	2,244.00	138.19
99	4	572.5	0.0	575.0	508.6	650.0	156.0	758.0	0.7740	0.0298	0.1962	4,909.50	142.03
100	4	482.0	0.0	487.5	428.8	642.0	139.5	642.0	0.7806	0.0165	0.2029	4,217.76	153.77
101	4	329.5	0.0	333.0	290.3	370.0	56.0	465.0	0.8760	0.0025	0.1216	2,766.36	110.18
102	4	559.0	0.0	563.5	492.5	650.0	77.0	780.0	0.8465	0.0041	0.1494	4,702.11	118.64
103	4	168.5	0.0	174.5	148.9	212.0	32.5	228.0	0.8224	0.0055	0.1721	1,478.34	118.38
104	4	366.5	0.0	368.5	327.5	441.0	83.0	457.0	0.8224	0.0095	0.1680	3,109.02	115.79
105	4	503.0	0.0	529.0	442.5	639.0	112.0	701.0	0.8171	0.0166	0.1663	4,458.74	156.50
106	4	328.0	0.0	307.5	266.0	352.0	69.5	386.0	0.8031	0.0141	0.1827	2,612.90	127.27
107	4	255.5	0.0	263.0	230.9	306.0	74.5	331.0	0.8014	0.0098	0.1888	2,218.52	144.33
108	4	573.0	0.0	585.5	502.6	638.0	153.0	682.0	0.7982	0.0136	0.1882	4,800.24	136.03
109	5,1#	270.0	270.0	233.0	266.0	270.0	268.0	271.0	0.9189	0.0812	0.0000	2,325.14	106.13
110	5,1	310.0	343.0	345.0	361.0	349.5	314.5	390.5	0.9212	0.0788	0.0000	2,963.61	113.76
111	5,2	580.0	583.0	587.0	528.0	576.5	591.0	629.5	0.8858	0.1142	0.0000	4,946.48	153.86
112	5,1	123.0	121.0	142.0	140.0	124.5	127.5	131.5	0.8599	0.1401	0.0000	1,122.39	137.55
113	5,1	477.0	488.0	454.0	454.0	462.0	423.0	540.5	0.8205	0.0154	0.1641	4,115.69	67.71
114	5,2	588.0	571.0	612.0	605.0	631.5	529.5	630.5	0.7932	0.0318	0.1750	5,189.42	84.87
115	5,1	567.0	566.0	572.0	611.0	597.0	551.0	616.0	0.8301	0.0142	0.1557	5,064.19	67.73
116	5,2	633.0	661.0	641.0	639.0	666.5	614.0	690.5	0.9083	0.0917	0.0000	5,632.85	129.64
117	5,1	585.0	601.0	631.0	674.0	631.0	586.0	676.0	0.8776	0.1224	0.0000	5,495.17	98.24
118	5,2	563.0	614.0	610.0	605.0	635.5	599.5	630.5	0.8738	0.1262	0.0000	5,192.91	139.94
119	5,1	559.0	576.0	589.0	663.0	637.5	524.5	675.5	0.8802	0.1198	0.0000	5,310.84	113.82
120	5,2	551.0	595.0	580.0	599.0	627.0	598.0	629.5	0.8893	0.1107	0.0000	5,041.39	137.99
121	5,1	105.5	100.0	111.0	133.0	109.5	105.5	120.5	0.9151	0.0849	0.0000	1,003.77	113.90
122	5,1	430.5	424.0	391.0	421.0	441.5	425.0	450.5	0.9372	0.0628	0.0000	3,722.08	102.01
123	5,2	587.0	576.0	619.5	594.0	616.0	582.5	629.5	0.7105	0.0587	0.2308	5,162.08	117.99
124	5,1	596.5	603.0	625.0	654.0	635.0	552.0	675.5	0.7707	0.0265	0.2028	5,296.20	96.29
125	5,2	366.0	393.0	317.0	445.0	450.5	439.5	450.5	0.6795	0.0945	0.2261	3,517.04	112.50
126	5,1	602.0	583.0	625.0	668.0	625.5	592.5	675.5	0.8469	0.0066	0.1465	5,371.99	115.82

Shift No.	Mill #	Head Saw Run Time	Resaw Run Time	Edger Run Time	Trimmer Run Time	Chipper Run Time	Debarker Run Time	Compressor Run Time	% 4 to 8 Qtr	% Pallet	% Cant + Tim	Total kWh	SEC
127	5,2	569.0	584.0	582.0	601.0	630.5	602.5	630.5	0.8662	0.0012	0.1326	5,127.90	138.43
128	5,1	576.5	581.0	614.0	573.0	634.5	597.0	675.5	0.9064	0.0004	0.0932	5,311.83	119.39
129	5,2	584.5	585.0	616.0	566.0	532.0	583.0	630.5	0.7665	0.0002	0.2333	4,690.13	151.36
130	5,1	496.0	492.0	462.0	542.0	572.5	457.5	585.5	0.8583	0.0962	0.0455	4,642.43	115.25
131	5,1	79.0	75.0	97.0	99.0	79.0	83.0	90.5	0.9200	0.0800	0.0000	761.18	126.86
132	5,1	526.5	541.0	532.0	566.0	557.5	477.0	585.5	0.9275	0.0725	0.0000	4,700.60	128.95
133	5,2	579.0	580.0	542.0	606.0	626.0	571.0	629.5	0.7670	0.0758	0.1571	4,710.43	171.11

Table A.6. Amperage Consumption in amps of Individual Motors and Load Factor of Unlogged Motors in Sawmill 1

Shift No.	Head Saw (200 hp)	Resaw (60 hp)	Edger (50 hp)	Trimmer (10 hp)	Chipper (150 hp)	Debarker (50 hp)	Compressor (60 hp)	Carriage Feed Motor (100 hp)	Top Saw (40 hp)	Log Turner (40 hp)	Dust Collector (15 hp)	Chip blower (30 hp)	Unlogged Motors Load Factor
1	82.36	23.39	52.16	19.60	30.80	41.86	153.15	30.81	2.72	14.05	14.96	42.20	0.3204
2	83.26	25.78	55.21	20.07	31.37	42.89	155.37	29.44	13.54	13.00	15.58	45.93	0.3091
3	81.63	25.17	52.46	19.48	31.69	45.16	156.77	28.83	12.67	13.76	14.92	35.00	0.3080
4	84.12	26.24	52.26	19.48	31.83	42.48	157.32	30.07	10.63	13.82	15.60	27.51	0.3222
5	83.94	25.06	52.88	19.48	29.68	42.67	150.35	30.05	7.50	13.82	14.89	31.93	0.3207
6	86.24	25.85	54.24	20.09	31.03	47.32	146.01	30.53	1.64	13.34	15.86	31.79	0.2881
7	84.41	27.76	53.24	20.49	29.91	49.08	150.71	30.76	6.81	14.08	15.54	31.28	0.3258
8	83.60	25.17	52.82	20.76	29.97	46.91	153.56	28.75	6.82	13.42	16.22	36.54	0.2901
9	79.37	24.42	50.79	20.74	29.72	48.13	159.79	30.79	12.79	15.66	14.84	26.86	0.3668
10	83.95	26.30	53.45	20.53	30.87	47.93	156.57	31.15	9.63	14.43	14.94	36.64	0.2989
11	81.60	24.75	52.17	20.59	29.49	44.59	154.56	29.50	10.57	15.03	15.46	42.03	0.2984
12	79.89	26.01	53.34	20.84	30.01	41.91	148.64	29.23	2.42	13.35	15.02	35.44	0.2969
13	80.55	25.32	52.59	20.64	30.45	42.20	152.98	30.26	4.55	12.78	14.93	38.51	0.3004
14	79.63	23.73	51.34	20.61	28.90	37.58	154.28	28.48	5.74	13.22	15.01	45.04	0.2957
15	87.65	25.58	50.50	20.98	27.95	40.89	157.20	27.42	3.40	13.00	14.52	63.31	0.3002
16	88.44	24.76	50.74	20.45	29.92	40.14	153.85	30.39	9.88	13.18	14.84	30.57	0.2858
17	72.06	22.39	52.05	20.74	29.62	33.68	156.13	25.84	8.93	12.73	15.87	49.95	0.3059
18	82.15	21.81	51.39	20.41	26.97	38.19	154.34	31.18	9.84	13.31	14.80	38.54	0.3049
19	74.48	25.79	53.02	20.50	29.02	39.76	154.30	29.93	11.08	12.97	14.65	39.99	0.3342
20	78.08	24.80	52.54	20.57	29.41	36.53	155.77	29.87	9.77	11.88	14.85	42.36	0.2846
21	77.74	25.69	52.20	20.45	29.88	38.95	154.12	29.48	10.91	13.92	14.89	40.60	0.3018
22	79.11	26.48	51.85	20.42	30.55	39.19	153.86	29.61	12.02	12.92	15.16	34.58	0.3090

Table A.7. Amperage Consumption in amps of Individual Motors and Load Factor of Unlogged Motors in Sawmill 2

Shift No.	Main Saw (200 hp)	Carriage Motor (150 hp)	Edger (50 hp)	Trimmer (25 hp)	Compressor (40 hp)	Chipper (187 hp)	Debarker (85 hp)	Chip Blower (30 hp)	Barn Sweep (5 hp)	Conveyor (15 hp)	Unlogged Motors Load Factor
23	142.34	59.16	22.33	25.11	47.29	84.99	68.42	7.33	2.76	7.04	0.2839
24	142.22	66.40	22.88	25.12	47.04	86.99	66.10	8.14	3.38	8.27	0.2502
25	141.18	66.50	22.56	25.12	46.84	83.67	60.37	7.16	3.45	7.84	0.2522
26	137.95	61.71	21.26	25.12	46.22	87.79	60.40	9.87	2.99	7.33	0.2592
27	135.91	58.33	21.26	25.11	45.37	85.60	50.13	7.19	2.43	6.35	0.2805
28	134.73	63.65	22.63	25.12	45.43	87.55	55.57	9.67	3.68	8.32	0.2294
29	133.24	53.75	23.69	25.12	48.47	85.96	46.13	7.23	2.42	6.47	0.2921
30	138.25	64.31	22.16	25.12	47.81	84.79	51.70	9.68	3.31	7.87	0.2423
31	138.08	61.58	22.72	25.12	47.78	85.55	53.73	7.49	2.98	7.59	0.2574
32	137.86	64.22	22.51	25.12	47.57	82.34	55.57	9.79	3.59	7.98	0.2477
33	139.18	62.35	22.21	25.12	46.99	84.93	50.08	7.10	3.14	7.66	0.2525
34	135.71	58.92	22.73	25.12	47.85	88.93	60.73	7.34	2.89	6.98	0.2705
35	138.98	73.71	23.56	25.12	46.89	86.56	62.61	7.26	3.09	9.94	0.2433
36	140.63	58.72	23.10	25.12	47.53	89.18	66.11	8.51	2.79	6.88	0.2827
37	138.20	67.65	22.27	25.12	47.44	84.93	54.41	12.20	3.82	8.84	0.2760
38	136.79	62.09	23.38	25.12	47.92	87.85	56.96	9.03	3.12	8.08	0.2624
39	138.80	62.09	22.85	25.12	47.81	84.40	55.45	7.39	3.49	7.53	0.2516
40	138.19	61.26	22.42	25.12	47.26	83.45	54.63	8.44	3.17	7.51	0.2518
41	139.05	71.65	22.65	25.13	46.53	82.21	68.32	6.49	3.90	9.80	0.2794
42	140.98	60.74	23.79	25.12	47.21	89.64	65.03	7.40	3.93	7.92	0.2584
43	134.49	54.17	22.66	25.12	47.44	86.32	42.78	7.77	2.58	6.85	0.2797
44	136.87	65.22	23.54	25.12	48.28	88.66	61.18	11.72	3.42	7.53	0.2473
45	136.92	62.04	23.25	25.12	48.47	91.77	60.64	10.03	2.97	7.41	0.2627
46	133.31	78.96	22.03	25.10	46.39	89.29	45.09	11.03	3.11	6.81	0.2402
47	135.26	66.50	23.50	25.12	48.54	85.64	53.68	10.23	3.41	7.84	0.2513
48	137.90	58.86	22.64	25.12	46.13	86.92	47.30	7.39	2.87	7.06	0.2681
49	142.08	66.26	22.71	25.12	46.32	84.54	47.75	10.33	3.49	8.02	0.2384
50	138.02	67.67	22.12	25.12	45.86	84.52	50.73	7.04	3.83	8.41	0.2399
51	135.46	59.23	22.00	25.12	45.95	85.43	58.19	7.55	3.30	7.13	0.2678
52	175.93	68.13	23.07	25.12	46.66	83.28	48.00	11.29	3.96	8.89	0.2417
53	137.46	66.06	22.59	25.12	45.86	84.12	54.51	7.44	3.26	7.46	0.2510
54	136.67	46.82	23.72	25.11	44.79	81.26	51.47	7.11	2.62	6.77	0.3216
55	139.64	64.50	22.98	25.12	46.96	82.45	56.90	8.03	3.53	7.67	0.2459
56	142.87	93.25	23.08	25.10	45.65	83.20	47.89	7.28	2.51	6.81	0.3650
57	138.58	65.14	22.85	25.12	47.78	86.23	63.63	7.49	3.10	7.30	0.2571

Table A.8. Amperage Consumption in amps of Individual Motors and Load Factor of Unlogged Motors in Sawmill 3

Shift No.	7 Feet Saw (345 hp)	Edger (200 hp)	Trimmer (180 hp)	6 feet Carriage Feed (300 hp)	Gang Saw (418 hp)	Chipper (200 hp)	Debarker (210 hp)	Sorter Chain (50 hp)	Compressor (150 hp)	Hydraulic Pump (60 hp)	Unlogged Motors Load Factor
58	190.95	52.80	97.86	207.62	156.29	119.28	97.18	11.61	164.28	88.18	0.4879
59	231.34	60.59	108.45	203.45	153.28	103.16	76.91	11.42	171.06	64.18	0.5235
60	201.10	61.15	107.82	214.53	164.88	125.15	118.74	9.89	171.06	105.73	0.5038
61	200.88	61.56	107.05	210.41	170.27	132.64	114.64	11.58	170.75	110.89	0.4959
62	223.93	63.05	107.54	221.19	185.72	135.61	116.22	10.68	170.73	103.86	0.4891
63	209.41	62.29	109.81	207.59	171.69	102.01	122.87	13.11	170.01	141.48	0.5348
64	181.27	61.98	107.71	224.30	155.72	133.34	115.29	12.29	171.10	103.72	0.4943
65	187.39	60.40	107.20	213.79	157.33	128.29	110.96	12.19	171.76	110.18	0.4951
66	221.25	85.71	128.76	242.38	171.87	178.66	142.18	11.54	189.32	132.27	0.5871
67	185.64	60.63	108.85	224.70	153.53	130.36	115.69	9.68	172.14	116.92	0.4991
68	191.32	62.26	108.01	219.02	163.36	115.66	117.96	9.36	174.44	117.11	0.5050
69	159.92	43.04	91.29	178.33	144.31	100.69	99.85	10.27	142.70	109.48	0.4198
70	156.53	41.88	89.00	193.87	140.90	119.31	85.44	9.58	142.70	185.48	0.4147
71	132.47	42.59	81.65	171.13	133.26	74.36	87.15	10.47	142.70	92.30	0.3860
72	141.91	41.41	79.16	184.86	118.81	147.43	80.79	10.35	135.54	92.08	0.4077
73	199.89	62.30	109.57	207.71	156.42	130.95	109.67	11.21	171.35	116.71	0.4999
74	171.82	60.43	107.39	228.65	147.25	134.38	114.45	9.00	171.35	119.64	0.4761
75	174.27	63.41	109.27	215.35	155.26	149.75	121.34	11.33	171.35	116.90	0.4785
76	184.98	61.83	108.57	206.82	158.53	123.50	108.95	10.09	171.35	114.98	0.5039
77	179.60	62.30	108.27	208.74	148.22	146.95	114.08	10.97	171.35	102.94	0.4727
78	186.50	63.61	109.28	209.26	155.26	135.85	114.61	9.81	171.35	117.72	0.4780
79	177.56	61.47	108.68	212.35	149.67	132.75	113.39	10.20	171.35	112.90	0.4905
80	197.72	61.34	107.59	202.86	163.33	107.61	112.81	10.49	171.35	182.58	0.5083
81	191.89	63.06	108.78	209.51	163.42	139.72	115.52	11.16	171.35	169.70	0.4833
82	205.47	61.22	107.86	206.20	162.41	120.76	113.94	10.43	171.35	116.28	0.5050

Table A.9. Amperage Consumption in amps of Individual Motors and Load Factor of Unlogged Motors in Sawmill 4

Shift No.	Head Saws (350 hp)	Edger (175 hp)	Trimmer (57.5 hp)	Carriage feeds (250 hp)	Chipper (200 hp)	Debarker (80 hp)	Log Turner (20 hp)	Compressor (100 hp)	Unlogged Motors Load Factor
83	225.91	60.87	45.18	139.28	74.30	134.22	41.49	79.24	0.3496
84	221.80	59.57	44.28	144.02	71.88	114.42	37.30	77.58	0.3566
85	227.65	60.27	41.94	142.19	70.95	88.71	27.93	77.07	0.3732
86	223.63	60.67	43.96	138.73	71.27	118.66	42.55	77.52	0.3584
87	227.59	60.28	44.48	143.60	69.64	125.74	42.57	77.43	0.3562
88	205.98	60.93	45.81	102.90	85.35	136.53	35.05	76.69	0.3482
89	217.25	61.84	44.41	142.15	73.82	120.82	36.70	78.04	0.3528
90	218.14	61.62	42.31	142.79	71.44	102.86	44.06	76.81	0.3679
91	226.69	61.75	43.83	139.69	71.46	115.10	42.43	77.62	0.3608
92	222.75	62.29	48.31	139.90	71.40	153.06	37.49	77.10	0.3355
93	228.18	60.88	45.89	134.45	69.18	146.47	40.58	76.55	0.3521
94	233.60	61.69	37.63	127.22	70.92	65.04	53.05	68.45	0.4168
95	259.14	61.53	57.89	140.16	73.23	166.42	11.86	78.33	0.3214
96	213.43	62.03	42.02	136.67	75.11	90.51	29.41	81.17	0.3666
97	220.80	61.89	45.74	138.47	76.03	127.41	36.99	79.87	0.3464
98	219.55	61.13	41.24	142.70	72.10	84.82	38.34	77.36	0.3770
99	227.31	61.03	42.40	140.38	70.55	92.27	41.39	78.42	0.3742
100	226.92	60.84	44.00	135.03	69.97	113.59	34.26	78.80	0.3607
101	211.80	60.94	43.98	135.48	69.09	142.94	71.54	77.83	0.3553
102	212.51	60.39	43.79	139.52	70.36	154.28	83.93	77.46	0.3566
103	226.13	60.81	47.07	135.82	69.32	176.98	53.31	78.45	0.3415
104	217.63	61.79	43.33	144.82	68.82	118.87	52.86	77.91	0.3579
105	228.73	61.20	48.73	128.11	68.71	174.01	41.38	77.68	0.3390
106	224.03	62.27	44.59	119.26	69.65	122.49	44.88	77.75	0.3592
107	229.56	61.47	42.02	148.92	70.78	88.50	36.74	76.10	0.3715
108	223.89	61.56	42.91	139.10	72.58	102.12	42.45	75.94	0.3658

Table A.10. Amperage Consumption in amps of Individual Motors and Load Factor of Unlogged Motors in Sawmill 5

Shift No.	Resaw (150 hp)	Edger (50 hp)	Trimmer (100 hp)	Main Saw + Carriage Feed (250 hp)	Gang Saw (100 hp)	Debarker (130 hp)	Chipper (300 hp)	Compressor (300 hp)	Log Turner (20 hp)	Log Deck (20 hp)	Line Bar Hdy. (10 hp)	Unlogged Motors Load Factor
109	87.51	33.30	32.11	211.53	108.89	64.17	200.95	111.33	23.27	23.30	5.61	0.3674
110	87.59	32.92	40.69	210.39	103.86	63.23	200.38	111.11	20.17	22.34	6.30	0.3646
111	85.44	32.79	36.28	198.44	99.30	63.20	200.90	114.66	23.86	22.18	5.53	0.3527
112	86.72	33.17	33.92	205.66	137.17	63.75	199.50	112.35	19.72	18.90	6.79	0.3644
113	84.56	33.13	35.51	206.76	103.83	66.50	199.19	111.07	21.36	26.00	6.62	0.3566
114	85.41	33.09	34.97	206.16	117.80	65.94	197.82	111.99	24.33	25.93	5.93	0.3639
115	91.53	33.25	36.51	209.30	110.12	65.31	198.83	109.54	22.12	24.03	6.31	0.3601
116	85.34	32.97	35.79	209.70	107.63	63.20	199.27	112.73	21.94	23.03	5.78	0.3612
117	97.40	33.28	33.84	211.27	120.34	63.08	198.66	109.68	22.65	23.14	6.07	0.3696
118	83.95	32.95	34.14	207.06	111.27	62.54	198.60	110.97	21.85	21.71	5.63	0.3612
119	91.07	33.06	38.35	204.47	126.49	63.94	196.01	110.65	21.54	24.72	6.75	0.3676
120	81.89	33.21	36.04	203.95	105.86	63.33	198.13	111.31	21.72	21.46	5.48	0.3595
121	95.46	33.56	38.82	211.85	138.27	66.44	196.76	112.99	25.40	23.81	7.59	0.3609
122	94.53	33.45	34.85	205.42	106.79	64.53	197.69	109.74	22.49	23.27	5.74	0.3607
123	80.85	33.70	34.37	202.98	122.11	63.91	196.17	111.27	23.73	23.28	5.60	0.3619
124	83.71	32.81	38.38	207.08	106.62	62.17	196.68	110.47	21.14	24.77	6.31	0.3655
125	80.29	32.48	40.17	199.38	124.55	62.27	196.49	113.87	20.98	18.53	4.84	0.3624
126	86.77	32.94	36.88	208.12	119.69	62.82	199.37	106.57	22.59	23.55	6.34	0.3604
127	78.19	32.81	36.36	205.52	116.20	62.63	201.79	112.67	21.61	21.56	5.63	0.3610
128	88.44	33.16	35.06	208.66	122.69	63.02	202.13	110.66	21.43	22.28	5.96	0.3623
129	76.49	33.08	43.29	194.43	69.97	63.38	205.59	114.33	19.44	19.68	5.82	0.3518
130	89.47	32.95	35.85	210.36	129.59	64.44	202.01	111.61	22.78	25.39	6.80	0.3748
131	82.98	32.37	37.69	212.02	160.60	66.04	195.24	112.69	26.17	22.56	7.67	0.3567
132	92.63	33.36	38.35	209.65	96.19	64.17	199.58	112.56	20.99	25.43	6.49	0.3700
133	80.63	32.97	45.87	204.40	39.83	63.80	203.35	116.43	21.86	23.74	5.88	0.3521

Table A.11. Run Time in Minutes of Individual Motors in Sawmill 1

Shift No.	Head Saw (200 hp)	Resaw (60 hp)	Edger (50 hp)	Trimmer (10 hp)	Chipper (150 hp)	Debarker (50 hp)	Compressor (60 hp)	Carriage Feed Motor (100 hp)	Top Saw (40 hp)	Log Turner (40 hp)	Dust Collector (15 hp)	Chip blower (30 hp)	Unlogged Motors (163 hp)
1	488	487	491	505	556	217	555.5	488	488	487	556	556	505
2	62	75	75	76	82	22	75	62	62	75	82	82	75
3	556	565	604	580	704	217	665	556	556	565	704	704	630
4	567	553	593	580	708	648	667.5	567	567	553	708	708	630
5	223	222	228	226	298	76	265.5	223	223	222	298	298	235
6	347	351	360	356	423	142	370	347	347	351	423	423	395
7	225	224	235	228	299	77	273.5	225	225	224	299	299	240
8	338	342	359	349	394	124	390	338	338	342	394	394	390
9	119	118	142	123	184	37	154	119	119	118	184	184	120
10	435	411	462	464	569	167	506.5	435	435	411	569	569	510
11	501	442	514	512	643	166	549	501	501	442	643	643	570
12	575	568	605	579	708	220	584	575	575	568	708	708	630
13	540	558	579	571	730	231	659	540	540	558	730	730	630
14	538	537	562	572	712	233	663.5	538	538	537	712	712	630
15	145	163	185	216	311	66	276.5	145	145	163	311	311	240
16	240	239	254	242	285	109	285	240	240	239	285	285	285
17	105	105	105	105	114	27	105	105	105	105	114	114	105
18	576	554	599	578	716	183	662.5	576	576	554	716	716	630
19	181	192	192	196	258	58	229.5	181	181	192	258	258	195
20	362	374	394	380	444	117	435	362	362	374	444	444	435
21	558	504	587	574	710	213	662.5	558	558	504	710	710	630
22	554	555	582	571	718	218	666	554	554	555	718	718	630

Table A.12. Run Time in Minutes of Individual Motors in Sawmill 2

Shift No.	Main Saw (200 hp)	Carriage Motor (150 hp)	Edger (50 hp)	Trimmer (25 hp)	Compressor (40 hp)	Chipper (187 hp)	Debarker (85 hp)	Chip Blower (30 hp)	Barn Sweep (5 hp)	Conveyor (15 hp)	Unlogged Motors (30 hp)
23	278	278	251	255	286	267	284	267	284	251	270
24	204	204	199	210	236	241	219	241	219	199	240
25	451	451	439	465	560	510	450	510	450	439	510
26	486	486	447	465	554	498	487	498	487	447	510
27	199	199	174	180	232	181	198	181	198	174	180
28	228	228	211	225	274	271	209	271	209	211	270
29	144	144	118	120	148	135	142	135	142	118	120
30	346	346	327	345	388	393	353	393	353	327	390
31	487	487	446	465	560	509	510	509	510	446	510
32	467	467	424	465	560	493	433	493	433	424	510
33	481	481	445	465	567	512	493	512	493	445	510
34	312	312	278	285	347	293	300	293	300	278	300
35	105	105	102	120	158	157	153	157	153	102	150
36	346	346	309	315	375	319	341	319	341	309	330
37	143	143	141	150	189	174	147	174	147	141	150
38	483	483	435	465	557	532	504	532	504	435	510
39	483	483	446	465	559	508	434	508	434	446	510
40	458	458	423	435	527	474	455	474	455	423	480
41	27	27	26	30	36	37	30	37	30	26	30
42	430	430	388	405	504	447	359	447	359	388	450
43	125	125	100	105	152	98	117	98	117	100	105
44	356	356	352	360	405	394	348	394	348	352	405
45	421	421	391	405	476	460	435	460	435	391	450
46	49	49	59	60	60	61	59	61	59	59	60
47	451	451	436	465	566	528	450	528	450	436	510
48	263	263	233	240	305	272	255	272	255	233	255
49	219	219	216	225	246	255	224	255	224	216	255
50	386	386	363	405	505	467	363	467	363	363	450
51	343	343	308	315	379	341	302	341	302	308	330
52	142	142	142	150	184	176	146	176	146	142	180
53	454	454	455	465	571	528	472	528	472	455	510
54	62	62	44	45	89	44	51	44	51	44	45
55	420	420	409	420	467	469	409	469	409	409	465
56	83	83	57	60	115	71	69	71	69	57	60
57	401	401	405	405	456	435	435	435	435	405	450

Table A.13. Run Time in Minutes of Individual Motors in Sawmill 3

Shift No.	7 Feet Saw (345 hp)	Edger (200 hp)	Trimmer (180 hp)	6 feet Carriage Feed (300 hp)	Gang Saw (418 hp)	Chipper (200 hp)	Debarker (210 hp)	Sorter Chain (50 hp)	Compressor (150 hp)	Hydraulic Pump (60 hp)	Unlogged Motors (517.5 hp)
58	478.8	489	525	478.8	463.2	501	561.6	525	571	561.6	480
59	115.5	129	151.8	115.5	115.2	157.8	226.8	151.8	120	226.8	120
60	351.3	355.8	433.2	351.3	334.2	403.8	345.6	433.2	390	345.6	360
61	396.6	406.8	430.8	396.6	246	447	394.8	430.8	420.6	394.8	390
62	82.8	82.8	88.2	82.8	82.8	91.8	82.8	88.2	90	82.8	90
63	126	129	157.8	126	109.8	162.6	115.8	157.8	120.6	115.8	120
64	353.7	351.6	394.8	353.7	343.8	384.6	348	394.8	390	348	360
65	243.3	247.2	256.2	243.3	214.2	280.8	247.8	256.2	240	247.8	240
66	213.3	214.8	211.8	213.3	192	240	210.6	211.8	210	210.6	210
67	469.8	486	529.2	469.8	447	537	472.8	529.2	504.6	472.8	480
68	475.2	505.2	535.8	475.2	457.2	561.6	465.6	535.8	511.2	465.6	480
69	477.9	511.8	550.2	477.9	456	538.8	423	550.2	510	423	480
70	466.8	502.8	522	466.8	469.8	535.8	276	522	510	276	480
71	494.4	511.2	547.8	494.4	456	540	463.8	547.8	510	463.8	480
72	493.2	505.2	523.8	493.2	439.2	484.8	498.6	523.8	510	498.6	480
73	478.5	502.2	517.8	478.5	448.2	522	465.6	517.8	510	465.6	480
74	262.5	328.2	363	262.5	255	387	304.8	363	345	304.8	315
75	159	160.8	163.2	159	151.2	160.8	154.8	163.2	165	154.8	165
76	305.1	318	355.8	305.1	265.8	346.8	301.2	355.8	330	301.2	300
77	174.6	175.2	177	174.6	171	177.6	175.2	177	180	175.2	180
78	442.5	487.8	522	442.5	399	537.6	442.2	522	510	442.2	480
79	476.4	499.2	510	476.4	436.8	540	475.2	510	510	475.2	480
80	96.9	100.2	107.4	96.9	70.2	133.8	67.2	107.4	90	67.2	90
81	382.2	387	417.6	382.2	373.2	412.8	235.2	417.6	420	235.2	390
82	477.6	523.8	522.6	477.6	454.8	552.6	472.8	522.6	510	472.8	480

Table A.14. Run Time in Minutes of Individual Motors in Sawmill 4

Shift No.	Head Saws (350 hp)	Edger (175 hp)	Trimmer (57.5 hp)	Carriage feeds (250 hp)	Chipper (200 hp)	Debarker (80 hp)	Log Turner (20 hp)	Compressor (100 hp)	Unlogged Motors (301.5 hp)
83	174	181.5	155.1	174	195	53.5	53.5	196	195
84	369.5	371	328.7	369.5	411	112.5	112.5	476	405
85	574	571.5	514.2	574	661	218.5	218.5	724	600
86	562.5	582	490.5	562.5	646	143	143	674	600
87	504.5	530.5	448.5	504.5	605	130.5	130.5	616	555
88	42.5	44	35.3	42.5	51	10.5	10.5	53	45
89	265.5	280	242.8	265.5	314	85.5	85.5	347	300
90	276	287.5	254.8	276	337	71	71	420	300
91	553	587.5	492	553	654	145	145	688	600
92	146	149.5	133.9	146	192	46	46	201	180
93	384.5	397	328.9	384.5	425	85	85	486	420
94	365	381.5	315.2	365	421	65	65	554	330
95	73	71	74.5	73	136	36	36	168	120
96	443	457.5	397.7	443	497	165.5	165.5	555	465
97	296	311	259.3	296	325	88.5	88.5	348	330
98	256.5	257.5	235.3	256.5	301	76	76	390	270
99	572.5	575	508.6	572.5	650	156	156	758	600
100	482	487.5	428.8	482	642	139.5	139.5	642	525
101	329.5	333	290.3	329.5	370	56	56	465	355
102	559	563.5	492.5	559	650	77	77	780	600
103	168.5	174.5	148.9	168.5	212	32.5	32.5	228	195
104	366.5	368.5	327.5	366.5	441	83	83	457	395
105	503	529	442.5	503	639	112	112	701	600
106	328	307.5	266	328	352	69.5	69.5	386	330
107	255.5	263	230.9	255.5	306	74.5	74.5	331	270
108	573	585.5	502.6	573	638	153	153	682	600

Table A.15. Run Time in Minutes of Individual Motors in Sawmill 5

Shift No.	Resaw (150 hp)	Edger (50 hp)	Trimmer (100 hp)	Main Saw + Carriage Feed (250 hp)	Gang Saw (100 hp)	Debarker (130 hp)	Chipper (300 hp)	Compressor (300 hp)	Log Turner (20 hp)	Log Deck (20 hp)	Line Bar Hdy. (10 hp)	Unlogged Motors (256 hp)
109	270	233	266	270	270	268	270	271	270	268	268	266
110	343	345	361	310	343	314.5	349.5	390.5	343	314.5	314.5	342
111	583	587	528	580	583	591	576.5	629.5	583	591	591	582
112	121	142	140	123	121	127.5	124.5	131.5	121	127.5	127.5	130
113	488	454	454	477	488	423	462	540.5	488	423	423	482
114	571	612	605	588	571	529.5	631.5	630.5	571	529.5	529.5	598
115	566	572	611	567	566	551	597	616	566	551	551	584
116	661	641	639	633	661	614	666.5	690.5	661	614	614	647
117	601	631	674	585	601	586	631	676	601	586	586	627
118	614	610	605	563	614	599.5	635.5	630.5	614	599.5	599.5	604
119	576	589	663	559	576	524.5	637.5	675.5	576	524.5	524.5	608
120	595	580	599	551	595	598	627	629.5	595	598	598	592
121	100	111	133	105.5	100	105.5	109.5	120.5	100	105.5	105.5	117
122	424	391	421	430.5	424	425	441.5	450.5	424	425	425	427
123	576	619.5	594	587	576	582.5	616	629.5	576	582.5	582.5	601
124	603	625	654	596.5	603	552	635	675.5	603	552	552	611
125	393	317	445	366	393	439.5	450.5	450.5	393	439.5	439.5	410
126	583	625	668	602	583	592.5	625.5	675.5	583	592.5	592.5	625
127	584	582	601	569	584	602.5	630.5	630.5	584	602.5	602.5	596
128	581	614	573	576.5	581	597	634.5	675.5	581	597	597	614
129	585	616	566	584.5	585	583	532	630.5	585	583	583	562
130	492	462	542	496	492	457.5	572.5	585.5	492	457.5	457.5	523
131	75	97	99	79	75	83	79	90.5	75	83	83	90
132	541	532	566	526.5	541	477	557.5	585.5	541	477	477	534
133	580	542	606	579	580	571	626	629.5	580	571	571	565

Table A.16. Energy Consumption in kWh of Individual Motors in Sawmill 1

Shift No.	Head Saw (200 hp)	Resaw (60 hp)	Edger (50 hp)	Trimmer (10 hp)	Chipper (150 hp)	Debarker (50 hp)	Compressor (60 hp)	Carriage Feed Motor (100 hp)	Top Saw (40 hp)	Log Turner (40 hp)	Dust Collector (15 hp)	Chip blower (30 hp)	Unlogged Motors (163 hp)	Total kWh (968 hp)
1	327.19	125.76	97.29	81.96	212.20	74.41	446.09	176.95	7.57	58.03	92.41	150.88	417.15	2,267.90
2	42.02	21.34	15.73	12.63	31.88	7.73	61.10	21.48	4.79	8.27	14.19	24.22	59.78	325.18
3	369.47	156.96	120.38	93.54	276.48	80.28	546.62	188.64	40.17	65.93	116.64	158.48	500.27	2,713.86
4	388.26	160.19	117.73	93.54	279.31	225.52	550.62	200.66	34.38	64.84	122.64	125.26	523.36	2,886.31
5	152.38	61.41	45.80	36.45	109.60	26.57	209.31	78.85	9.54	26.02	49.27	61.20	194.34	1,060.73
6	243.60	100.16	74.18	59.21	162.64	55.05	283.27	124.65	3.25	39.73	74.50	86.47	293.41	1,600.11
7	154.61	68.64	47.53	38.67	110.83	30.96	216.13	81.43	8.74	26.76	51.62	60.15	201.62	1,097.69
8	230.01	95.04	72.04	59.98	146.31	47.65	314.01	114.36	13.14	38.94	70.96	92.58	291.76	1,586.78
9	76.89	31.81	27.40	21.12	67.76	14.59	129.03	43.12	8.68	15.68	30.33	31.78	113.50	611.69
10	297.28	119.30	93.80	78.88	217.64	65.58	415.82	159.46	23.90	50.32	94.40	134.08	393.03	2,143.49
11	332.81	120.74	101.87	87.27	235.00	60.64	444.92	173.94	30.20	56.36	110.43	173.78	438.51	2,366.45
12	373.93	163.10	122.60	99.90	263.27	75.53	455.16	197.76	7.95	64.33	118.14	161.34	482.31	2,585.32
13	354.09	155.97	115.67	97.59	275.51	79.86	528.61	192.28	14.02	60.51	121.07	180.80	488.05	2,664.01
14	348.73	140.64	109.60	97.59	255.01	71.74	536.73	180.28	17.60	60.23	118.72	206.25	480.38	2,623.49
15	103.46	46.02	35.49	37.51	107.73	22.11	227.90	46.79	2.81	17.98	50.14	126.63	185.76	1,010.33
16	172.78	65.31	48.96	40.98	105.67	35.84	229.91	85.83	13.52	26.73	46.98	56.03	210.00	1,138.54
17	61.59	25.95	20.76	18.03	41.84	7.45	85.96	31.93	5.35	11.34	20.09	36.62	82.83	449.74
18	385.20	133.38	116.93	97.68	239.28	57.25	536.13	211.31	32.34	62.57	117.68	177.48	495.29	2,662.51
19	109.74	54.66	38.67	33.27	92.79	18.89	185.68	63.75	11.44	21.13	41.99	66.35	168.04	906.38
20	230.10	102.40	78.64	64.70	161.84	35.01	355.29	127.22	20.18	37.68	73.25	120.95	319.18	1,726.44
21	353.12	142.94	116.40	97.20	262.87	67.97	535.38	193.54	34.74	59.52	117.38	185.38	490.20	2,656.64
22	356.76	162.24	114.64	96.53	271.79	69.99	537.28	193.03	37.98	60.83	120.91	159.68	501.99	2,683.65

Table A.17. Energy Consumption in kWh of Individual Motors in Sawmill 2

Shift No.	Main Saw (200 hp)	Carriage Motor (150 hp)	Edger (50 hp)	Trimmer (25 hp)	Compressor (40 hp)	Chipper (187 hp)	Debarker (85 hp)	Chip Blower (30 hp)	Barn Sweep (5 hp)	Conveyor (15 hp)	Unlogged Motors (30 hp)	Total kWh (817 hp)
23	228.07	94.79	33.03	33.38	121.18	133.98	191.22	13.2	5.29	11.92	37.77	903.83
24	167.22	78.07	26.83	27.49	99.47	123.78	142.45	13.23	4.99	11.11	29.59	724.23
25	367	172.86	58.35	60.88	235.01	251.96	267.34	24.65	10.49	23.23	63.37	1,535.14
26	386.43	172.86	55.99	60.88	229.43	258.14	289.45	33.18	9.82	22.12	65.14	1,583.44
27	155.89	66.91	21.8	23.56	94.32	91.48	97.67	8.78	3.24	7.46	24.88	595.99
28	177.05	83.64	28.13	29.46	111.53	140.08	114.29	17.68	5.19	11.85	30.52	749.42
29	110.59	44.61	16.47	15.71	64.28	68.52	64.46	6.59	2.32	5.15	17.27	415.97
30	275.7	128.25	42.69	45.17	166.23	196.74	179.61	25.68	7.89	17.37	46.56	1,131.89
31	387.6	172.86	59.7	60.88	239.73	257.11	269.68	25.74	10.27	22.83	64.69	1,571.09
32	371.09	172.86	56.24	60.88	238.68	239.69	236.8	32.56	10.48	22.83	62.24	1,504.35
33	385.85	172.86	58.23	60.88	238.72	256.74	242.96	24.53	10.43	23.01	63.46	1,537.67
34	244.05	105.95	37.24	37.31	148.76	153.85	179.29	14.51	5.86	13.09	39.98	979.89
35	84.11	44.61	14.16	15.71	66.38	80.24	94.26	7.69	3.19	6.84	17.98	435.17
36	280.46	117.1	42.05	41.24	159.71	167.97	221.85	18.32	6.43	14.35	45.96	1,115.44
37	113.91	55.76	18.5	19.64	80.34	87.25	78.71	14.33	3.79	8.41	20.4	501.04
38	380.8	172.86	59.92	60.88	239.18	275.95	282.51	32.41	10.61	23.72	65.93	1,604.77
39	386.42	172.86	60.05	60.88	239.46	253.15	236.8	25.32	10.23	22.67	63.22	1,531.06
40	364.79	161.71	55.88	56.95	223.15	233.56	244.59	26.99	9.72	21.43	59.55	1,458.32
41	21.64	11.15	3.47	3.93	15.01	17.96	20.17	1.62	0.79	1.72	4.13	101.59
42	349.4	150.55	54.4	53.02	213.2	236.58	229.72	22.33	9.53	20.74	57.29	1,396.76
43	96.9	39.03	13.35	13.75	64.61	49.95	49.25	5.14	2.04	4.62	14.47	353.11
44	280.85	133.83	48.82	47.13	175.22	206.25	209.5	31.16	8.04	17.88	49.36	1,208.04
45	332.25	150.55	53.57	53.02	206.74	249.25	259.58	31.13	8.73	19.56	58.24	1,422.62
46	37.65	22.3	7.66	7.85	24.94	32.16	26.18	4.54	1.24	2.71	7.1	174.33
47	351.61	172.86	60.36	60.88	246.15	266.99	237.69	36.44	10.34	23.08	63.16	1,529.56
48	209.04	89.22	31.08	31.42	126.07	139.59	118.7	13.56	4.94	11.1	33.68	808.4
49	179.35	83.64	28.9	29.46	102.1	127.28	105.25	17.78	5.27	11.69	29.96	720.68
50	307.06	150.55	47.31	53.02	207.51	233.05	181.21	22.18	9.39	20.59	53.19	1,285.06
51	267.81	117.1	39.93	41.24	156.05	172	172.93	17.38	6.72	14.81	43.54	1,049.51
52	143.99	55.76	19.3	19.64	76.92	86.54	68.97	13.41	3.9	8.52	21.44	518.39
53	359.69	172.86	60.57	60.88	234.63	262.24	253.18	26.5	10.38	22.91	63.07	1,526.91
54	48.84	16.73	6.15	5.89	35.72	21.11	25.83	2.11	0.9	2.01	7.13	172.42
55	338.03	156.13	55.37	54.98	196.52	228.32	229.03	25.41	9.73	21.18	56.34	1,371.04
56	68.35	44.61	7.75	7.85	47.04	34.88	32.52	3.49	1.17	2.62	10.79	261.07
57	320.29	150.55	54.53	53.02	195.24	221.47	272.39	21.99	9.09	19.95	57.01	1,375.53

Table A.18. Energy Consumption in kWh of Individual Motors in Sawmill 3

Shift No.	7 Feet Saw (345 hp)	Edger (200 hp)	Trimmer (180 hp)	6 feet Carriage Feed (300 hp)	Gang Saw (418 hp)	Chipper (200 hp)	Debarker (210 hp)	Sorter Chain (50 hp)	Compressor (150 hp)	Hydraulic Pump (60 hp)	Unlogged Motors (517.5 hp)	Total kWh (2,630.5) hp
58	967.33	273.79	559.78	953.53	864.35	673.82	567.53	52.11	1,284.08	550.56	1,718.02	8,464.90
59	282.7	82.88	179.37	225.39	210.82	183.55	181.38	14.82	280.99	161.81	460.87	2,264.58
60	747.45	230.73	508.95	722.88	657.87	569.8	426.74	36.61	913.21	406.22	1,330.60	6,551.06
61	842.91	265.54	502.48	800.43	500.1	668.53	470.65	42.65	983.12	486.71	1,418.81	6,981.93
62	196.17	55.36	103.35	175.67	183.6	140.37	100.07	8.05	210.34	95.6	322.95	1,591.53
63	279.17	85.21	188.81	250.89	225.08	187.03	147.96	17.68	280.66	182.13	470.87	2,315.49
64	678.35	231.08	463.32	760.98	639.2	578.24	417.21	41.47	913.43	401.27	1,305.60	6,430.15
65	482.36	158.32	299.25	498.93	402.35	406.17	285.92	26.7	564.3	303.52	871.73	4,299.55
66	499.3	195.23	297.16	495.9	393.98	483.47	311.38	20.9	544.23	309.69	904.51	4,455.75
67	922.73	312.46	627.67	1012.56	819.36	789.33	568.81	43.78	1,189.02	614.53	1,757.46	8,657.71
68	961.92	333.54	630.6	998.31	891.73	732.41	571.12	42.87	1,220.70	606.18	1,778.46	8,767.84
69	808.58	233.58	547.31	817.43	785.64	611.7	439.21	48.32	996.25	514.84	1,478.30	7,281.16
70	773.09	223.32	506.18	868.04	790.29	720.77	245.23	42.74	996.25	569.1	1,460.50	7,195.51
71	692.94	230.85	487.34	811.51	725.49	452.73	420.32	49.04	996.25	475.89	1,359.40	6,701.76
72	740.49	221.84	451.78	874.5	622.99	805.88	418.91	46.34	946.25	510.4	1,435.88	7,075.26
73	1,011.96	331.77	618.21	953.31	837.03	770.72	531.01	49.62	1,196.25	604.1	1,760.46	8,664.44
74	477.2	210.31	424.74	575.7	448.29	586.39	362.75	27.91	809.23	405.41	1,100.27	5,428.20
75	293.17	108.12	194.3	328.43	280.28	271.5	195.33	15.81	387.02	201.17	579.19	2,854.32
76	597.11	208.49	420.92	605.26	503.1	482.92	341.25	30.69	774.04	385.01	1,109.16	5,457.95
77	331.78	115.74	208.8	349.59	302.61	294.27	207.85	16.59	422.2	200.49	624.3	3,074.22
78	873.14	329.03	621.57	888.19	739.64	823.44	527.02	43.77	1,196.25	578.71	1,683.46	8,304.22
79	894.96	325.42	603.95	970.34	780.54	808.27	560.3	44.48	1,196.25	596.46	1,727.46	8,508.43
80	202.71	65.18	125.9	188.55	136.89	162.34	78.83	9.63	211.1	136.4	335.65	1,653.18
81	775.95	258.77	494.99	768.05	728.16	650.31	282.54	39.83	985.14	443.72	1,382.81	6,810.27
82	1,038.26	340.06	614.21	944.61	881.9	752.43	560.18	46.6	1,196.25	611.19	1,778.46	8,764.15

Table A.19. Energy Consumption in kWh of Individual Motors in Sawmill 4

Shift No.	Head Saws (350 hp)	Edger (175 hp)	Trimmer (57.5 hp)	Carriage feeds (250 hp)	Chipper (200 hp)	Debarker (80 hp)	Log Turner (20 hp)	Compressor (100 hp)	Unlogged Motors (301.5 hp)	Total kWh (1,534 hp)
83	377.04	106.65	67.73	217.95	135.35	77.74	19.24	179.88	322.65	1,504.23
84	786.09	213.36	140.67	478.6	275.96	139.35	36.38	427.67	683.62	3,181.70
85	1,253.40	332.51	208.41	734.04	438.12	209.85	52.9	646.25	1,059.77	4,935.25
86	1,206.55	340.87	208.41	701.81	430.11	183.69	52.74	605.14	1,017.77	4,747.09
87	1,101.31	308.71	192.78	651.52	393.57	177.64	48.16	552.39	935.81	4,361.89
88	83.97	25.88	15.63	39.33	40.66	15.52	3.19	47.07	74.16	345.41
89	553.26	167.15	104.2	339.41	216.53	111.83	27.2	313.62	500.89	2,334.09
90	577.49	171.02	104.2	354.43	224.91	79.06	27.12	373.61	522.39	2,434.23
91	1,202.43	350.23	208.41	694.75	436.59	180.68	53.33	618.45	1,024.77	4,769.64
92	311.94	89.89	62.52	183.7	128.07	76.22	14.95	179.47	285.83	1,332.59
93	841.54	233.33	145.88	464.92	274.64	134.78	29.9	430.86	699.94	3,255.79
94	817.84	227.18	114.62	417.61	278.92	45.77	29.89	439.2	651.02	3,022.05
95	181.45	42.17	41.68	92.02	93.04	64.86	3.7	152.41	182.56	853.89
96	906.9	273.95	161.51	544.49	348.7	162.16	42.19	521.74	806.9	3,768.55
97	626.88	185.79	114.62	368.61	230.83	122.07	28.38	321.91	541.02	2,540.12
98	540.17	151.94	93.78	329.18	202.72	69.79	25.26	349.41	481.75	2,244.00
99	1,248.22	338.76	208.41	722.77	428.37	155.83	55.97	688.4	1,062.77	4,909.50
100	1,049.10	286.31	182.36	585.35	419.62	171.54	41.43	585.87	896.18	4,217.76
101	669.38	195.89	123.38	401.48	238.8	86.66	34.73	419.12	596.92	2,766.36
102	1,139.43	328.5	208.41	701.39	427.23	128.61	56.02	699.75	1,012.77	4,702.11
103	365.47	102.44	67.73	205.82	137.28	62.27	15.02	207.16	315.15	1,478.34
104	765.04	219.81	137.13	477.33	283.5	106.81	38.03	412.33	669.04	3,109.02
105	1,103.54	312.52	208.41	579.51	410.16	210.99	40.18	630.66	962.77	4,458.74
106	704.82	184.84	114.62	351.81	229.03	92.16	27.04	347.56	561.02	2,612.90
107	562.59	156.05	93.78	342.18	202.33	71.38	23.73	291.73	474.75	2,218.52
108	1,230.53	347.93	208.41	716.81	432.56	169.14	56.3	599.79	1,038.77	4,800.24

Table A.20. Energy Consumption in kWh of Individual Motors in Sawmill 5

Shift No.	Resaw (150 hp)	Edger (50 hp)	Trimmer (100 hp)	Main Saw + Carriage Feed (250 hp)	Gang Saw (100 hp)	Debarker (130 hp)	Chipper (300 hp)	Compressor (300 hp)	Log Turner (20 hp)	Log Deck (20 hp)	Line Bar Hdy. (10 hp)	Unlogged Motors (256 hp)	Total kWh (1,686 hp)
109	266.68	87.57	111.24	477.78	303.62	95.32	262.02	244.03	38.55	65.77	9.18	363.39	2,325.14
110	339.09	128.20	191.30	545.60	367.88	110.21	338.22	350.96	42.44	73.99	12.11	463.60	2,963.61
111	562.24	217.25	249.48	962.84	597.87	207.00	559.34	583.80	85.33	138.03	19.97	763.33	4,946.48
112	118.43	53.16	61.85	211.62	171.41	45.05	119.95	119.50	14.64	25.37	5.29	176.12	1,122.39
113	465.75	169.75	209.99	825.05	523.28	155.91	444.43	485.57	63.96	115.81	17.10	639.08	4,115.69
114	550.47	228.60	275.55	1014.08	694.61	193.52	603.31	571.10	85.22	144.57	19.18	809.21	5,189.42
115	584.71	214.67	290.57	992.76	643.64	199.46	573.25	545.77	76.79	139.42	21.25	781.91	5,064.19
116	636.66	238.55	297.90	1110.42	734.73	215.06	641.41	629.59	88.96	148.90	21.67	868.99	5,632.85
117	660.73	237.00	297.04	1033.93	746.90	204.86	605.39	599.72	83.50	142.81	21.71	861.58	5,495.17
118	581.81	226.89	269.01	975.21	705.53	207.80	609.51	565.91	82.31	137.07	20.60	811.26	5,192.91
119	592.07	219.78	331.18	956.19	752.44	185.87	603.46	604.58	76.11	136.55	21.62	830.99	5,310.84
120	549.96	217.43	281.18	940.07	650.44	209.89	599.95	566.74	79.28	135.17	20.00	791.28	5,041.39
121	107.75	42.04	67.25	186.97	142.79	38.85	104.05	110.13	15.58	26.45	4.89	157.02	1,003.77
122	452.40	147.63	191.09	739.78	467.60	151.99	421.52	399.89	58.50	104.13	14.89	572.66	3,722.08
123	525.63	235.64	265.94	996.77	726.37	206.34	583.58	566.56	83.84	142.79	19.91	808.71	5,162.08
124	569.72	231.45	326.89	1033.32	663.94	190.20	603.16	603.56	78.22	143.99	21.26	830.49	5,296.20
125	356.15	116.21	232.85	610.46	505.48	151.68	427.50	414.92	50.58	85.75	12.99	552.48	3,517.06
126	570.96	232.38	320.85	1048.13	720.59	206.28	602.24	582.28	80.81	146.93	22.96	837.58	5,371.99
127	515.41	215.55	284.59	978.27	700.82	209.15	614.44	574.60	77.41	136.80	20.72	800.14	5,127.90
128	579.96	229.77	261.66	1006.33	736.17	208.52	619.38	604.64	76.38	140.05	21.75	827.22	5,311.83
129	505.04	229.97	319.13	950.68	422.74	204.78	528.21	583.06	69.75	120.84	20.71	735.22	4,690.13
130	496.86	171.81	253.07	872.85	658.43	163.39	558.51	528.58	68.75	122.32	18.99	728.87	4,642.43
131	70.24	35.44	48.60	140.12	124.39	30.38	74.49	82.49	12.04	19.72	3.89	119.38	761.18
132	565.63	200.33	282.73	923.40	537.40	169.65	537.35	533.08	69.65	127.72	18.92	734.74	4,700.60
133	527.85	201.68	362.06	990.06	238.54	201.90	614.78	592.83	77.77	142.74	20.50	739.72	4,710.43

Table A.21: Electrical Parameters of Sawmill Motors

	Sawmill 1			Sawmill 2			Sawmill 5		
Motor	***hp***	***PF****	***Voltage****	***hp***	***PF****	***Voltage****	***hp***	***PF****	***Voltage****
Head Saw	200	0.60	470	200	0.41	487	150	0.60	483
Re-saw	60	0.80	478	-	-	-	150	0.85	460
Top Saw	40	0.28	470	-	-	-	-	-	-
Edger	50	0.60	478	50	0.42	486	50	0.85	460
Trimmer	10	0.90	477	25	0.37	488	100	0.94	480
Debarker	50	0.60	473	85	0.70	487	130	0.40	480
Gang saw	-	-	-	-	-	-	100	0.75	477
Carriage feed Motor	100	0.38	478	150[#]	0.41	487	100	0.60	483
Air Compressor	60	0.86	474	40	0.64	485	300	0.60	467
Chipper	150	0.40	494	150	0.42	487	300	0.35	478
Chip Blower	30	0.62	474	30	0.48	487	-	-	-
Dust Collector	15	0.81	475	37[#]	-	-	-	-	-
Log turner	40	0.47	474	-	-	-	20	0.44	483
Conveyor	-	-	-	15	0.48	487	-	-	-
Barn Sweep	-	-	-	5	0.48	487	-	-	-
Log Deck	-	-	-	-	-	-	20	0.76	480
Line Bar Hydraulic	-	-	-	-	-	-	10	0.46	460
Unlogged Motors	163	-	-	30	-	-	256	-	-
Total	**968**	-	-	**817**	-	-	**1,686**	-	-

***** Average values, hp – motor horsepower, PF – power factor, #Chipper and Dust Collector were monitored together

Table A.21: Electrical Parameters of Sawmill Motors

	Sawmill 3			Sawmill 4		
Motor	***hp***	***PF****	***Voltage****	***hp***	***PF****	***Voltage****
Head saw 1	172.5	0.77	476	200	0.71	468
Head saw 2	172.5	0.77	476	150	0.73	465
Carriage feed motor 1	150	0.71	468	150	0.67	465
Carriage feed motor 2	150	0.71	468	100	0.65	467
Chipper	200	0.84	465	200	0.69	469
Debarker 1	210	0.76	474	40	0.81	463
Debarker 2	-	-	-	40	0.79	464
Edger 1	200	0.79	465	100	0.71	471
Edger 2	-	-	-	75	0.75	469
Air compressor	150	0.99	479	100	0.85	472
Gang Saw	418	0.88	470	-	-	-
Trimmer	180	0.81	466	57.5	0.72	465
Sorter Chain	50	0.63	470	-	-	-
Hydraulic Pump	60	0.83	464	-	-	-
Log Turner	-	-	-	20	0.65	462
Unlogged Motors	517.5			301.5	-	-
Total	**2,630.5**	-	-	**1,534**	-	-

***** Average values, hp – motor horsepower, PF – power factor

Table A.22: Stepwise Regression for Model 1

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is SEC on 10 predictors, with N = 108

Step	1	2	3	4	5	6	7	8
Constant	45.51	-14.91	-14.69	-15.01	-37.84	-25.82	-27.23	-28.19
Motor hp	0.0466	0.0545	0.0456	0.0533	0.0724	0.0744	0.0789	0.0818
T-Value	9.20	12.58	10.45	9.01	12.96	14.82	14.73	20.60
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Density		1.20	1.34	1.27	1.05	0.78	0.80	0.78
T-Value		7.08	8.56	7.92	7.75	5.86	6.10	6.05
P-Value		0.000	0.000	0.000	0.000	0.000	0.000	0.000
Double Line			18.3	15.0	8.3	9.7	3.4	
T-Value			4.76	3.59	2.33	3.01	0.80	
P-Value			0.000	0.001	0.022	0.003	0.424	
4 to 8 Qtr + Pallet				-0.00027	-0.00139	-0.00172	-0.00162	-0.00163
T-Value				-1.91	-7.03	-9.12	-8.45	-8.61
P-Value				0.059	0.000	0.000	0.000	0.000
Min					0.078	0.105	0.106	0.107
T-Value					7.03	9.32	9.51	9.75
P-Value					0.000	0.000	0.000	0.000
Cant + Tim						-0.00185	-0.00223	-0.00231
T-Value						-5.11	-5.62	-6.01
P-Value						0.000	0.000	0.000
Resaw							-8.8	-11.0
T-Value							-2.16	-3.67
P-Value							0.034	0.000
S	19.7	16.2	14.8	14.6	12.0	10.8	10.6	10.6
R-Sq	44.38	62.36	69.10	70.15	79.89	84.02	84.73	84.63
R-Sq(adj)	43.86	61.64	68.21	68.99	78.90	83.07	83.66	83.72
PRESS	42558.5	29414.0	24698.5	24263.4	16656.1	13809.7	13515.4	13304.6
R-Sq(pred)	42.19	60.05	66.45	67.04	77.38	81.24	81.64	81.93

Table A.23: Stepwise Regression for Model 2

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is SEC on 9 predictors, with N = 108

Step	1	2	3	4	5	6	7	8	9
Constant	156.15	116.15	79.07	71.23	80.29	79.89	66.39	76.15	93.31
Maint	-19.7	-24.3	-20.3	-17.8	-18.8	-18.8	-16.0	-14.0	-13.2
T-Value	-7.44	-10.32	-8.85	-7.37	-8.42	-8.62	-6.37	-7.35	-8.26
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Density		1.24	1.21	1.30	1.37	1.37	1.40	0.89	0.64
T-Value		6.50	6.97	7.57	8.63	8.75	9.06	6.89	5.53
P-Value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Temp			0.52	0.41	-0.01				
T-Value			4.78	3.62	-0.07				
P-Value			0.000	0.000	0.942				
Double Line				12.6	30.5	30.3	28.6	29.6	24.6
T-Value				2.75	5.18	6.85	6.51	8.91	8.53
P-Value				0.007	0.000	0.000	0.000	0.000	0.000
Resaw					19.6	19.4	14.4	29.3	19.5
T-Value					4.37	5.91	3.67	8.58	6.05
P-Value					0.000	0.000	0.000	0.000	0.000
hp x Min							0.00001	0.00009	0.00011
T-Value							2.20	9.09	12.58
P-Value							0.030	0.000	0.000
4 to 8 Qtr + Pallet								-0.00198	-0.00222
T-Value								-8.82	-11.62
P-Value								0.000	0.000
Cant + Tim									-0.00223
T-Value									-6.66
P-Value									0.000
S	21.4	18.1	16.5	16.0	14.8	14.7	14.4	10.9	9.10
R-Sq	34.31	53.14	61.58	64.20	69.85	69.85	71.21	83.74	88.74
R-Sq(adj)	33.69	52.25	60.47	62.81	68.37	68.68	69.80	82.78	87.95
PRESS	50139.3	36604.6	30304.4	28851.0	24871.8	24413.5	23795.9	13712.0	10398.0
R-Sq(pred)	31.89	50.28	58.84	60.81	66.22	66.84	67.68	81.37	85.88

Table A.24: Stepwise Regression for Model 3

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is SEC on 9 predictors, with N = 108

Step	1	2	3	4	5	6	7	8	9
Constant	156.15	116.15	79.07	71.23	80.29	79.89	71.29	98.59	122.20
Maint	-19.7	-24.3	-20.3	-17.8	-18.8	-18.8	-18.3	-25.7	-28.3
T-Value	-7.44	-10.32	-8.85	-7.37	-8.42	-8.62	-8.49	-12.08	-14.73
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Density		1.24	1.21	1.30	1.37	1.37	1.40	1.04	0.80
T-Value		6.50	6.97	7.57	8.63	8.75	9.07	7.38	6.10
P-Value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Temp			0.52	0.41	-0.01				
T-Value			4.78	3.62	-0.07				
P-Value			0.000	0.000	0.942				
Double Line				12.6	30.5	30.3	29.8	35.1	31.7
T-Value				2.75	5.18	6.85	6.88	9.41	9.54
P-Value				0.007	0.000	0.000	0.000	0.000	0.000
Resaw					19.6	19.4	17.0	38.0	31.5
T-Value					4.37	5.91	5.03	8.92	8.04
P-Value					0.000	0.000	0.000	0.000	0.000
Min							0.0177	0.0793	0.1055
T-Value							2.21	6.90	9.51
P-Value							0.029	0.000	0.000
4 to 8 Qtr + Pallet								-0.00142	-0.00162
T-Value								-6.61	-8.45
P-Value								0.000	0.000
Cant + Tim									-0.00223
T-Value									-5.62
P-Value									0.000
S	21.4	18.1	16.5	16.0	14.8	14.7	14.4	12.1	10.6
R-Sq	34.31	53.14	61.58	64.20	69.85	69.85	71.22	79.91	84.73
R-Sq(adj)	33.69	52.25	60.47	62.81	68.37	68.68	69.81	78.72	83.66
Mallows Cp	329.3	207.1	153.4	138.1	102.9	100.9	93.8	38.5	8.7
PRESS	50139.3	36604.6	30304.4	28851.0	24871.8	24413.5	23730.7	16910.0	13515.4
R-Sq(pred)	31.89	50.28	58.84	60.81	66.22	66.84	67.77	77.03	81.64

Table A.25: Stepwise Regression for Model 4

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15

Response is Total kWh on 9 predictors, with N = 108

Step	1	2	3	4	5	6	7	8	9
Constant	-287.3	374.4	547.0	383.1	394.8	553.4	563.0	393.0	345.2
hp x Min	0.00534	0.00510	0.00513	0.00515	0.00491	0.00492	0.00470	0.00456	0.00449
T-Value	73.94	75.54	85.18	88.92	70.47	73.05	40.17	36.68	38.66
P-Value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Maint		-197	-225	-180	-211	-219	-221	-234	-236
T-Value		-7.36	-9.25	-6.71	-8.52	-9.11	-9.37	-10.06	-10.16
P-Value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cant + Tim			-0.0258	-0.0271	-0.0128	-0.0120	-0.0117	-0.0070	
T-Value			-5.39	-5.90	-2.58	-2.50	-2.48	-1.44	
P-Value			0.000	0.000	0.011	0.014	0.015	0.152	
Double Line				143	258	361	342	375	395
T-Value				3.33	5.81	6.49	6.19	6.87	7.45
P-Value				0.001	0.000	0.000	0.000	0.000	0.000
Resaw					243	326	277	281	315
T-Value					5.17	6.08	4.87	5.10	6.32
P-Value					0.000	0.000	0.000	0.000	0.000
Temp						-3.8	-3.4	-3.8	-4.0
T-Value						-2.90	-2.60	-3.00	-3.13
P-Value						0.005	0.011	0.003	0.002
4 to 8 Qtr + Pallet							0.0056	0.0093	0.0100
T-Value							2.22	3.35	3.65
P-Value							0.029	0.001	0.000
Density								4.8	5.6
T-Value								2.86	3.55
P-Value								0.005	0.001
S	231	189	168	160	143	138	136	131	132
R-Sq	98.10	98.75	99.02	99.11	99.30	99.35	99.38	99.43	99.42
R-Sq(adj)	98.08	98.72	98.99	99.08	99.26	99.31	99.34	99.38	99.38
PRESS	5841286	3907799	3139170	2888926	2355002	2220127	2132237	2018104	2027969
R-Sq(pred)	98.04	98.69	98.95	99.03	99.21	99.26	99.29	99.32	99.32

Table A.26: Unlogged Motors in Sawmill 1 to 5

Sawmill 1	
Motor Name	**Motor size (hp)**
Off bearer	3
Carriage Setworks	5
Infeed Cant deck	9
Infeed /outfeed rollers	3
cant cross over deck	3
Jump Chains	3
Trim Saw 1	3
Trim Saw 2	3
Trim Saw 3	3
Trim Saw 4	3
Trim Saw 5	3
Green Chain	5
Transfer chain	5
Oversize Belt	10
Vibrating Conveyor	5
Rotary Screen	8
Infeed debarker Deck	10
Debarker Hydraulic pump	10
Debarker Drag Chain	5
Small saw dust belt	2
Desk conveyor 1	3
Desk conveyor 2	3
Desk conveyor 3	3
Desk conveyor 4	3
Webster vibrating conveyor	5
Knife Grinder	5
Rip Saw	40
Total	**163**

Sawmill 3	
Motor Name	**Motor size (hp)**
Hydraulic Pump Carriage	27.5
Hydraulic Log Turner	30
Hydraulic Pump Carriage	30
Hydraulic Log Turner	30
Hydraulic Board descrambler	20
Hydraulic Transfer Chains	20
Center Line Chain	25
Package Outfeed Chains 1	15
Package Outfeed Chains 2	20
Unscrambler pump	20
Conveyor and Rolls pump	30
Sorter Pump	50
Haul out Chains	20
Unscrambler pump	20
Stacker and lift pump	20
Out feed pump	20
Trimmer block belt	15
Vibrator	15
Chip Transfer bin	15
Air Compressor	75
Total	**517.5**

Sawmill 2	
Motor Name	**Motor size (hp)**
Hydraulic Board descrambler	15
Vibrating Conveyor	15
Total	**30**

Sawmill 5	
Motor Name	**Motor size (hp)**
Hydraulic Log Turner	30
Hydraulic Board descrambler	20
Hydraulic Transfer Chains	20
Center Line Chain	15
Package Outfeed Chains 1	15
Package Outfeed Chains 2	20
Unscrambler pump	20
Conveyor and Rolls pump	20
Sorter Pump	25
Vibrating Conveyor	6
Hydraulic Pump Carriage	20
Hydraulic Log Turner	25
Hydraulic Pump Carriage	10
Unscrambler	5
Cross tie outfeed	5
Total	**256**

Sawmill 4	
Motor Name	**Motor size (hp)**
Infeed Decks	20
Hydraulic Power Units	20
Inside Feed Decks	30
Carriages	10
Drop Belts	20
Edger Feed Motor	5
Roll Case Drive	10
Collection Deck	7.5
Unscrambler	5
Cross tie outfeed	5
Sawdust + Chip Belts	6
Sawdust + Chip Augers	20
Cross over Belts	6
Sawdust Chain	5
Log turners hydraulic power unit	40
Dust Collector	15
Sawdust Conveyor	5
Hydraulic Power Unit Edger	10
Main dust Conveyor	15
Short dust Conveyors	9
Chip Conveyor	5
Shaker	5
Grading Deck	5
Green Chain	15
Cooling Fans	3
Total	**301.5**

Table A.27: Operation Cost Report of Sawmill 4 for Sawing Poplar during Data Logging Period

PO 5-16 Operation Report

	Date > Species >	5/16/11 PO	5/17/11 PO	5/18/11 PO	5/19/11 PO	date 5 PO	date 6 PO	Run Total PO
Grade	$/MBF	BF	BF	BF	BF	BF	BF	BF
4/4 FAS	$525	6633	13874	9216	9416			39139
4/4 1COM	$350	4527	6654	6628	6204			24013
4/4 2 COM	$300	1965	3719	4659	3557			13900
8/4 FAS/1F	$575	1282	1962	964	1068			5276
8/4 1COM	$400	2516	3546	3008	2238			11308
8/4 2 COM	$300	8140	12192	14178	11656			46166
8/4 3A COM	$500		1008					1008
14X4	$350	4138	6370	7182	5548			23238
1X6	$325	196	201	231	74			702
Total BF Lbr sawn		29397	49526	46066	39761			164750
SEL & BRT		27%	32%	22%	26%			27%
1COM		24%	21%	21%	21%			21%
2COM & LOWER		49%	47%	57%	52%			52%
Lumber value		$11,354.33	$19,731.43	$17,156.08	$15,154.36			$63,396.20
Lumber Avg /MBF		$386	$398	$372	$381			$385
Sawing Time (hr)		7 HRS	10 HRS	10 HRS	9.5 HRS			
Sawing Cost		$4,847.40	$7,000.00	$7,000.00	$6,562.95			$25,410.35
Sawing Cost /MBF Lbr		$165	$141	$152	$165			$154
Debarker 1 BF		9777	18756	16915	13351			58799
Debarker 2 BF		11281	19205	16939	15164			62589
Total BF		21058	37961	33854	28515			121388
# logs sawn 1		93	165	175	133			566
# logs sawn 2		105	143	191	136			575
Total # logs sawn		198	308	366	269			1141
Overrun		40%	30%	36%	39%			36%
		4/4 FAS	4/4 1 COM	4/4 2 COM	8/4 FAS	8/4 1 COM	8/4 2 COM	
BF Lumber SY>KY		39139	24013	13900	5276	11308	46166	139802
$ Lumber SY>KY		$20,547.97	$8,404.55	$4,170.00	$3,033.70	$4,523.20	$13,849.80	$54,529.22
T/L Dust Apulled								
T/L Chips Pulled								
T/L Bark Pulled								
Log Cost		$7,643.70	$13,699.30	$11,649.70	$9,756.81			$42,749.51
Log Avg Cost /MBF		$363	$361	$344	$342			$352
Log Ave BF		106	123	92	106			106
Profit /hr								
Profit /MBF lumber		-$39	-$20	-$32	-$29			-$29
Profit /MBF logs		-$54	-$25	-$44	-$41			-$39
Total Profit		-$1,136.77	-$967.87	-$1,493.62	-$1,165.41			-$4,763.66

Table A.28: Sample Format used for Collecting Saw Blade Material and Maintenance Data Filled by Sawmill 4

How many hours can these saws work between re-sharpening? (Blade life)

Type of Saw	Blade Life
Head Saw	5 HOUR
Resaw	
Edger	1 WEEK
Trimmer	1 WEEK

Time required for re-sharpening (also mention whether it is done in house or sent outside)

Type of Saw	Re-sharpening Time	Place it is Done
Head Saw	1 HR 45 MIN	IN HOUSE
Resaw		
Edger	N/A	OUTSIDE
Trimmer	N/A	OUT SIDE

What is the material of the blade?

Type of Saw	Blade Material	Did the blade material changed recently, then when
Head Saw	SWEDISH Steel	NO
Resaw		
Edger	NOT SURE	
Trimmer	NOT SURE	

Time required to change saw and when will they do that (during production or break time or maintenance)?

Type of Saw	Time required to change saw	Changed during
Head Saw	18 MIN	LUNCH
Resaw		
Edger	30 MIN	AFTER WORK HR
Trimmer	20 MIN	AFTER WORK HR

Saw Parameters:

Equipment	Head Saw	Resaw	Edger	Trimmer
Type of Saw (Circular or Band)	BAND		CIRCLE	CIRCLE
Thickness of Saw	.078		3/16"	3/16"
Length	40'		24"	18"
Width	10"		10"	10"
Diameter	20' LOOP	—	18-20"	18-20"
Number of teeth	240		25	60
Tooth Spacing	2"		1 1/2"	1/2"
Tooth width	.148		1/4"	1/8"
Tooth Angle				
Hook angle	30		30	30
switch width				