The Impact of Vacuum-Drying on Efficiency of Hardwood Products Manufacturing

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Abstract

Increasing global competition, high stumpage and energy prices, and the slowing housing market have challenged the U.S. hardwood lumber industry during the past several years. Many wood product manufactures are trying to remain in business by implementing continuous improvement programs like lean manufacturing. However, the lumber drying process where lumber is kiln-dried in large batches, can significantly increase manufacturing and inventory lead-time; and is a process that tends to limit how "lean" the remaining process can become. Vacuum drying has the potential to reduce drying times, reduce batch sizes and achieve product quality comparable or superior to conventional drying.

The overall goal of this research was to evaluate how vacuum-drying technology could support further lean implementation in manufacturing of hardwood products. Specifically, to estimate conventional and vacuum drying times, quality, and costs for drying 4/4 red oak lumber; to determine by the use of feasibility analysis (cash flow, net present value, and internal rate of return) differences between conventional and vacuum drying for 4/4 red oak lumber; and to determine if the high capital cost of vacuum drying equipment can be justified with the reduction of WIP and cycle time, while meeting desired throughput. The study includes a cost analysis of vacuum and conventional drying, and a determination of the potential financial gains associated with the reduced drying times via vacuum drying.

It was determined that vacuum drying quality was equal or better than conventional drying with less checking, end splits, drying stress and shrinkage. Compared to conventional drying, vacuum drying times with air drying and without air drying were 67% less and 70% less, respectively. Conventional and vacuum with no air drying scenarios were determined to be financially feasible when compared using Net Present Value and Internal Rate of Return analysis. However, vacuum drying with no air drying had better NPV and IRR values than conventional drying. The scenario of vacuum with air drying was not feasible. Two case studies, each employing the three drying scenarios (conventional drying, vacuum with air drying, and vacuum without air drying), were used to determine the impact of cycle times and work in process. It was determined that the cycle times for vacuum drying were 87% and 95% less than conventional drying for the first case study and 51% and 90% less than conventional drying for the second. WIP was 48% and 84% less in the first case study and 43% and 92% less than conventional drying for the second. Cycle time was reduced by 87% and 51% for Plant C and D, respectively. Finally it was determined that the reduction of WIP represented a cost saving of 73% and 76% for the two case studies. The reduction in costs, faster drying rates, and equal quality, and reduced cycle times make vacuum drying a potential technology available for improvement of the competitiveness for flooring manufacturers.

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CHAPTER 1

INTRODUCTION, OBJECTIVES, AND PROBLEM STATEMENT

1.1 INTRODUCTION

Lumber is the most important product derived from hardwood forests in the eastern United States (Luppold and Bumgardner 2008). However, the U.S. hardwood lumber industry has faced many challenges during the past several years. Increasing global competition, high stumpage and energy prices, and the slowing housing market have been some of the major reasons for declining production in the U.S. (Buehlmann et al. 2007, 2010; Buehlmann and Schuler 2009; Gazo and Quesada 2005; Grushecky et al. 2006; Pepke et al. 2010). Czabke et al. (2008) stated that in the last decade, the US-American and German wood and wood-based industries have suffered significant market share losses, due to growing competition. An example of this is the increase in wood product imports from China due to weaker regulations, their ability to build furniture, and an abundant supply of cheap labor (Bo et al. 2006).

Wood products industries need to change their business model in order to remain competitive and one way to increase competitiveness is by implementing continuous improvement programs. Continuous improvement programs include initiatives to reduce lead times and inventory produce in very small batches, gear production toward demand instead of stock replenishment, and improve quality (Quesada and Buehlman 2011), all of which fit under the concept of lean manufacturing.

Lean manufacturing is a system that focuses on delivering customer value while minimizing waste. Lean manufacturing incorporates strategies and tools such as just-in-time manufacturing and cellular plant layouts to reduce production costs by increasing product quality, speed of delivery, and reducing inventory (Hansen 2005). Though lean manufacturing is widely used in many industries, the system is infrequently used by U.S. wood product manufactures since the raw materials used are highly variable and periodically unavailable. Lean manufacturing implementation in the wood industry requires substantial planning, testing and new approaches (Hansen 2005).

Lead-time reduction has become a common goal for wood product supply chains. However, the drying process remains elusive to these efforts in the hardwood industry. Water must be removed from the wood prior to its manufacture into goods such as flooring, furniture and other mill work; therefore, it must be dried. Lumber is normally kiln-dried in large batches, which consumes a large percentage of the total manufacturing time. Drying times can vary greatly, for example, 4/4 hardwood lumber can range (From 4 to 30 days) depending on species, initial moisture content and method of drying, When lumber is air-dried first, the total drying time is much longer. For example, air-drying red oak from green to 20 % MC takes 60 to 120 days (Simpson 1991). Air drying is often done to reduce drying costs and increase kiln throughput. Research is needed on alternatives to conventional drying technology that would allow manufacturers to achieve a leaner production system.

According to the lean manufacturing philosophy, improvements in product mix (e.g. species, size, and grade) and time flexibility can lead to higher customer satisfaction, reduced costs and increase competitiveness (Quesada and Buehlman 2001). Vacuum drying has the potential of achieving shorter drying times, drying smaller and mixed (two or more species) loads, and achieving at least the same drying quality as conventional drying, while allowing delivery of the product to the customer on time. These potential benefits can help to improve the overall hardwood supply chain in the U.S. and hopefully increase competitiveness.

Vacuum drying of hardwood lumber has been proven (particularly in Europe and in the USA) in many applications to be a more economical alternative to drying using conventional methods, with similar or better quality outcomes (Savard et al. 2004). Vacuum drying allows drying at low temperatures, and faster drying with fewer defects. Water in wood at sub-atmospheric pressure can be vaporized and moved at temperatures below 100 ^{o}C as rapidly as for high temperature drying at atmospheric pressure. Therefore, vacuum drying has the benefits of high temperature drying without the danger of developing defects in some susceptible species.

Vacuum technology is well suited for thick and refractory species that are commercially desirable such as oak (Hee-Suk et. al2004).

In a very demanding market, a one-day difference in lead time can improve the competitiveness of an industry. Consequently, any reduction in drying time can have great potential benefits (like small batches, reduced costs, less inventory spaces, and faster throughput) for wood product manufacturers. In addition, the industry could benefit from a technology that allows it to dry lumber rapidly and in small batches, avoiding the need to dry mixed loads (different species at the same time), which can lead to a higher occurrence of drying defects and longer drying times, or to accumulate excessive lumber inventories (Rice et. al 1994).

As the secondary wood products industry tries to increase their competitiveness, many are moving towards using business improvement concepts such as lean manufacturing. However, no matter how streamlined and efficient a hardwood manufacturing and supplying process can be, one single process contributes to the bulk of process lead-time: the drying of lumber. For example, one supply chain study found that in the production of kitchen cabinets, lumber drying takes up to 60 percent of the total lead-time (Espinoza 2009). Research is needed to develop the best alternative for traditional lumber drying that would reduce lead times, allowing for order flexibility, while maintaining quality and reducing costs.

Vacuum drying technology has the potential to dry very small batches of lumber in very short times, and with comparable or better quality. However, this technology has not been as widely adopted as its advantages would suggest. Probable reasons for its limited implementation include higher initial cost of equipment (especially when heating is carried out by radio frequency), higher complexity of maintenance and operation than conventional drying, and industry resistance to change. Research is very limited regarding the economic and technical feasibility of vacuum drying compared to traditional drying methods from a present value of the investment, rate of return on investment and total unit cost perspective. Benefits of this technology, mainly dramatically reduced drying times and higher flexibility, must be weighed against a higher initial investment. Lean manufacturing can lead to higher customer satisfaction and reduction of inventory. Such potential benefits, if successfully implemented, can help sustain a more effective hardwood supply chain in the U.S. and make the wood products industry more competitive.

1.2 Objectives:

The overall goal of the project is to evaluate vacuum-drying technology and its economic feasibility to support the lean manufacturing of hardwood products compared to conventional drying technology. The specific objectives are:

1.1.1 To estimate conventional and vacuum drying times, quality, and costs for drying 4/4 red oak lumber

1.1.2 To determine by the use of feasibility analysis (cash flow, net present value, and internal rate of return) differences between conventional and vacuum drying for 4/4 red oak lumber

1.1.3 To determine if the high capital cost of vacuum drying equipment can be justified by the reduction of WIP and cycle time, while meeting desired throughput.

1.3 Potential Outcomes

This research will result in the development of information for the hardwood industry about alternatives to conventional drying, which should lead to improve lead-times and reduced costs. The expected potential outcomes are the following:

a) An economic feasibility analysis of conventional and vacuum-drying for 4/4 red oak lumber used for flooring manufacturing.
b) A value stream map and future state map for two case studies of hardwood flooring manufacturing based on one part of their line production: 3.25” red oak pre-finished and un-finished flooring.
c) A demonstration of how WIP, throughput and cycle time can be reduced in hardwood flooring manufacturing through the adoption of vacuum drying technology.

CHAPTER 2

LITERATURE REVIEW

This chapter is a review of the technologies of conventional and vacuum drying, lean manufacturing, and simulation. Information regarding types of conventional and vacuum kilns, drying times, drying quality and drying costs is described from section 2.1 to 2.10. Section 2.11 describes the concepts of lean manufacturing, value stream map and future state map. The last section, 2.12, is about the description of simulation, Simio^{TM} software and how lean manufacturing can be combined with simulation.

2.1 WOOD DRYING

Drying is very important step for hardwood manufacturing because it helps to produce a product with less quality losses, and at the same time improves profit. For example, lumber with less than 20% maximum moisture content has little risk of developing stain, and decay. Mechanical properties, such as modulus of rupture, modulus of elasticity, compressive strength, and shear strength, increase with decrease in moisture content. Removal of excess water reduces weight, which also reduces shipping and handling costs. Properly dried lumber can be cut to precise dimensions and machined more easily and efficiently. Also, finishes like paint and varnish can be more effectively applied and maintained (Jia 2006).

The main goal of drying is to remove moisture content. Moisture content can be defined as the amount of water contained in wood, which can be presented as free or bound water. Free water refers to the water contained in the cell cavities, and bound water is the water that is presented between the cell walls.

The movement of water or removal of moisture content occurs in four ways during the drying process: (1) liquid water moving through cell structure by capillary action, or free water bulk flow; (2) water vapor moving from high pressure to low pressure zones, or water vapor bulk flow; (3) water vapor diffusion, due to relative humidity gradients; and (4) water molecules from cell walls through diffusion due to differences of moisture content (Chen 2003; Simpson

1991). Above fiber saturation point (FSP) the limiting factor is energy transfer; below FSP, mass transfer becomes the controlling factor (Koumoutsakos et. al 2001). As drying progresses, less free water is available and most of the mass transfer occurs by diffusion, which is a much slower process than bulk flow (Rosen, 1980), thus temperature is increased significantly in the late stages of drying to maintain an optimum drying rate. Although, longitudinal diffusion is 10 to 15 times faster than transversal diffusion, this difference is more than offset by the relatively large ratio between length to width (or thickness) of lumber.

Drying is affected by environmental factors such as temperature, relative humidity and air flow. Wood is often dried using a single method, such as kiln drying, or via combined methods, such as air drying and then kiln drying. A combination of methods is usually used to increase the throughput of dry kilns and reduce the drying cost for slow drying species or thicknesses.

Air drying is where the lumber is placed outdoors and the natural flow of air and heat from the sun is used for drying the wood. The lumber is stacked in piles allowing the air to pass through the pile and dry the wood. It is often the most economical and energy saving method to remove water from wood (Dening et. al 2000). Usually, it is used to obtain a moisture content of 20-25% and then the drying process is complemented by kiln drying to achieve a final average moisture content of 7-8% (Forest Product Laboratory1999).

The drying rate completely depends on the weather conditions, which means that the temperature, relative humidity and air flow cannot be controlled. Degrade is frequent due to rainy periods or excessive sunny periods, which can increase checks, splits or warp, for example. Also, the drying times are longer which causes excessive inventories (Dening et. al 2000).

One of the advantages of air drying is that is a method that reduce energy costs. Dening et. al (2000) established that each 1% of moisture content removed by the use of air drying can save around 50 to 85 BTUs per board feet; while for a kiln drying of 50 MBF, each 1% moisture content that is removed can save approximately 2.5 to 4.25 x 10^6 BTUs (Dening et. al 2000).

Kiln dying consists of using one or more chambers that are designed to provide and control temperature, relative humidity and air flow for the proper drying of wood. During kiln drying, schedules are used to control the temperature, relative humidity, and air flow, allowing the lumber to dry at a safe rate without producing degrade. Drying schedules vary by species, thickness, and grade.

The designs of the kilns have changed through years. There has been modification in the mechanism of heat, the arrangements of the fans, and the control of relative humidity or wet bulb temperature. Also, different materials have been used for the chamber construction. Section 2.2 and 2.3 will describe two types of kiln drying: conventional and vacuum.

2.2 CONVENTIONAL DRYING

Conventional drying refers to air drying + kiln drying. Kiln drying is performed in a closed chamber or building in which air is rapidly circulated over the surface of the wood being dried. The initial drying temperatures that are used go from 100° to 170° F and final temperatures from 150° to 200° F. Control of relative humidity or EMC is necessary to avoid shrinkage-associated defects and to equalize and condition the wood to the degree of precision needed (MacMillen et. al 1978).

Air velocities through the load in drying hardwoods generally are between 200 and 450 feet per minute and are required for uniform evaporation of water from the surface of lumber and to bring heat to the lumber. Moreover, the temperature and the relative humidity are managed by semiautomatic dry- and wet-bulb temperature recorder-controllers (MacMillen et al 1978). In general, for drying hardwoods, two types of conventional kilns are used: 1) package-loaded compartment kilns and 2) track-loaded compartment kilns. There are two basic heating systems: steam and hot air (or direct-fired). The most common are steam-heated. However, the direct-fired kiln, with supplemental steam or water spray for humidification, has been used occasionally for hardwoods (Simpson 1991).

A conventional dry kiln is usually composed of the following parts (Rubberwood Processing Manual 2007):

a) Kiln body and door: metal structure framework.
b) Air circulation system: the air inside kiln is circulated by fans, which are directly connected to motors, and located in the upper side or end position inside the kiln.
c) Heating and spraying system: the heat sources are steam or hot water.
d) Temperature and humidity system: The temperature and humidity detection usually use dry and wet bulb temperature method, and the moisture content detection could use weighing or electric resistance methods.
e) Stacking and stack transportation system: this system consists of folks, or stacking machine, stack trolley, and unstacking machine.
f) Lab equipment: includes electric oven with fan inside, electric balance, moisture content meter, air speed meter, saws, ruler, digital vernier calipers, and record paper.

2.3 Vacuum drying

The primary force in vacuum drying of wood is the total pressure difference between the wood and the chamber rather than diffusion as in conventional drying. The prevailing control in the moisture transfer mechanism is water vapor bulk flow from the ends and diffusion through the lateral faces (Chen 1998; Waananen et. al 1993).

Moreover, when temperatures approach the boiling point of water, steep total pressure differences are caused by the fast generation of vapor (Waananen et. al1993), contributing to the acceleration of the moisture movement through wood. Free water, in both liquid and vapor phases, travels in the longitudinal direction, and bulk flow is accelerated by the much greater longitudinal permeability [longitudinal-to-transverse ratios ranging between 30,000 to 400,000,000 (Siau, 1984)], which causes water to migrate lengthwise, leaving the individual lumber pieces through the ends (Avramidis and Zwick, 1992; Zwick and Avramidis, 2000). Consequently, the movement of water through wood increases, leading to shorter drying times than can be achieved at atmospheric pressure, and with similar or better quality than conventional drying.

2.3.1 Types of Vacuum Drying Systems

Vacuum drying heat transfer needs to be done continuously. This characteristic leaded to the development of different methods to transfer heat to wood. Vacuum drying can be separated into four types (Chen and Lamb 2003) based on the method of transferring heat to the wood:

a) Convection using hot air as in cyclic systems
b) Radio-frequency dielectric heating.
c) Conduction by direct contact with a hot plate or electric heating blanket.
d) Convection using superheated steam at high temperature.

In cyclic vacuum drying, lumber is heated up and then a vacuum is drawn in the chamber. Drying occurs while there is temperature gradient and pressure difference between the ambient and inside the wood. Wood temperature drops rapidly and then the cycle is repeated. There are two distinct phases: rapid drying and then as drying slows down when the pressure inside the material approaches the ambient pressure (Chen and Lamb 2003).

Radio frequency (RF) drying technology constitutes a combination of two special methods: heating by high frequency current and drying in vacuum where the boiling point of water is decreased with decreasing pressure. The intensity of the heating depends directly on the moisture content of the wood and the electric field, while the moisture movement depends on the permeability of the wood and the internal pressure gradient. According to Resch (2006), RF heat penetration can be done with a small electric field, which makes possible the heating of the entire stack of lumber.

Regarding conduction by direct contact with a hot plate, the stacks of wood are laid out between aluminum heating plates. Hot water or oil flows through the plates to heat the lumber to the required temperatures (Kanagawa and Yasujima 1993).

Superheated steam vacuum drying (SSV) consists of a process that uses low pressure conditions to make the superheated steam circulate through the lumber layers producing a vacuum process inside the kiln. Superheated steam has better heat transfer properties than hot air at the same temperature (Kudra 2002). However, steam under vacuum has lower heat capacity (due to lower density) and lower drying rates than with hot moist air used in conventional drying. However, this can be compensated by circulating air at high speeds, of about 10 m/s and with frequent fan reversals (Pang and Pearson, 2004).

2.4 Comparison of Vacuum and Conventional Drying Rates

Any drying technology should meet the following objectives: (1) provide the shortest drying time possible, (2) consume minimum amount of energy, (3) have the lowest drying costs possible, and (4) result in adequate drying quality (Ressel 2002; Wengert, 1988).

Vacuum drying has been shown to be from 3 to 17 times faster than conventional drying (Chan and Lamb 2007). Vacuum drying rates are greatly influenced by permeability, thermal conductivity, and method used for heating the wood. This section focuses on drying times for vacuum drying using radio frequency, microwave and superheated steam.

Drying times using radio frequency heating are significantly shorter than conventional drying, since the temperatures are higher in the lumber core than on the surface. Moyne and Martin (1982) resolved in their study that the acceleration of the drying rate was product of the pressure flow that occurs in vacuum conditions.

Tables 1 and 2 show a brief summary of drying times for various hardwoods and softwoods products using conventional and several different types of vacuum drying technology. The data was gathered from different authors: Fortin (1998), Yamsaengsug (2005), Avramidis et al (1994), and Mottonen (2006), Welling and Riehl (1999), and Harris and Taras (1984), Leiker and Adamska (2004), and Redman (2011).

Table 1. Typical Drying Times for Various Hardwood Products Dried Using Conventional and Several Different Types of Vacuum Drying Technology

Species	Product	Initial State	Drying Time (days)					Reference
			Conventional	Vacuum				
				Superheated steam	Platen	High Frequency	Microwave	
			Hardwood					
Yellow Birch	4/4	Green	15-20	-	2-2.5	-	-	Fortin 1998
		Pre-dried	7-8	-	1-1.5	-	-	Fortin 1998
	8/4	Green	35-40	-	6-7	-	-	Fortin 1998
		Pre-dried	20-25	-	1.5-2	-	-	Fortin 1998
		30%	-	-	-	-	-	Fortin 1998
		Green	30	6	-	-	-	Satho and Yamsaengsug 2005
		Green	13	5	-	-	-	Mottonen 2006
White Oak	8/4	Green	85-95	30	-	-	-	Fortin 1998
Red Oak	4/4	Green	25-30	8-9	-	-	-	Fortin 1998
		Pre-dried	18-22	4	3	-	-	Fortin 1998
		40-45%			-	-	-	Fortin 1998
	8/4	Green	85-95	28-30	-	-	-	Fortin 1998
	8/4	green	63 days	4	-	-	-	Avramidis et al 1994
Mixed of Oak	5/4	Green	42	-	-	3	-	Harris and Taras (1984)
Hard Maple	4/4	Green	10-14	5	1.6	0.6	-	Fortin 1998
		Pre-dried	6-9	3-4	1	-	-	Fortin 1998
		30%	-	-	-	-	-	Fortin 1998
	8/4	Green	30-35	8	2.5-4	6.2	-	Fortin 1998
		Pre-dried	15-20	5-6	3	-	-	Fortin 1998
		30%	-			-	-	Fortin 1998
	4/4	Green	10	3	-	-	-	Satho and Yamsaengsug 2005
	4/4	Green	-	-	-	-	1	Leiker and Adamska (2004)
	8/4	Green	30	-	7	-	-	Satho and Yamsaengsug 2005
Trembling Aspen	2x6	Green	6-7	1.5-2	-	-	-	Fortin 1998
	2x8	-	-	-	-	-	-	Fortin 1998
	2x10	-	-	-	-	-	-	Fortin 1998
	8/4	Green	7-10	2-4	-	-	-	Satho and Yamsaengsug 2005
Black Locust		Green		5-2	-	-	-	Welling and Riehl 1999
Beech	4/4	Green			-	-	4.5	Leiker and Adamska (2004),
Blue spotted gum	4/4	Green	61	25	-	-	-	Redman (2011)

Table 2. Typical Drying Times for Various Softwoods Products Using Conventional and Several Different Types of Vacuum Drying Technology

Species	Product	Initial State	Drying Time (days)					Reference
			Conventional	Vacuum				
				Superheated steam	Platen	High Frequency	Microwave	
Softwood								Fortin 1998
Hemlock-Fir Group	4/4	60-80%	10-12	5-14	-	-	-	Fortin 1998
	3/6	70-91%	9-14	6-7	-	-	-	Fortin 1998
Larch	5/4	Green	7.5-12.5	3-5	-	-	-	Fortin 1998
	4/4	47%	-	22	-	-		Fortin 1998
White Pine	3/10	Green	50-55	-	-	8-9		Fortin 1998
	8x8	Green	-	-	-	18-20	-	Fortin 1998
	4/4	Green	5	-	2	-	-	Satho and Yamsaengsug 2005
Douglas Fir	4/4	30-45%	10-14	1.5-7	-	-	-	Fortin 1998
Subalpine Fir	2/6	62-82%	3-5	2.5-6	-	-	-	Fortin 1998
Red Cedar	6/4	Green	27	-	-	6	-	Avramidis et al 1994
Spruce	4/4	Green	-	-	-	-	2.5	Leiker and Adamska (2004)

It can be seen in Tables 1 and 2 that vacuum drying rates are faster than conventional drying. For example, 4/4 red oak averaged 8 days when it is dried from the green state and 4 days when it is air dried; while conventional takes a total of 25 to 30 days from air drying, and then 8 to 9 days kiln drying, or 20 to 30 days when only kiln dried. In the case of 8/4 air dried sugar maple, it can be seen that if sugar maple is platen heated, drying rates are 83% less than conventional; while with superheated steam, drying rates are 69% less than conventional.

In the case of softwoods, vacuum drying rates for 6/4 red cedar are 77% less than conventional drying when lumber is green dried. Douglas fir air dried to 30-45% takes an average of 14 days to be dried by kiln drying and on average 7 days to be dried by using superheated steam. In the case of 5/4 larch, the vacuum drying rate is 50% less than conventional.

According to Tables 1 and 2, vacuum drying has the capacity of drying lumber faster than conventional drying for hardwoods and softwoods.

2.5 Comparison of Vacuum and Conventional Drying Quality

In drying, the most common defects are classified as fracture, distortion, warp, or discoloration. These defects are caused by an interaction of wood properties with processing factors such as drying temperature (Simpson 1991). Drying rate can be defined as the time that it takes to remove water from the wood to a specific or desired moisture content.

In fracture or distortion, the defects that can be further defined are surface and end checks, collapse, and honeycomb. Surface checks occur early in drying when the shell of a board is stressed in tension enough to fracture the wood. End checks occur because of the rapid longitudinal movement of moisture causes the end to dry very quickly and develop high stresses which can lead to fracture. Collapse is a distortion, flattening, or crushing of wood cells caused by shrinkage. Honeycomb is an internal crack that occurs in the later stages of kiln drying when the core of a board is in tension (Simpson 1991).

Warp is any deviation of the face or edge of a board from flatness or any edge that is not at right angles to the adjacent face or edge. Warp can be produced by differences between radial, tangential, and longitudinal shrinkage in the piece as it dries or by growth stresses. Warp is aggravated by irregular or distorted grain and the presence of juvenile and reaction wood. The six major types of warp are bow, crook, twist, oval, diamond, and cup (Simpson 1991)

There are two types of discoloration: chemical and fungal. Chemical discoloration is the result of oxidative and enzymatic reactions with chemical compounds in wood. This can cause the degradation of the cell wall. Chemical discolorations can be presented in the wood as pinkish and yellowish hues through gray and reddish brown to dark brown shades. Fungal stains are usually bluish discolorations in the wood caused by mold fungi, decay fungi, bacteria, and others. Generally, stains may be caused by fungi that grow in the sapwood (Simpson 1991).

As an alternative, vacuum drying has the potential to improve the quality of dried wood products. Vacuum drying increases water movement within the wood; as a result, the severity of the moisture gradient is reduced. Drying in these conditions can result in less internal stress, so checks and splits are less likely to develop. Some vacuum drying systems like platen and high frequency are appropriate to the application of a constant top load, which minimizes warp problems during the drying process. According to Rice and Wengert (1987), Virginia Tech in the mid-1980s conducted several runs in a commercial vacuum kiln with heated platens, drying several hardwood and softwood species, from ¾ to 4 in. in thickness. They reported overall quality to be good, with little checking.

In a study conducted by Leiker and Adamska (2004) on beech, spruce and maple, the authors reported that surface checks and honeycomb were absent, except when overheating was forced. However a moisture distribution was present and for 50mm samples, the MC was lowest at the center and maximum in the layer immediately below the surface. Consequently, Wengert and Lamb (1982) evaluated several methods for drying 5/4 and 8/4 red oak lumber. They recorded the number of the drying checks in lumber dried by radio frequency vacuum (RFV), cyclic vacuum drying and pre-drying followed by kiln drying. Vacuum drying had substantially fewer checks including end, surface and internal checks. They also found that RFV had less crook (36% less than pre-dried). Simpson (1987) dried red oak of 4/4 and 10/4 thicknesses using a heating blanket vacuum system and reported no surface checking and low (2 to 2.2%) honeycombing. Avramidis et al. (1994) found no internal and surface checks in RFV.

In vacuum drying technology oxygen is reduced, which reduces the incidence of chemical discoloration caused by the oxidation of certain natural compounds in the wood (Fortin 1998). Moldrup (1992) established that with vacuum drying, lumber is similar in color after drying to the color before it. A study carried by Welling and Riehl (1999) using *Robinia psuedoacacia,* determined that using high pressure steam treatment temperatures, ranging from 100 – 140ºC, (maximum vessel pressure of 13 bar) can produce the desired brown colors while also reducing case hardening defects as a final conditioning stage of drying. In a study performed by Rice and Wengert (1987), the authors reported very good color for several hardwood and softwood species after been dried with heated platens.

RF drying has several advantages over conventional drying, like no wood extractive staining, reduced surface checking, no internal stresses, and good MC uniformity. Degrade is about half of that of conventional drying, and shrinkage is also reduced (Avramidis, 1999). In a laboratory-scale experience, thick squares (4 and 10 inches thick) of western red cedar and hemlock were dried in 24 and 32 hours, respectively. Drying quality was good, measured by shell and core MC differences (around 0.65 percent, compared with 8-12 percent in conventional drying) total shrinkage about half compared to conventional drying, no internal checking, and no discoloration (Avramidis and Zwick, 1992).

2.6 Property Changes in Vacuum Drying

Wood is an anisotropic material, which means that its dimensions change differently in three directions: tangentially, radially, and longitudinally. Dimensional changes, shrinkage, and swelling in wood take place below the fiber saturation point (FSP) where all of the water exists only within the cell wall. The method of how water is removed between vacuum and conventional drying can lead to differences in the amount of shrinkage that takes place, thus there are also differences in the type and amount of drying stresses.

Wood shrinks and swells differently in each plane of reference. Longitudinal shrinkage occurs because of the orientation of the micro fibrils in the S-2, so as the wood dries there is a measurable shortening of the cell. Longitudinal shrinkage is considerably larger in compression wood than in normal wood. Differences with the transverse plane are due to the alternation of late wood and early wood increments within the annual ring, influence of wood rays on the radial direction, and the chemical composition of the middle lamella. Meanwhile, tangential shrinkage is greater than radial shrinkage due to the presence of ray tissue, frequent pitting on radial walls, domination of summerwood in the tangential direction, and differences in the amount of cell wall material radially versus tangentially (Simpson 1991).

The shrinkage of red oak lumber dried by RFV was measured by Harris and Taras (1984) to be approximately 30% less than that dried by conventional kiln drying. For RFV, red oak was dried from green to 5.5% MC with an average shrinkage of 4.1% radially and 7.5% tangentially. By comparison, in conventional drying, red oak dried from green to 7.8% MC, had shrinkage values of 5.6% and 10.3% in the radial and tangential direction respectively. In comparison with dehumidification drying and conventional kiln drying, lumber dried by RFV has lower compressive strength, bending stiffness, bending strength, shear strength, and hardness. However these differences are not statistically significant except for compressive strength (Taniguchi and Nishio 1991, Lee and Harris 1984). There was no difference in hardness or toughness between oak lumber dried by RFV and by conventional kiln drying according to Wengert and Lamb (1982).

Regarding stresses, Harris and Taras (1984) found that drying stresses in vacuum drying are similar to those in conventional kiln drying. They also stated that smaller residual stresses and less degrade were found for lumber that was cyclic vacuum dried compared to lumber that was conventionally dried. However, Trofatter et al (1986) reported that conventional kiln drying maintains a lower moisture gradient through the board thickness than RFV does. The variation among boards ranges from 2 to 28% MC for RFV compared to 7 to 11% MC for conventional drying.

2.7. COMPARISON OF METHODS TO DETERMINE DRYING LUMBER COSTS

One of the goals of this project is to estimate conventional and vacuum drying costs for drying 4/4 red oak lumber. To be able to achieve this comparison, a methodology for calculating the costs associated with each method must be developed. Literature describing how to determine the cost of lumber drying has been analyzed and is presented in this section.

There have been many published methods for determining the costs associated with of drying lumber, which range from basic cost accounting methods to more in-depth feasibility analyses. The cost accounting approach is used to collect, analyze and evaluate a process and to provide detailed cost information that can be used to evaluate the current state and various alternatives. In cost accounting methods, costs are usually divided into two groups: 1) fixed, and 2) variable, where fixed costs do not differ with the volume of production and variable costs do (Stewart 1995). The fixed costs of drying lumber include those associated with energy consumption and the capital investment for equipment, while the variable costs would include labor and maintenance. Basic cost accounting methods are usually used to determine drying costs at a given time or to evaluate specific cost components such as energy. The objective of a feasibility study is to determine if the business prospect of a company can be practical and viable (Hoagland and Williamson 2000). Variables such as tax position, cash flow, capital investment, discounted rate of return, are used to perform the analysis. Examples of this type of analysis include discounted cash flow models or investment analysis. Feasibility study methods, while they incorporate much of the same information used in cost accounting methods (such as the fixed and variable costs associated with production) tend to place more emphasis on providing information that can be used for capital investment decisions. The information provided by these methods includes net present value, discounted rates of return, etc. Since both cost accounting and feasibility analysis include information on the fixed (like kilns and buildings) and variable costs (like energy consumption) associated with lumber drying, these will be reviewed to determine variables appropriate for the model developed for the project.

2.7.1 Cost Accounting Methods

Goulet and Ouimet (1968) published one of the first papers describing an accounting approach for estimating the costs associated with drying lumber. McMillen and Wengert (1978) further developed the methodology so that it could be used in hardwood lumber drying operations. The model was developed to assist those who wanted to conduct a cost analysis of their own drying operations. The authors cautioned that the model was a general overview methodology and not a complete analysis of "all costs and energy use." While the model included variable and fixed cost information for both air-drying and kiln drying, the authors suggested that if more lumber is dried annually using air-drying or kiln drying, a separate analysis should be run for each. This model uses 69 inputs to obtain the drying costs (Appendix I). Fortin (2010) also developed a cost accounting methodology for determining the cost of lumber drying; however, he developed it for Microsoft Excel spreadsheets. His model contains both fixed and variable costs similar to those presented in McMillen and Wengert (1978) (Appendix I), however, his methodology also includes a detailed analysis of the theoretical energy consumed in kiln drying.

Other papers that propose methods for calculating annual drying costs are actually more focused on a particular aspect of the drying process rather than the total overall cost. For example, Reeb (2011) described a methodology for calculating drying costs based on simplified categories of annual fixed and variable costs. However, the main focus of his work was a detailed comparison of different fuels for drying lumber. The model includes 25 variables that are summarized in Appendix I. Redman (2011) developed a model for comparing the costs associated with conventional kin drying and vacuum kiln drying. The goal of his analysis was to determine the size of operation required to make vacuum drying more cost effective than conventional drying for several different species. He divided costs into four main variables: finance, kiln capacity, operational costs and wood characteristics. While the model provides some fixed and variable costs associated with drying, it focuses on costs related to dry *Eucalyptus pilularis and Corymbia*. Costs related to labor for stacking and moving material, land and maintenance costs, etc. are not included.

2.7.2. Feasibility Studies

Drying feasibility studies are focused more on determining the long-term return on investment for a drying operation rather than focusing on only the annual drying costs. However, the annual drying costs, including fixed and variable costs, are important in determining the financial feasibility of a drying operation; therefore, evaluating literature on this subject can provide useful information about what variables should be included in calculating annual drying costs.

Engalichev and Eddy (1970) were some of the first to develop a computer program to evaluate the cash flow for purchasing equipment for drying lumber. Holmes and Bilek (1983) also developed a modified discounted cash flow computer program to analyze the economics associated with lumber drying. The model was based on programs and analyses developed by the authors for other investment decision-making in the forest products industry. The analysis was based on the after-tax time value of investment capital, operating costs, and income cash flows. The computer program uses 70 inputs to estimate the feasibility of a drying operation, including many of the fixed and variable costs associated with determining the annual cost of drying lumber. These inputs are summarized in Table Appendix I.

Govett et. al (2006) developed a model for feasibility or investment analysis of a drying operation using Microsoft Excel. The program, DRYFEAS, consists of a spreadsheet that includes different aspects of the drying process beginning at the year ''0'' of investment and includes the option to analyze the costs to a period of 20 years. The user introduces the required inputs and estimations for the first year, and the amount of years to be analyzed are estimated (Govett et al 2006). One of the goals of the model was to provide the ability to easily change variables to see if the financial performance can be improved. The inputs of the program are divided in main five sections which are: lumber, kiln, and pre-dryer information, process lumber inventory estimates based on green price and kiln usage, dry lumber inventory estimates based on dry price without volume loss to shrinkage adjustment, manufacturing cost data, and other variable costs. The model includes a total of 85 inputs (Appendix). The model also includes a detailed breakdown of the fixed and variable costs used in calculating an annual drying cost or a drying cost per MBF.

2.8 Economic Feasibility study

Three indicators that are often used for developing an economic feasibility analysis are: 1) Cash flow, 2) Net present Value (NPV), and 3) Internal Rate of Return. These three methods help to determine if the performance of a project is economically viable.

Ercan (2011) defined cash flow as: "the difference between inflow and outflow." A cash flow is composed by the cash flow from operations, investment opportunities and financing activities. The cash flow from operations refers to the income that is generated (for example sales), the cash flow of investment opportunities refers to the assets (like equipment and buildings); and the cash flows of financing activities refer to the loan investment and interest rate (Kewon et. al 2006).

Zhang (2009) describes the Net NPV as: “the total present value of all the investment spent on a project subtracted from all the revenue gained from the project over a certain time period. An interest rate is used to discount future spending or revenue into current value.” Arati (2009) describes the net present value (NPV) as: “the sum of the expected net cash flows, measured in today’s dollars. Today’s dollars implies the present value (PV) of receipts and expenditures (cash flows).”

The NPV is used to compare the economic viability between different projects. Present value is calculated by multiplying future expenditures and receipts by the appropriate discount rate, the formula to calculate the NPV is (Zhang 2009):

$$NPV = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+i)^t}$$

Where i: is the interest rate;

t: is the year;

n: is the economic life of a system

R_t: is the revenue earned, which is also the water bill reductions in year t

C_t: are the cost of a system in year t, including initial costs, operation costs and maintenance costs.

A positive NPV indicates that a project is economically viable, while a negative indicates that it is not viable (Zhang 2009). This rule can be helpful when comparing two or more projects to determine which one is more feasible. Some of the advantages in using NPV as a financial tool are the following (Erturk 2011):

1. It shows the overall profitability of a project
2. It provides a very sharp criterion to accept or reject a project: Only the projects having positive NPV should be accepted.

3. If the discounted payback period of a project is lower than the lifetime, NPV helps us to find out the effect of the remaining cash flows after payback period on the profitability of the project.

However, some of the disadvantages that the NPV can show are the following (Erturk 2011):

1. It does not measure the risk of cash flows.
2. Positive NPV only shows that the rate of return of the relevant project is higher than the discount rate, which can be considered as not a sufficient criterion to measure the profitability of a project in terms of the rate of return of the project

The Internal Rate of Return (IRR), according to Zhang (2009), Ercan (2011), and Brealey and Myers (2003), is defined as: "the interest rate that can make NPV equal to zero." Arati (2009) defined the IRR as: "the annualized rate of return that is possible to earn on the newly invested capital." When the NPV is positive, the IRR will be greater than the discount rate; while when the NPV is negative, the IRR will be less than the discount rate (Lang and Merino 1993). This relationship helps to determine if a project is economically feasible, so when the IRR is bigger than the interest rate, the project is considered as feasible (Zhang 2009).

2.9 Lean Manufacturing

The industrial environment is changing; manufacturing organizations are under pressure to improve productivity and quality while reducing costs (Gulshan 2012). Lean manufacturing proposes a simple, feasible, reliable, cost effective, revolutionary, synergistic, and complete philosophy that can be implemented in wood industries to reduce and eliminate waste. In lean manufacturing, waste can be defined as anything that adds unnecessary costs to the product without adding value, where value is defined as the product that a costumer is willing to pay. Therefore, this philosophy helps improve the product flow through process, shortens the manufacturing lead times, reduces defects, and supports continuous improvement (Lean Enterprise Institute 2007).

The lean manufacturing philosophy has evolved from the Toyota production system. Lean manufacturing is a way of thinking, a culture where all employees are supported to continuously look for ways to improve the process with the philosophy of eliminating all non-value added activities. Also, lean thinking discards the traditional pricing formula, which states that (Quesada et al 2011):

Price = cost + profit

Lean thinking focuses on increasing the value to better serve customers and, at the same time, eliminate wastes to increase profits. Under the lean thinking approach, the pricing formula is reformulated to

Profit = price – cost

Therefore, the only way to increase profits is by reducing wastes, thereby reducing costs.

According to Gulshan (2012) waste specifically means any activity that absorbs resources but creates no value. Value is determined by the customer in terms of products and services that meets a need. Derived from the Toyota Production System (TPS), the effort towards meeting the objective of increasing value-added work is to focus on eliminating seven basic types of waste:

1. Over processing: inappropriate or inefficient production steps.
2. Overproduction: producing too much too soon resulting in reduced capacity to fulfill immediate demand.
3. Excessive inventories: excess raw material, work in process, or finished goods that take time, space, energy, and other resources away from fulfilling immediate demand.
4. Waste in motion: walking, reaching, stacking, searching, and any other movement that does not add value.
5. Waiting: periods of inactivity for people, information, or goods.
6. Transportation: unnecessary movement of goods or information.
7. Defects: production of out-of-spec parts or communication errors.

2.9.1 VALUE STREAM MAP AND FUTURE STATE

Value stream mapping (VSM) was developed by Toyota to assist companies with the concept of lean manufacturing. Value stream mapping is a visual representation of the material and information flow of a particular product family (Tapping et. al 2002). It consists of the creation of a current state map and a future state map. The current state map graphically represents the flow of information and material as a product goes through the manufacturing process. The future state map shows the improvements of the system by elimination or reduction of the non-value added activities (Carr 2005). VSM is vital for understanding changes and opportunities for improvement (Quesada and Buehlmann 2011). Figure 2 shows an example or a VSM.

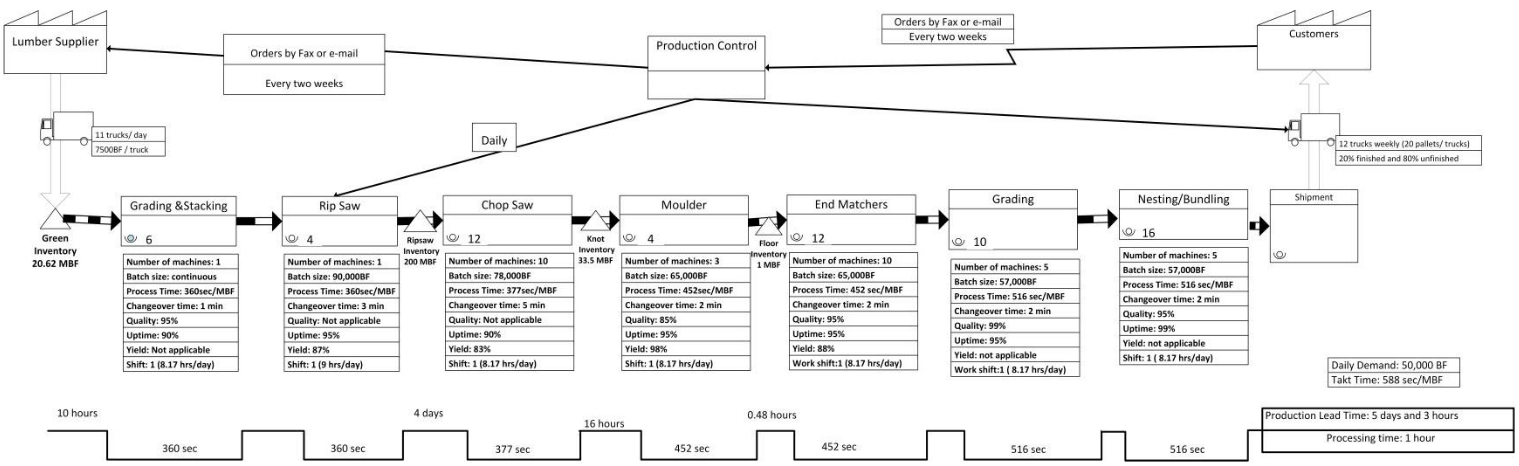


Figure 1. Value Stream Map for a Flooring Manufacturer

2.10. LITTLE'S LAW

Little's Law is a helpful tool for industrial engineers to determine if a production line is working well or not. In lean manufacturing, Little's Law can be helpful to determine the necessary WIP amount that a production line needs to meet customer demand.

In general, production lines are based on three parameters: cycle time (CT), throughput (TH), and work in process inventory (WIP), which are defined as:

a) CT: "average time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing (the time the part spends as WIP)" (Hopp et al 2001).
b) TH: "average output of a production process (machine, workstation, line plant) per unit time" (Hopp et al 2001).
c) WIP: "inventory between the start and end points of a product routing" (Hopp et al 2001).

Little's Law is defined as the relationship between Work-In-Process, throughput and flow time of a production system, and it is represented by the following formula:

WIP= TH *CT

It is used to predict system behavior and validate operational improvements in a variety of production scenarios. Little's Law also provides a measure of the stability in the current system. This measure can provide the maximum achievable operational improvements that a production line or system can have. Little's Law can be applied to a single machine, a production line or a complete manufacturing facility (Rust 2008).

Little's Law uses two key parameters to predict or measure the stability of a system: the bottleneck rate (r_b) and the raw process time (T_o). Hoppe et. al (2001) describes the r_b as: "the rate (parts per unit time or jobs per unit time) of the workstation having the highest long term utilization; and the T_o as: " the sum of the long-term average process times or each workstation in the line." After these values are calculated, Little's Law determines the Critical WIP (WIP_0). Hopp et. al (2001) defines the WIP0 as: "the WIP level for which a line with given values of r_b and T_o but having no variability achieves maximum throughput (r_b) with minimum cycle time (T_o)." The formula that is used to calculate this value is the following (Hopp et. al 2001):

$$W_o = r_b T_o$$

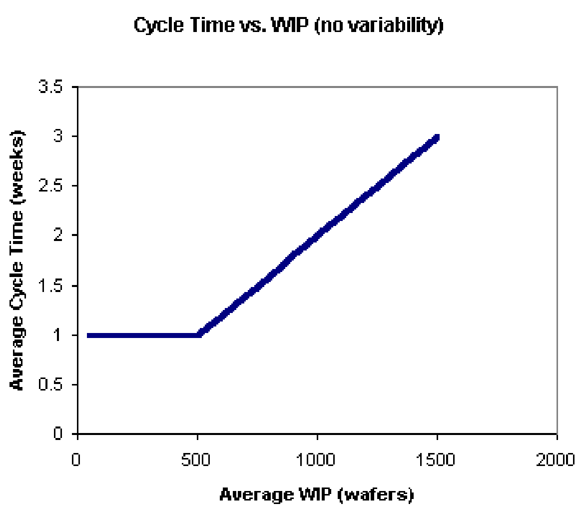
Where,

W_0= Critical WIP

r_b= bottleneck rate

T_0= raw process time

Little's Law gives three scenarios to be compared, which are Best-case performance, practical worst case, and worst case performance. The Best-case performance indicates the maximum throughput and minimum cycle time for a given level of WIP for any system having parameters r_b and T_o. The worst case performance indicates the maximum cycle time and the minimum throughput possible for a line with bottlenecks rate r_b and raw process time T_o. (Hopp et al 2001).



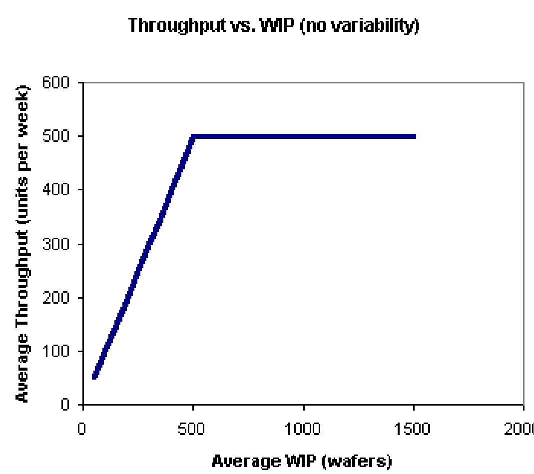


Figure 2. Cycle Time and Throughput vs. Wip (Hopp Et Al 2001)

The minimum cycle time for a given WIP level w is given by:

$$CT_{best} = \begin{cases} T_0 & \text{if } w \le w_0 \\ w / r_b & \text{if } w > w_0 \end{cases}$$

Where

CT: Cycle Time

W_o: Critical WIP

T_o: Raw process time

r_b: Bottle neck

The maximum throughput for a given WIP level w is given by:

$$TH_{best} = \begin{cases} w / T_0 & \text{if } w \le w_0 \\ r_b & \text{if } w > w_0 \end{cases}$$

Where

TH: throughput

W_o: Critical WIP

T_o: Raw process time

r_b: Bottle neck

The worst case cycle time for a given WIP level w is given by:

$$\mathbf{CT = wT_o}$$

The worst case throughput for a given WIP level w is given by:

$$TH_{worse} = 1/T_o$$

Little's Law predicts the stability of the system by comparing the actual values of TH, WIP and CT of the system with the obtained values from the scenario that it is been compared (best, practical worst, and worst case). Little's law would allow the comparison of TH, WIP and CT, measures of the system in study, and calculate the Critical WIP to determine if the system in study is working efficiently or not.

2.11 Modeling and Simulation

A model is a close approximation of a real system and incorporates most of its outstanding features; and modeling is the process to produce it. The purpose of a model is to allow the specialist to predict the effect of changes into the system. A mathematical model is used when a simulation study is needed to be performed. This type of model can be classified in the following (Anu 1997):

1. Deterministic: input and output variables
2. Stochastic: at least one of the input or output variables is probabilistic.
3. Static: time is not taken into account.
4. Dynamic: time varying interactions among variables are taken into account.

Simulation is the operation of a model of a system. According to Selvaraju (2009): "Simulation is a tool used in manufacturing to improve processes by observing and predicting the performance of the process desired." Also, simulation can be used to validate a model before the existing system is modified or a new one is built; so, the chances of failure can be reduced and performance can be optimized (Anu 1997).

Selvaraju (2009) states the following: "Simulation is generally used as an analysis and decision-making tool in three classes of problems: 1) design problems, 2) planning problems, and 3) operational problems. Design problems generally deal with system configuration issues and simulation tools are primarily used to evaluate candidate designs to aide in the design selection process. Planning problems generally deal with how existing or proposed systems will be used. Operational problems relate to the actual use of the system."

According to Anu (1997), the steps to develop a simulation model are:

1. Identify the problem
2. Formulate the problem
3. Collect and process real data
4. Formulate and develop a model.
5. Validate the model
6. Document model for future use.
7. Select appropriate experimental design.
8. Establish experimental conditions for runs.
9. Perform simulation runs,
10. Interpret and present results.
11. Recommend further course of action

To perform a simulation model, software is needed. This software can be divided into two groups: simulation language or a manufacturing-oriented simulation language. In the first one the model is developed by programming. This group allows the user to have modeling flexibility. Some examples are: Arena, AweSim, Extend, GPSS/H, Micro Saint, MODSIM III, SES/workbench, SIMPLE, SIMSCRIPT II.5, SIMUL8, and SLX. (Law and McComas 1998).

According to Law and McComas (1998) a manufacturing-oriented simulation language '' is one where the modeling constructs are specifically oriented toward manufacturing or material handling. One advantage of this type of software is that programming time may be reduced due to powerful constructs for such things as conveyors and AGVS'' Some example of programs are Automod and Quest.

The benefits to use simulation according to Anu (1997) are:

1. Obtain a better understanding of the system by developing a mathematical model of a system of interest, and observing the system's operation in detail over long periods of time.

2. Test hypotheses about the system for feasibility.

3. Compress time to observe certain phenomena over long periods or expand time to observe a complex phenomenon in detail.

4. Study the effects of certain informational, organizational, environmental and policy changes on the operation of a system by altering the system's model; this can be done without disrupting the real system and significantly reduces the risk of experimenting with the real system.

5. Experiment with new or unknown situations about which only weak information is available.

6. Identify the "driving" variables - ones that performance measures are most sensitive to – and the inter-relationships among them.

7. Identify bottlenecks in the flow of entities (material, people, etc.) or information.

8. Use multiple performance metrics for analyzing system configurations.

9. Employ a systems approach to problem solving.

10. Develop well designed and robust systems and reduce system development time.

Simulation uses variability to quantify the reduction of the effects. There are two types of variation, random and structural. Random variability refers to the internal variation of the machine, process, material availability and customer demand. Structural variability is when a system component does not produce the same activity in the same way every time. As an example, a machine's processing time can be 2 minutes for type A and 3 minutes for type B. Another example, a product could be shipped every day to a customer but it is only done on Mondays and Thursdays, with the purpose to minimize setups. Both structural and random variation contributes to the need for inventory, excess capacity, and increased production lead times (Hopp and Spearman 2007). In general, each source of system randomness needs to be modeled by an appropriate probability distribution (Heitz 2010).

The following are some sources of randomness in simulated manufacturing systems (Strandige and Marvel 2006):

• Arrivals of orders, parts, or raw materials

• Processing, assembly, or inspection times

• Machine failures

• Machine repair times

• Loading/unloading times

• Setup times

2.12 Lean and Simulation

Value stream mapping (VSM) has become the favorite tool to apply lean concepts. VSM is a mapping tool that is used to describe supply chain networks. It maps the production and material flow (Rother and Shook 1999). However, VSM has some disadvantages as suggested by Lian and Van Landeghem (2002):

1. VSM is a paper and pencil based technique used primarily to document value streams. It is composed by physically walking along the value stream and recording what happens on the floor, which will limit both the level of detail and the number of different processes that can be addressed.

2. In real world situations, many companies are of a high variety, low volume type, meaning that many value streams are composed of many tens or hundreds of industrial parts and products. This adds a level of complication (and variability) that cannot be addressed by normal methods.

Value Stream Map works like a design tool. It graphically presents the vision of how the process is working. While simulation is an analysis tool, and is used to evaluate the model and validate that vision (Donatelli and Harris 2001), VSM helps to formulate hypotheses to conduct actual experiments in a plant rather than on the computer. However, when there is no plant to do actual experiments, simulation is a helpful tool to develop and see the possible effects of applying experiments. According to Donatelli and Harris (2001), simulation gives to the value stream map a fourth dimension, time. This means that after being simulated, the VSM is no longer just a snapshot; but also a moving picture, offering perceptions that may have been missed if VSM was not simulated.

According to Grimard and Marvel (2005), to validate a lean model with simulation helps to achieve the company's goal of minimizing cycle time and having an effective production with a desired throughput rate. Also, the process of simulation can help to understand the following concepts of lean manufacturing: line balancing against Takt time, pull versus push manufacturing, batch versus one-piece flow, Kanban inventory control, and process variability reduction (Schroer 2004).

Many researchers conducting case studies have identified the importance of using discrete simulation to validate the VSM and future state map before implementation. Lian and Van Landeghem (2007) found limitations in VSM and recognized additional benefits of using simulation as a training tool beyond just quantifying the benefits of the improvements. McClelland (1992) identified simulation as a method that firms could use to evaluate the impact of implementing a new manufacturing strategy or analyzing possible alternatives being considered. Kumar and Phrommathed (2006) used simulation to model a sheeting operation at a pulp and paper manufacturer where simulation reduced the possibility of ineffectively redesigning a critical process. Comm and Mathaisel (2005) studied a lean manufacturing application of a labor-intensive industry in China. Simulation improved the use of VSM by addressing the complexity and number of the process steps in the system analysis.

Van Landeghem and Debuf (1997) state other benefits of applying simulation as a validation tool for lean manufacturing:

1. Simulation as a Cost Saving Tool: The use of a simulation model can help managers see the effects before a big implementation: the impact of layout changes, resource reallocation, etc. on the key performance indicators before and after lean transformation without huge investment.

2. Simulation as a training tool: In most companies, especially when they are small, new concepts are hard to introduce. Simulation has proven to be a powerful eye-opener.

In general, simulation helps to compare the performance of a lean system or design to the one that currently exists before any change is done. Also, it provides a convincing basis for manufactures to adopt lean manufacturing. For the project, simulation is proposed as a method to determine how vacuum drying can impact the TH, WIP and CT of part of a flooring production line.

2.13 SimioTM Simulation Software

Simio™ simulation software is a simulation framework based on intelligent objects. The software was built in .NET technology which integrates google 3D warehouse. Simio™ was designed to be used by advanced users of simulation as well as for beginners (Kelton et al 2010)

A model is created by the combination of one or more objects that will represent the physical parts of a system. For example, the objects can be a machine, robot, ship, airplane, bus, etc.

(Pedgen 2007). In Simio™, objects are built under the concept of object orientation. According to Pedgen (2007), object oriented programming is constructed "as a collection of cooperating objects that are instantiated from classes. These classes are designed using the core principles for abstraction, encapsulation, polymorphism, inheritance, and composition."

The abstraction principle can be explained as the principle to develop the classes' structure as simple as possible. Encapsulation means that only the object can change its state. Polymorphism is the principle that gives messages or indications to trigger object actions. Inheritance allows the development of a more specialized class of an object by the property of sub-classing (an object deriving from another object). Finally, Composition permits the creation of new object classes by the combination of existing object classes (Pedgen 2007).

In Simio™, the object framework is created on the same basic principles of object oriented programming languages, though the principles are applied by a modeling framework instead of a programming framework (Pedgen 2007). The authors Sturrock and Pegden (2010) established the following example to better understand this concept: "The Microsoft development team that designed C# applied these basic principles in the design of the programming language. Although these same principles drive the design of Simio™, the result is not a programming language, but a graphical modeling system."

In Simio™, objects are created by instantiation. According to Sturrock and Pedgen (2010) instantiation occurs when the properties that govern the behavior of the object are specified. The authors in their research gave the following example: "the properties for a machine might include the setup, processing, and teardown time, along with a bill or materials and an operator required during the setup. The creator of the object decides on the number and the meaning of the properties. The properties in Simio™ are strongly typed and can represent numeric values, Booleans, strings, object references, dates and times, etc." In Simio™, objects are located in the standard library. Table 3 shows the objects that are presented in the standard library and a brief description of their function.

Table 3. Simio™ Objects characteristics (Sturrock and Pegden 2010)

Object	Characteristics
Source	Creates entity objects with an specific arrival pattern
Sink	Eliminates the entities that have been processed in the system
Server	Represents a process like a machine
Combiner	Combines several entities together to create a specific product, for example a pallet
Separator	Splits a group of entities or it can make copies of a single entity

Simio™ also provides statistical analysis. After an experiment is run, the result report can display SMORE plots which are composed by different statistical parameters like Mean, Confidence Interval for the Mean, Upper Percentile Value, Confidence Interval for the Upper Percentile Value, Lower Percentile Value, Confidence Interval for the Lower Percentile Value, Median, Maximum Value, and Minimum Value (Sturrock and Pegden 2010). Figure 3 shows and example of a SMORE Plot. The yellow dot represents the mean values, the yellow box represents the confidence intervals of the mean, and the blue box represents the upper and lower confidence intervals of the percentiles. The black bar represents the maximum and minimum range of the data analyzed (Sturrock and Pegden 2010).

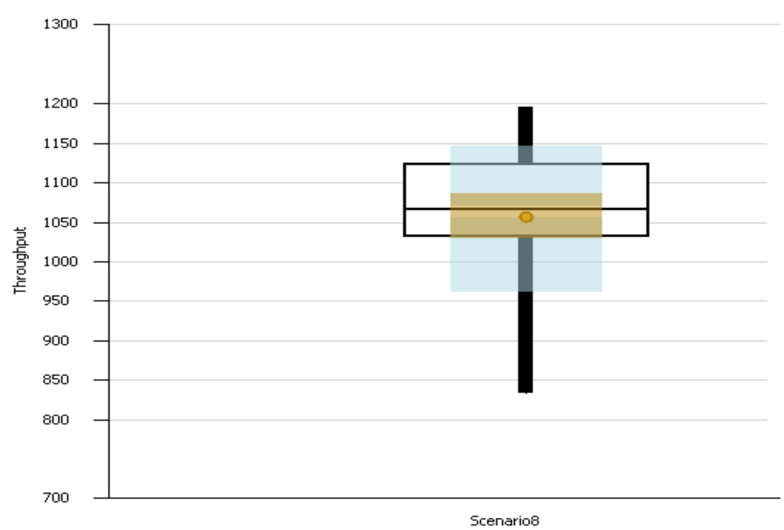


Figure 3. SMORE Plot in Simio™

Also, the software displays histograms as a result of the response during a simulation run experiment. The SMORE plots will be used to determine the statistics for the output variables analyzed in the simulation models (like TH, WIP, CT).

2.14 Case Study

A case study is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context when the boundaries between phenomenon and context are not clearly evident, and in which multiple sources of evidence are used” (Yin 1984). This methodology is particularly useful when “what”, “how”, and “why” type of questions are leading the research, and there is a little or no control over behavioral events (Yin 1984, Stuart et al., 2002). According to Eisenhardt (1989) case studies typically combine data collection methods such as archival searches, interviews, questionnaires, and observation.

However, this type of study has been questioned in terms of the quality of the research that can be carried out, so Kidder (1981) and Yin (1984) suggest a list of tactics to ensure validity, external validity and reliability to the research performed. Table 4 shows a brief summary of these tactics.

Table 4. Tactics to Ensure Quality in Case Study Research (Yin 1984)

Quality Test	Tactic
Construct validity	1. Utilize more than one source of information (e.g., semi structured interviews, site visits, literature review, documentation review, observation) 2. Use key personnel in the observed phenomenon to review data collected. **For the study this will be obtained from an operator in the company.** 3. Great detail in establishing and documenting the evidence leading to conclusion
External validity	1. Focus on key elements for observed phenomenon to compare with data obtained from literature, current frameworks and previous research in the field. **For the research the key elements would be cycle times, throughput, suppliers, kiln structure.**
Reliability	1. Develop and document research protocol with great detail 2. Create electronic files with all the material collected during the study

CHAPTER 3

METHODOLOGY

This chapter describes the methods used to answer the three objectives and achieve goal of the project: to evaluate vacuum-drying technology and its economic feasibility to support the lean manufacturing of hardwood products compared to conventional drying technology. For this project the term conventional drying will refer to air drying plus kiln drying. Air drying uses outdoor conditions of temperature, relative humidity and airflow to remove water from wood. The lumber is stacked into piles and allowed to dry to 20-25% moisture content. Once the lumber reaches a 20-25% moisture content a conventional kiln is used to dry the wood to the final target moisture content of 6-8%. Vacuum drying is a type of kiln drying where the temperature at which water boils is determined by the pressure in the kiln vessel and it allows for the boiling of water at lower temperatures. Vacuum drying can be done for both green or air dried wood. For objective one, the difference between conventional and vacuum drying in terms of quality, drying times and costs were determined by using data collected from: 1) companies that sell vacuum drying equipment, 2) companies using the different drying technologies, and 3) literature. For vacuum drying, four companies that sell vacuum equipment were contacted, but only one provided information. Then, five companies that use this technology were contacted; only one provided information. Information from literature review was also used to complete objective 1. For conventional drying three companies using this drying technology were visited and information was collected. The data for vacuum and conventional drying were qualitatively compared. A cash flow analysis was developed using the cost data gathered for objective one. Then the net present value and internal rate of return was calculated for objective 3. Two case studies were developed using data from two companies visited for objective 1. The case studies were carried out to determine the impact of vacuum drying versus conventional drying with the goal of meeting the demand of one flooring line. A flooring line is the equipment used to manufacture flooring. Often, flooring companies will have multiple flooring lines or multiple lines of production. To reduce complexity, each case study was composed of only one flooring line. For each case study, a value stream map was created with the purpose of showing cycle times, throughput and WIP for a hardwood flooring production line. Each flooring line represented an actual production line from a hardwood flooring company. A simulation model was then developed for the VSM and changes made to the drying technology used to measure the impact on cycle time, throughput and WIP. The obtained results were qualitatively compared to the values suggested by Little's Law. The results for the simulation were used to create the future state map for each case study. Figure 4 shows an outline of the methods used for the project.

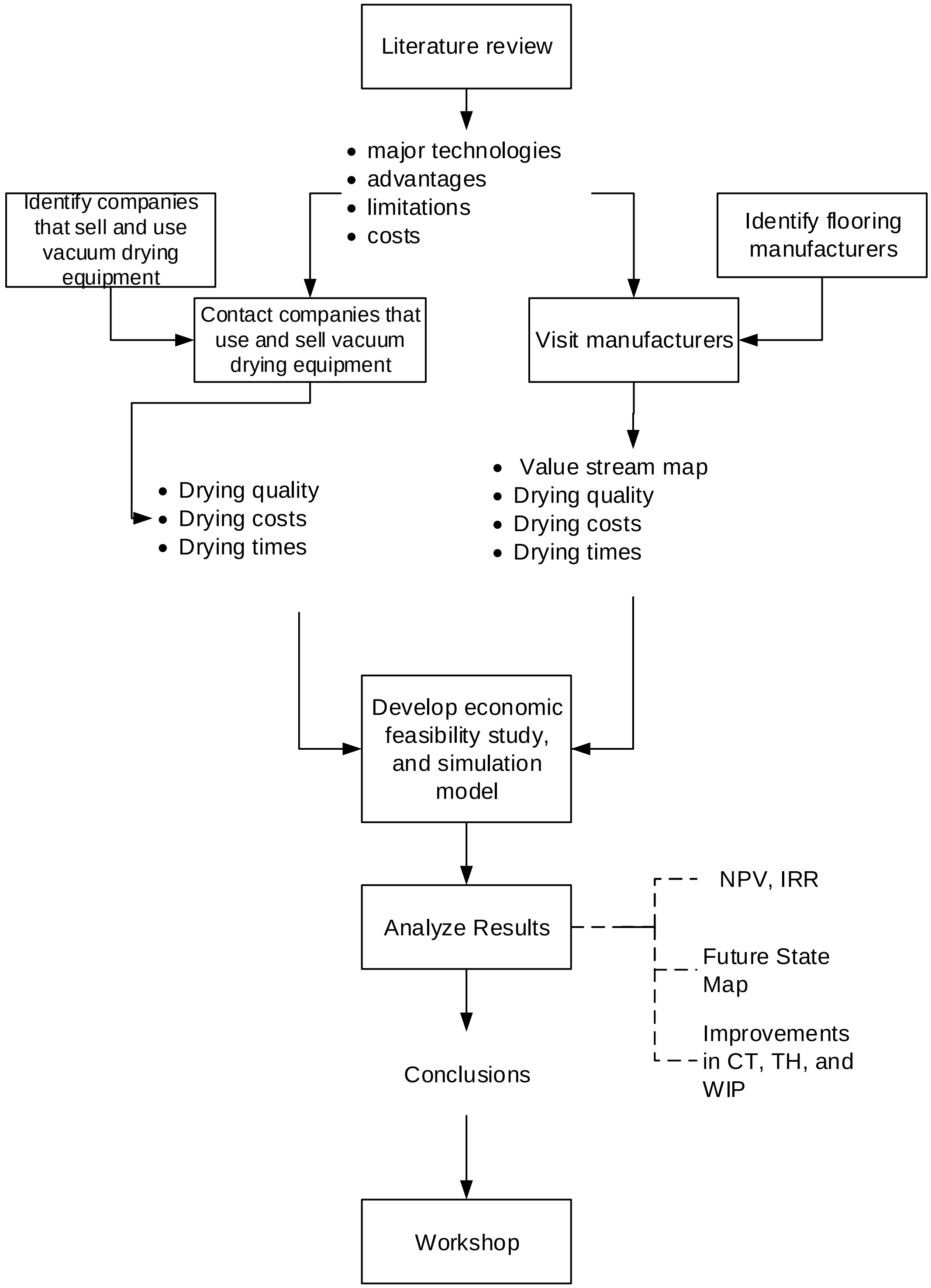


Figure 4. Outline of the methods used.

3.1 Differences between conventional and vacuum drying in terms of quality, time, and costs.

The first objective was to estimate differences between conventional and vacuum drying times, quality, and costs for drying 4/4 red oak lumber. Four quarter red oak lumber was chosen because of its difficulty to dry (longer drying times and quality issues), its common use to manufacture goods and the availability of manufactures that use it. An extensive review of literature regarding the current state of conventional and vacuum drying technologies was performed, where differences known between how water is removed during the drying process, available technologies, quality (like color, warp, shrinkage), drying rates, and costs were determined.

Manufactures of vacuum drying equipment in the United States were identified with the purpose of gathering information about the technology's quality, drying times, and costs. Four potential manufactures were found by an Internet search and they were contacted. Of the 4 companies contacted, only one provided information, and this company will be called company A in the results (Section 4). Then, industries in hardwood manufacturing in the United States using vacuum drying in their operations were contacted. Four companies were found by an internet search, and only one provided information for the project. This manufacturer will be referred to as company B in section 4. Table 5 summarizes the companies of vacuum drying that were identified and contacted. For conventional drying, three flooring companies utilizing conventional drying were identified , and participated in providing data on 4/4 red oak.

Table 5. Companies that sell and use vacuum drying equipment in the United States

Companies that sells vacuum drying equipment	Companies that use vacuum drying
HILDERBRAND BRUNNER	Michigan Chair Company
Vacutherm	C.A. Elliott Lumber Co.
PCS VacDry	Lewis & Huckleberry
9SCALE VACUUM PRODUCTS INC	Armstrong

Three instruments for data collection were created. The first data collection instrument was used for obtaining information about drying quality, and it was addressed to the company that sells and manufactures vacuum equipment. The data collection instrument was composed of 6 parts. The questions were as follows:

How does conventional drying/vacuum drying affect the following characteristics?

1. Color

2. Warp

3. Moisture Content uniformity

4. Drying stresses

5. Drying degrade

6. Internal, surface, and end-checks

The second data collection instruments were made to collect information about drying times, and costs for conventional and vacuum drying from Companies A and B and from the three flooring manufactures that use conventional drying. These two data collection instruments were based on literature reviewed in section 4.8, to identify the most appropriate cost information that should be collected and used to calculate and to compare drying costs

According to Boulet and Ouimet (1968), MacMillen and Wengert (1978), Fortin (2010), Reeb (2011), Redman (2011) Engalichev and Eddy (1990), Holmes and Bilek (1983), Govett et al (1996 and 2006), for a cost accounting approach, the fixed costs to be included are: buildings, kiln, stickers, pile roofs, pile bases, bolsters, depreciation, quantity of wood dried annually, storage sheds for stickers, fences, lighting systems, drainage systems, sprinkler systems, air drying area (include space between the piles), land value, taxable values, insurable values, and energy consumption. Energy consumption includes energy to heat wood, energy to heat water, to vaporize water, and BTU's per charge. Variable costs to be included are: maintenance, labor, and forklift costs. Other important costs to include in the data collection instrument are the cost of degrade, shrinkage of wood through the process, and green and dry inventory costs. Costs specific to the vacuum drying process include the energy associated with the operation of the vacuum pump. Table 6 shows the data collection instrument used to gather drying times and costs.

Table 6. Data collection instrument for conventional drying costs

FINANCE VARIABLES	VALUES
Direct investments (total costs)	
Buildings, sheds, etc.	
Kiln (including, auxiliary equipment, boiler, installation)	
Stickers	
Pile roofs	
Pile bases, bolsters	
Depreciation period for direct investments (years)	
Buildings, sheds, etc.	
Kiln, auxiliary equipment (including boiler)	
Stickers*	
Pile roofs*	
Pile bases, bolsters*	
Drying yard investments (Total costs)	
Temporary road construction (includes drying alleys)	
Fences	
Lighting systems	
Drainage systems	
Sprinkler systems	
Depreciation period for drying yard investments	
Fences	
Lighting systems	
Sprinkler systems	
Storage sheds for stickers, dried lumber, etc.	

*If it is applicable to the company

Continuation Table 6

OTHER FINANCE VARIABLES(If applicable)	**Values**
Maintenance of kilns and boiler ($).	
Maintenance and repair of yard ($)	
Snow removal ($/yr)	
Land area (ft2)	
Air drying area (include space between the piles) ($/Acre)	
Road area ($/Acre)	
Area for buildings, kiln, boiler, etc. ($/Acre)	
Land value ($/Acre)	
Annual interest rate (%)	
Tax rate to be applied to the total of taxable values (%)	
Insurance rate applied to the total of insurable values (%)	
CAPACITY VARIABLES	
Average price of lumber ($/M bm)	
Average drying degrades based on lumber value (percent as decimal)	
Average daily volume of lumber on yard and in kilns on any given day (M bm)	
Total capacity of kilns	
Number of Kilns	
Operational year	
Annual throughput (Mbf/yr)	
Run times	
Klin cycles per year	
Average length of kiln run (include loading and unloading time)	
Number of fans	
Fan rating (kW)	
Air drying time (weeks)	
`Final Drying time (hrs)	
Volume air dry yard (Mbf)	
Maximum drying temperature (F)	
Minimum drying temperature (F)	

Continuation Table 6

OPERATIONAL VARIABLES	Values
Forklift wage ($/yr)	
Lumber graders ($/yr)	
Wage for kiln operator and yard supervisor ($/yr)	
ENERGY COSTS	
Fuel consumption (hog waste) (tons/day)	
Fuel cost ($/ton)	
Annual electrical usage attributed to drying (kWh/yr)	
Electrical cost ($/kWh)	
Initial MC (%)	
Final MC (%)	
Raw Material Cost ($/MBF)	
Previews Energy Calculations	
Thermal loss (%)	
Wood basic density (Kg)	
Specific heat of hardwood (KJ/(Kg*oC)	
Specific heat of water (KJ/(Kg*oC)	
Heat of Vaporization (MJ/kg)	
Specific gravity at FSP	
Water density (kg/m3)	
Energy to heat wood (KJ)	
Energy to heat water (KJ)	
Energy to vaporize Water (KJ)	
Total BTUs/charge used for drying	
Total tons/charge used for drying	

The 3rd data collection instrument was used to collect information for vacuum drying, and was similar to Table 6; however, in the operational variables, it included the following: vacuum pump rating, vacuum pump usage, condenser fan rating, and condenser fan usage.

The data collection instrument for vacuum drying was e-mailed to the company that sells vacuum drying equipment and to the company that uses vacuum equipment. The data instrument for conventional drying was applied during the visits to the three flooring manufactures that use conventional drying.

3.2 Feasibility Analysis

One of the objectives of this project is to determine if vacuum drying is an economically viable activity for drying 4/4 red oak and to compare which technology: conventional or vacuum is more feasible. Two case studies were developed to calculate the cash flow, net present value and internal rate of return for the feasibility analysis.

To select the two companies for the case studies, a case selection methodology was used. A case selection is where the researcher chooses the case or cases (Seawright and Gerring 2008). Case selection depends on factors such as availability to the researchers, budget or time, among others (Stuart et al. 2007). Koulikoff-Souviron and Harrison (2005) suggested that the selection of cases is determined from participant observation, document analysis, surveys, questionnaires, interviews. For this project, the case selection was based on the following factors:

a) Two companies (Plant C and Plant D) were selected because the research had to be done in a limited time period; including more companies would have required more time and greater complexity. Both companies were flooring manufacturers. Flooring consists of a simple production line, while furniture or cabinet manufacture contains more complex production lines. Plant C is a bigger and more complex flooring manufacturer while Plant D is a smaller and less complex flooring manufacturer. Both companies were selected based on their use of 4/4 red oak, simple production lines and their willingness to provide data. By choosing two different manufacturer case studies, businesses that are in the same line of production will have an opportunity to use the methods and apply them to optimize their business.
b) The companies were willing to participate in the study, sharing information useful to accomplish the objectives of this research.

Plant C is part of a large, national, multi-facility hardwood manufacturing company that sells logs, lumber and flooring around the world, producing more than 100 million board feet of lumber and 10 million square feet of flooring annually. Most of their raw material comes from their own production facilities. However, some raw material comes from external suppliers. Most of their flooring production consists of 2.25” and 3.25” wide red and white oak pre-finished and un-finished flooring. An important aspect is that the company consists of a team formed by professionals in the areas of Lean Manufacturing, Statistical Process Control and Six Sigma, with the goal to have Continuous Improvement.

Plant D is a family business that produces unfinished and prefinished 2.25” and 3.25” wide red and white oak flooring. Flooring is their only business and all raw materials are purchased outside the company.

After the two companies were selected, the cost data obtained in section 3.1 for objective 1 was used to develop a cash flow analysis. Data was gathered for one 3.25” wide red oak flooring production line for both case studies. A cash flow can be defined as the schedule of payments for a certain period a business has to make in order to build a project. Microsoft Excel was used for the cash flow analysis. The formulas used to calculate total costs and depreciation are shown in Appendix II. Some assumptions were made to be able to estimate the rest of the variables for the cash flow analysis. These assumptions are summarized below:

1. Sales increase rate is of 4% per year.
2. Bank business loans go from $25,000 to $2,000,000, and they provide 80% of the requested value. For the companies we will assume that a loan of $2,000,000 was made where the bank approved 80% corresponding to $1,600,000 with an interest rate of 9%.

The steps proposed by Keown et al. (2006) were used to develop the cash flow, which are the following:

1. Operating Activities
2. Investing Activities

3. Financing Activities

Operating activities are those which produce either revenue or are direct cost of producing a product or service, in our case it refers to sales and the sales growth per year. Investing activities include buying and selling noncurrent assets, which will be used to generate revenues over a long period of time, in our case it refers to the costs of building, sheds, stickers, kilns and its respective depreciation. Financing activities -include borrowing and repaying money, issuing stock (equity) and paying dividends, for the project it was directed to the bank loan for the initial investment.

The cash flow analysis was conducted in Microsoft Excel for a period of 20 years. According to Govett et al.(2006), 20 years is a good year analysis period for drying investments due to the life expectations of the equipment. In the Microsoft Excel spreadsheet, 21 columns were used: 20 for the 20 years of evaluation of the project and 1 with year "0" to represent the initial investments.

Within the worksheet created, the sales values were calculated by increasing the value 4% each year. The sales increase rate is generally provided by the company in study; however the flooring manufactures in study could not provide this information. In examples from Keown et. al (2006) the sales increase rate were of 4%. The total fixed and variable costs obtained for objective 1 were used in the model. The formulas to calculate total costs and depreciation are shown in Appendix II. The income before depreciation and tax was calculated by subtracting costs from the sales. Then, the profits before taxes and interest were calculated by subtracting depreciation form the total costs of investing activities. Then, the tax rate was applied to the obtained results and the interest rate was applied to the loan. Finally the net cash flow was obtained by subtracting the depreciation and amortization values from the net profits.

After completing the cash flow analysis, the net present value and the internal rate of return were calculated using equations in Microsoft Excel. The formula that Excel uses to compute the values of NPV and IRR are, respectively, the following:

$$NPV = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+i)^t}$$ Equation I. Net Present Value

Where

i: is the interest rate;

t: is the year;

n: is the economic life of a system

R_t: is the revenue earned

C_t: is the cost of a system in year t, including initial costs, operation costs and maintenance costs.

$$\boldsymbol{IRR(X) = \ min_{d>0}\{E[NPV(X, D)] = 0\}}$$ Equation II. Internal Rate of Return

Where,

IRR(x) = Internal rate of return

E= discount rate

NPV= net present value

The values for NPV and IRR for vacuum and air drying for each case study were then compared.

3.3 Current Value stream map

A current state value stream map is a graphical illustration of a production line. It is used to identify the different work processes or a work station involved as raw material enters the system, is turned into a finished product and is shipped to the costumer. The VSM also identifies value added activities (work stations) and non-value added activities (inventory) in the production line.

Two VSMs were created for one part of plant C (case study 1) and plant D (case study 2), based on the Methodology of Rother and Shook (1999). The methods described by the authors mentioned before, state five steps that should be followed to create a VSM. The steps are:

1. Identify the product

2. Create a current VSM

3. Evaluate the Current map, identify problem areas

4. Create a future state map.

However, the product units were expressed in (MBF) rather than discrete units, as established in Shook and Rother (2003).

3.3.1 IDENTIFY THE PRODUCT

For case study 1, three visits were conducted and for case study 2, two visits were made. For both case studies, the first visit was made to see the manufacturing plant and to identify the different products that each company produces. Then, in a conversation with the production manager, it was determined which of their products had higher demand, and based on this value the product line was chosen. For plant C, the 3.25” wide red oak finished flooring was chosen, and for plant D, 3.25” wide red oak unfinished flooring

3.3.2 VSM CREATION

To create the VSM, a data gathering instrument was developed based on the methodology described by Shook and Rother (2003). to collect the information from each process in Plant C and D. The data was gathered during a second and third visit of Plant C and during a second visit for Plant D. Table 7 shows the data collection instrument for the two case studies.

Table 7. Data Collection instrument for the Value Stream Map for the Two Case Studies

Production Process
1. Description of changeover constraints, if applicable
2. Supplier of material and frequency of deliveries
Customer Requirements
1. Customer orders per month
2. Quantity contained in customer shipments
3. Frequency of shipments to customers
Work Time
1. Work day per month
2. Shifts per day at each process
3. Frequency and length of standard employees breaks
Production Control Data
1. Type of production control system
2. Frequency of receiving orders and method in which they are received
3. Variables influencing production control
4. Length of schedule and what processes receive the schedule.
Process Information
1.Operators required
2. Numbers of machines
3. Batch size
4. Cycle Time
5. Changeover time if applicable
6.Inventory
7. Setup time
8. Quality
9. Uptime
10. Yield

Processing times for each machine were measured using a stop watch. Thirty processing times were measured for each machine. Thirty is the minimum sample size to have accurate statistical results as suggested by Kelton et. al (2011) Also, Plant C provided additional data on their production rate for a period of a year (2013 period). Plant D was able only to provide data of their production rate for a month due to company's policies. Both companies provided information of their actual inventories.

After all the data was obtained, a current state map was created to graphically represent material and information flow. For this, every activity that was included in the process was drawn by using the different symbols shown in Figure 5. Microsoft Visio was used to draw the value stream maps. After inserting the appropriate symbols, the respective data was added (cycle time, TAKT time, work in progress (WIP), set up time, down time, number of workers, and scrap rate), for each process.

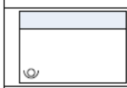
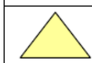
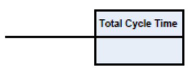
Symbols Used in Microsoft Visio	Meaning of the Symbol
	Process
	Timeline: waiting time and cycle time
	Inventory
	Production Flow
	Total Time

Figure 5. Value Stream Map Symbols (Apel et. al 2006)

3.3.3 Evaluation of the Current Map

For this step, the total lead times were calculated by dividing the inventory at each process by the daily demand of the production line. Then, all the values were summed and they are presented at the end of the time line. To calculate the total processing time, the values from each workstation or process were summed and presented at the end of the time line. After calculating the time, the production process was described starting the arrival of raw material until it is processed and shipped to the customer. Also, the process that contained higher inventory and was a bottleneck of the operation was identified.

Little’s Law is used to predict the system behavior of a company, by providing a relationship between Throughput, Work-in-Process (WIP) and Cycle Times (CT). Little’s Law can be represented by the following formula (Hopp et al.2001):

$$\boldsymbol{WIP = TH * CT}$$

Equation III. Little's Law Equation

Where

WIP: Work in process inventory

TH: throughput

CT: cycle times

The values obtained from the VSM were used to determine the performance of the two case studies using Little’s Law. First, a table was developed with each process and its corresponding production rate (MBF/ min for both Plant C and D). Then, the smallest value from all the production rates of the different processes was chosen to represent the bottleneck. According to Hopp et al.(2001) the bottleneck (r_b) is: “the rate parts per unit of the workstation having the highest long term utilization”. Then the raw process time (T_0) was calculated, which according to Hopp et al.(2001): “is the sum of the long term average process times of each workstation in the line.” After the bottleneck and raw process time were calculated, the critical WIP (W_0) was calculated. The W_0 indicates the ideal inventory that a system should have according to its corresponding values of bottleneck and raw process time (Hopp et al.2001). The W_0 was computed by the following formula:

$$\mathbf{W_0 = r_b \times T_0}$$

Equation IV. Critical WIP (WIP_0) Formula

Where

W_0= Critical WIP

R_b= bottleneck

T_0= raw process time

Little's Law gives three different scenarios (best case, worst case, and practical worst case) to be compared with the actual values of a company. However, Little's law does not provide information of how to improve the line. For the project, the actual values that each company or case study had were compared with the practical worst case of Little's Law to predict the system behavior: 1) the system is working efficiently, or 2) the system is not working efficiently. The worst practical case was calculated by the use of the following formula:

$$THpwc = \frac{w}{W_0 + w - 1} r_b$$

Equation V. Throughput Practical Worst Case Formula

Where,

THpwc= Throughput practical worst case

w= actual WIP

W_0= critical WIP

In lean manufacturing, a reduction in lead times, leads to a reduction in cost performance, an increase in earnings, and an increased competitive advantage for the industry (Apel et. al 2007). One way to reduce lead time is by improving the operation that is the bottleneck. Using Little's Law it was determined that drying was the bottleneck operation. One way to improve the drying process is by changing conventional drying to a faster technology like vacuum drying. To see the impact that vacuum drying technology could have in the line production, a simulation model was used.

3.4 Impact of Vacuum Drying on Throughput, WIP, and Cycle times.

The third objective of the project was to determine how vacuum drying can impact the WIP, TH and CT of a flooring manufacturer. The same two companies (C and D) selected for the case studies mentioned in section 3.2 of the feasibility analysis were used to evaluate the impact of using vacuum drying instead of conventional drying in their production. First, a value stream map representing the current state of the 3.25” wide red oak flooring line was created, and then a simulation model was developed based on the VSMs. The simulation was validated by comparing the values of processing times for the machines, and the throughput with the values obtained from the actual companies. In Plant C, the simulation model was validated, two new models were derived: one to simulate the 3.25” red oak flooring line, for both case studies, using vacuum drying with air drying, and one only using vacuum drying with no air drying, because vacuum drying can be used directly to green wood or it can be used with air drying. Finally, two future state maps were developed with the results obtained from the simulation. The future state map presented the improvements in WIP and cycle time that the 3.25” red oak flooring line can achieve by using vacuum technology.

3.4.1 SIMULATION MODEL

Often, companies that want to implement lean manufacturing use results reported from other manufactures that implemented lean as a guide. According to Detty and Yingling (2000), one of the problems with lean is that predicting inventory levels throughout the production line is difficult when using only a future state map. A value stream map does not show how the inventory levels will differ when using different scenarios with improvements (McDonald et. al 2002). This is why a complementary tool is needed to validate changes to the future state map. Simulation can create dynamic views of inventory levels, lead times and machine utilization for different future state map. Information of WIP, throughput and cycle time that is provided by simulation allows managers to compare the expected behavior of the proposed lean system towards the existing system before replacing it. Simulation can validate the improvement changes in the future state map for companies that want to adopt lean (Detty and Yingling 2000).

Simulation can help supplement value stream mapping by (Surya 2004):

a) Evaluating the impact of proposed map.

b) Analysis, evaluation and improvement for different scenarios of the future state map, and

c) For documenting areas of improvement.

Simulation was used to evaluate and validate the impact of lean manufacturing in the future state, which is important because in a deterministic model (like a value stream map) variation in WIP, TH, and CT cannot be observed. Simio™ software was used to model the current value stream map of the two case studies (Plant C and D) mentioned in section 3.2, and they were called base models.

Simio™ software is composed by different elements that can represent a workstation, shipment, the arriving of raw material, among others. These elements are called intelligent objects. The base models for Plant C and D were created using intelligent objects. The Plant C base model used the intelligent object called source to represent the arrival of raw material, 13 intelligent objects called servers to represent the air drying, the conventional kiln drying, the shop floor machines (Surface planner, Ripsaw, Moulder, Pre finishing), one intelligent object called combiner which batched the lumber in the kiln drying on batches of 75MBF (capacity of the kilns), one intelligent object called separator to split the batches in single units, and an intelligent object called sink to represent the shipment (Figure 6)

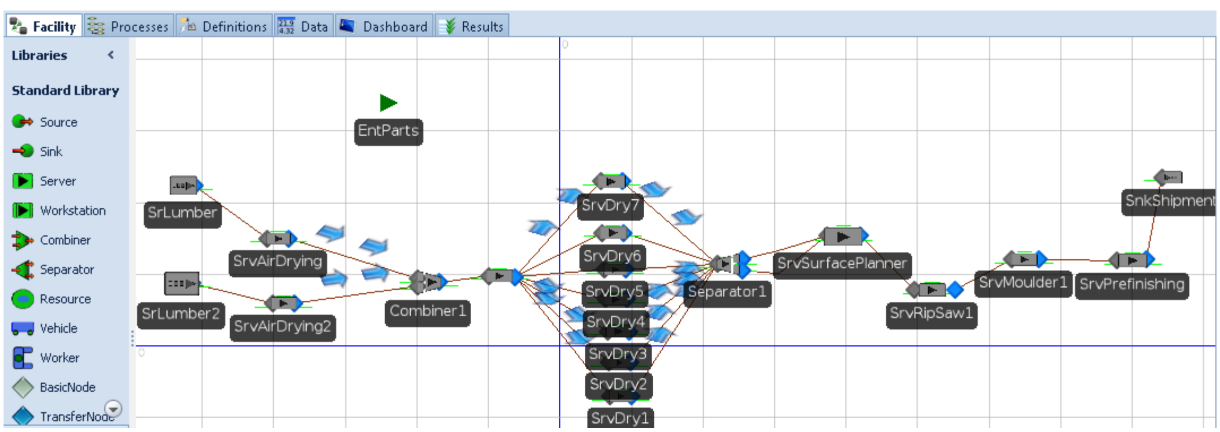


Figure 6. Plant C Simulation Model

The Plant D model was created by using the object source that represented the lumber arrivals, 45 servers that represented the air drying operation, the conventional kiln operation, and the shop floor machines, one combiner that batches the lumber for the kiln, one separator that split the batches into single units, Plant C the drying operation, and 4 sinks that represent the shipment operation. The information from each process (batch size, process time, inventory, work shift) was obtained from the current value stream map of Plant C and D, and was placed inside of the respective objects. For example,

FIGURE 7 represents the information placed for the intelligent object that represented the drying operation. It can be seen that in the spot called capacity type a work schedule to represent the work shift of 24 hours was used.

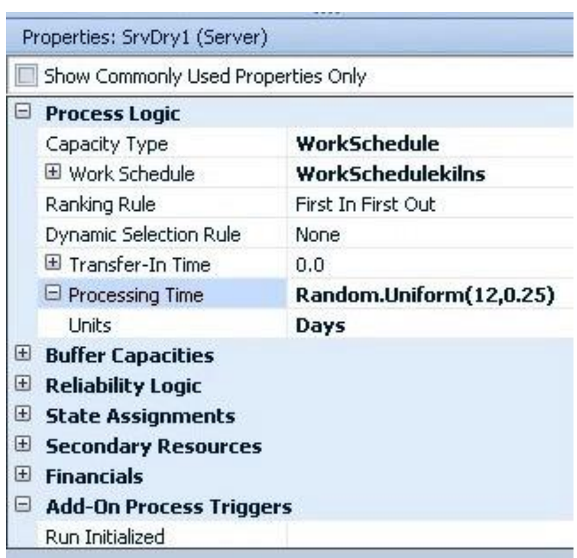


Figure 7. Representation of the Kiln Drying Operation for Plant C

Simulation incorporates randomness to models, which is called input modeling. Randomness in simulation is represented by random variables that can be continuous (example time) or discrete (example quantity). In Simio™ software one input model is the time based arrival process, which is called “Time Varying Arrival Rate” and it is presented in the object called *source*. Another input model is the processing time of each machine presented in the objects *server*, *workstation*, *combiners*, and *separators*. Randomness is derived from the distribution of the continuous or discrete values that comes from the data gathering; in our case, the processing times of the machines.

The steps to find the data distribution for the processing times of each process are the following (Joines and Robets 2012):

1) Collect data

2) Identify candidate distributions

3) For each candidate distribution

a) Estimate parameters for the candidate distributions
b) Compare candidate distribution to histograms
c) Compare the candidate distributions function to the data based function

4) Select the best representation of the input (the input model)

Processing times were gathered from the production rate of Plant C and D as mentioned in section 3.3.2 and times collected at the shop floor. 30 times were collected with the use of a stop watch from the shop floor. Then with this 30 values it was calculated the sample size for the by the use of the following formula:

$$n = \left[\frac{z_{\frac{\alpha}{2}} * \sigma}{E}\right]^2$$

Where

n= sample size

$Z_{\alpha/2}$= is known as the critical value, the positive value that is at the vertical boundary for the area of in the right tail of the standard normal distribution.

σ = the sample standard deviation

The simulation sample size was 70, α equals 0.05, and a standard deviation of 0.19 was used for the simulation models. The 70 points were gathered from the production rates provided by Company C (one year period) and D (one month period).

Then EasyFit software was used to do the input analysis (steps 2-4). EasyFit software is recommended by Simio™ and it fits a distribution to the data. The software contains over 50 standard possible distributions. EasyFit gave the probability distributions that fitted the data; and histograms were analyzed and tests of goodness of fit were applied. The obtained parameters of the distributions were written according to Simio™ codes. Results for Plant C and D are shown in Table 8 and 9 respectively.

Table 8. Probability distributions for each process at Plant C

Process	Distribution
Air drying	Random.Uniform(5.9,6.1)
Kiln drying	Random.Uniform(11.9,12.4)
Surface Planner	Random.LogLogistic(3.21,0.20)
Ripsaw	Random.Pert(1.89,1.92,3.54)
Moulder	Random.LogLogistic(5.09,0.63)
Prefinishing	Random.Weibull(1.38,0.21)

Table 9. Probability distribution for each process at plant D

Process	Distribution
Grading	Random.Uniform(5.9,6.1)
Air drying	Random.Uniform(5.9,6.1)
Kiln drying	Random.Uniform(7.8,8.2)
Ripsaw	Random.Uniform(5.9,6.1)
Chop saw	Random.Uniform(6.08,6.48)
Moulder	Random.Uniform(7.34,7.74)
End matchers	Random.Uniform(7.34,7.74)
Grading	Random.Uniform(8.4,8.08)
Nesting/bundling	Random.Uniform(8.4,8.08)

Then, the distributions calculated using EasyFit were used in the simulation model as the processing time of each process and were placed inside the intelligent objects, as shown in Figure 7.

Simio™ software experiments are used to define a set of scenarios to be executed using the model. The experiment is formed by scenarios, which are composed by control variables (such as the size of every input inventory) and output variables (as throughput, cycle time and WIP). For the project, throughput, WIP, and cycle time were the output variables that were analyzed. The obtained values were compared to the actual values of the case studies (provided in the value stream maps) to validate if the model was correct. The expressions that were used are the following:

Throughput = *sinkshipment.Inputbuffer.NumberEntered*

CT = *EntParts.TimeInSystem.Average*

WIP = *EntParts.NumberInSystem.Average*

Two models for each Plant (C and D) were then created using the base model but substituting vacuum drying for conventional drying (air drying plus kiln drying) to determine the impact on TH, WIP and CT of the production line. The number of vacuum kilns used for drying and to meet demand was determined by the total throughput that each plant has per year divided by the number of cycles per year the kilns have. The processing times were gathered from the results of the drying times analysis (Section 3.1). Two models were created: one using vacuum drying with air drying and another using only vacuum drying. The inventory amount used was gathered from the critical WIP calculated for the base model as mentioned in 3.3.1.3.

The simulation model for Plant C and D were both run for a period of 13 weeks to simulate an approximation of the time required to produce the inventory of each company (time line of the VSM). Each scenario was run with 30 replications because SimioTM needs a minimum of 30 replications to gather more accurate statistical results.

Then, the obtained results from the simulation were compared qualitatively to Little's Law values to determine the performance of the production line. Little's law values were calculated for each plant before the simulation model was performed as mentioned in section 3.3.3. The measuring of current values against those predicted by Little's Law, provides a measure of the stability in the current system, quantifying the maximum achievable operational improvements. Also, it is often used to build intuition about expected factory performance when implementing a change given by the current factory state (Rust 2008).

3.4.2 Future State Map

The objective of the future state value stream is to smoothen and level production flow while implementing the shortest lead time, highest quality, at the lowest cost (Rother and Shook, 1999). The future state map was created with the obtained results from the simulation mentioned in section 3.3.4. Visio software was used to create the future state map with the improvements of vacuum drying in the line production. The values obtained for each company from the two scenarios (vacuum with air drying and vacuum with no air drying) were qualitatively compared, and the one that presented less WIP, cycle time and met the desired throughput was chosen to create the future state map. The future state map reflected the reduction of CT and WIP. Reduction in WIP represented a reduction in costs for Plant C and D. The creation of the future state maps helped to determine how vacuum drying technology can impact the throughput, cycle time and WIP of 3.25" wide red oak flooring production lines.

CHAPTER 4

RESULTS OF DRYING QUALITY, TIMES AND COSTS FOR CONVENTIONAL AND VACUUM DRYING

One of the objectives of this project is to estimate conventional and vacuum kiln drying quality, times, and costs for 4/4 red oak lumber. Data for comparisons was collected from companies that manufacture drying equipment, companies that use conventional steam and vacuum drying equipment, and the literature review. Four manufactures of vacuum drying chambers were contacted; however only one agreed to supply information. This company will be referred to as company “A”. Five companies were identified as users of vacuum drying technology for their drying operations; however, only one agreed to provide information. This industry will be referred to as company “B”. Three companies using conventional drying (air drying + kiln drying) for their production provided information about drying quality, times and costs. Data collection methods are outlined in section 3.1.

4.1 Comparison between Vacuum and Conventional Drying Quality

Quality is an important aspect to be evaluated during the wood drying process since poor quality or degrade can cause a loss of value or reduce the ability to utilize the raw material; however, many lumber manufactures do not quantitative or qualitatively evaluate this aspect. Conventional drying (air drying + kiln drying) defects were analyzed to compare the differences between vacuum and conventional drying.

Since air drying is typically the process with the least amount of control over drying process, defects can be severe. When air drying is used to reduce the moisture content to 20-25% prior to kiln drying, most defects are started during the air-drying phase. For example, surface check and end checks are formed during the first 1/3 loss of moisture content. Air drying rate can be affected by different factors like species, thickness, grain pattern, yard characteristics, pile characteristics, and weather conditions (Dening et. al 2000, Reeb and Brown 2007).

Hart et. al (1992) and Wengert (1990) determined that the number of checks increased in the lumber that has been dried or partially air dried after moisture has been added. The open checks may cause yield losses from the lumber that might be used for furniture or saw mills. In a study done by Gammon (1971), the author found a 13% potential loss in 4/4 red oak after it was air dried. This percentage was mostly due to shrinkage, and most of the lumber degrade can be due to seasoning defects. The author mentioned that defects like warp, checks and splits can be caused to a lack of uniformity in the structure of the wood. In a study developed by the Forest Products Laboratory (1999), it was found that the tendency of checks in air dried oak was high; while the tendency of warp was intermediate.

Stains and discolorations are defects that can be presented in lumber been air dried. These types of stains are called chemical stains, which can darken the wood from gray to brownish colors. The most susceptible species to present chemical stains are white pine, hard maple, western hemlock, ash, birch, hickory, and others. Stains can also be cause by fungi that use wood as food. The typical stains are called “blue stains”, which usually grows in the sapwood of heartwoods and softwoods (Forest Products Laboratory 1999).

In conventional kiln drying, wood dries first from the outside and then the inside. The moisture content gradient produced creates stresses and drying defects. Drying schedules are used to reduce drying stresses by controlling the temperature, relative humidity, and air velocity. However, drying too fast at the beginning stage of a drying schedule can produce the following defects in the wood (Lamb and Wenegert 1982):

1. Surface Checks
2. End Checks
3. Internal Checks (Including Honeycomb)
4. Splits and Cracks
5. Collapse

By the contrary, if lumber is dried to slowly at a high relative humidity, it can produce defects such as: (Lamb and Wenegert 1982):

1. Fungal or Blue Stain
2. Chemical Stain or Graying
3. Warp (Especially Cup)
4. Mold and Mildew

The following defects are caused by poor stacking and stickering:

1. Warp (Especially Bow)
2. Uneven Drying

The three flooring manufactures that use conventional drying (air drying + kiln drying) in their daily operations did not quantify or evaluate the lumber quality; therefore, information from literature was used to compare conventional and vacuum drying quality aspects. However, the comparison from the literature refers to vacuum drying and kiln drying. The results are presented in table 10.

Table 10 Comparison of Vacuum and kiln Drying Quality

Technology	Characteristics						Source
	Color	War	Checks	MC	Shrinkage	Drying	

		p	Internal	Surface	end (coated)	uniformity		stresses	
Vacuum drying			none	none					Simpson 1987
			none	none					Avramidis et. al 1994
						Large Variation			Lamb and Wengert 1993
						2%-28%			Trofatter et al 1986
	similar in color after drying								Moldrup and Moldrup 1992
							4.1%-7.1%		Harris and Taras 1984
	Similar color after drying	4%	none	5%	none	2.9%-26.5%	11.25%		Wengert and Lamb 1982
Conventional Drying						Small variation			Lamb and Wengert 1993
						7% to 11%			Trofatter et al 1986
							5.6% to 10.3%		(Harris and Taras 1984
		11%	3%	9%	25%	5%-9.6%	12.30%		Wengert and Lamb 1982

From table 10, it can be seen that wood color after vacuum drying is similar to its initial color Moldrup and Moldrup (1992), Wengert and Lamb (1982). This could be due to the oxygen reduction present in vacuum drying technology, which reduces oxidation of certain natural compounds in the wood.

Internal and surface checks were not present in vacuum drying according to Simpson (1987) and Avramidis et. al (1994). These authors determined that for conventional drying internal and surface checks were 3% and 25% respectively. Shrinkage reported in the literature varied from 4.1% to 7.1%, for vacuum drying; while in conventional drying, shrinkage varied from 5.6% to 10.3%. In another study, shrinkage in vacuum drying was 11.25% and 12.30% in conventional drying. Stresses in vacuum are less frequent than in conventional because vacuum drying involves relatively low temperatures, so checks and splits are less likely to develop (Chen and Lamb 2007). However, in the study of Wengert and Lamb (1982), moisture content variation was higher in vacuum than conventional drying: from 2.9% to 28% and 5% to 9.6% respectively.

Also, data from Company A and B was collected in order to determine how vacuum drying affects the quality of the wood in terms of color, internal, surface and end checks, warp, and moisture content.

Company A and B do not quantify the quality of the lumber, but visually inspect the lumber before and after drying. Table 11 lists a brief description of drying degrade observed by company A and B for 4/4 red oak.

Table 11. Drying Degrade for Vacuum Drying According to Company A and B for 4/4 Red Oak

Company	Drying degrade for vacuum drying				
	Color	Warp	Internal, surface, end checks	Moisture Content Uniformity	Drying stresses
A	Not affected	No difference compared to conventional	Not presented	MC deviation +/- 1%	Not present
B	Not affected	No difference compared to conventional	Neither any better nor any worse than conventional	Problems with both conventional and vacuum	Not present

According to both Company A and B, vacuum drying does not affect the color of wood, and the wood comes out of the kiln looking as it did when it went in because of the absence of oxygen in the drying process. For example, Moldrup (1992) established that with vacuum drying, lumber is similar in color as it was before drying.

Company A and B stated that drying stresses are not present in their vacuum drying processes since as vapor accumulates in the chamber, the chamber pressure rises. The boiling point of water goes up with the chamber pressure. Evaporation from the wood slows. Water migrates from the wetter areas to the dryer areas in the wood. The wood warms. When the top end of the band is reached, the vacuum system begins to lower chamber pressure. The water in the wood boils even though the temperature is less than 105^{o}F. This process is repeated several times per hour, and stress can be non-existent. Also, since no stresses were observed, no surface checks were presented.

Warp can occur in boards that have tension wood; also, poorly manufactured boards containing excessive wane will also warp, as the sapwood of the tree cut in the warm afternoon tends to have a higher MC.

It can be said that vacuum technology is slightly better than conventional drying (air drying + kiln drying) in terms of shrinkage. In vacuum drying, shrinkage can vary from 4.1% to 7.1%, while surface checks can be approximately 5%. In conventional drying, internal checks can be approximately 3% and end checks 25%. However, conventional drying has better results in moisture content variation, ranging from 5% to 9.6%, while in vacuum drying the variation goes from 2.9% to 28%.

Drying defect rates obtained from this section were used to develop a comparison and determine the possible differences between conventional and vacuum drying. However, companies do not quantify this parameter which complicates the data gathering. The drying degrade rate, used for the other portions of the project was obtained from Table 10, in which warp was 3% and shrinkage 5%.

4.2 Drying Times for 4/4 Red Oak Vacuum and Conventional Drying

The same companies that provided the data on quality in section 4.1 provided data in regard to drying times. Drying times were also obtained from literature. Table 12 lists the drying times for vacuum and conventional drying provided by Company A and B, and the three flooring manufacturers, and literature review for 4/4 and 8/4 red oak.

Table 12. Comparison of Drying Rates between Conventional and Vacuum Drying for 4/4 and 8/4 red oak

Specie	thickness	Initial State	Drying Time				Reference
			Conventional	Vacuum			
				Superheated steam	Platen	High Frequency	
Red Oak	4/4	Green	25-30 days	8-9 days	-	-	Fortin 1998
		Green	-	8 days			Company A & B
		Air dried	18-22 days	4 days	3 days	-	Fortin 1998
		40-45%					Fortin 1998
		Air dried 20-25%	12 days				Company C and D
		Green	21 days				Dening et. al

							2000
		Air dried 20%	5 days				Dening et. al 2000
	8/4	Green	85-95 days	28-30 days	-	-	Fortin 1998
	8/4	Green	63 days	88 hrs			Avramidis et. al1994
	12/4	Green	150-180**	-	13-14 days	4-7**	Fortin 1998

It can be seen in Table 12 that vacuum drying times for 4/4 red oak average 8 days when it is dried from the green state, and 4 days when it is air dried to 20%; while conventional drying takes a total of 54 days, of which 42 days are for air drying and 12 days for kiln drying. The main difference between vacuum and conventional drying rates is that in vacuum drying the water movement is done by longitudinal diffusion, while in conventional drying it is transversal diffusion. Thus, in vacuum drying, most moisture transfer occurs through the end-grain (wood can be 10,000 times more permeable in the longitudinal direction compared with the transverse direction) (Chen and Lamb, 2007).

For this project an average drying rate of 8 days will be used for vacuum drying with no air drying, while an average of 4 days was used for the case of vacuum with air drying to 40 to 45% MC for a total of 26 days. The conventional drying rates will be 42 days of air drying to a 20-25% moisture content and then 12 days of kiln drying for a total of 54 days.

4.3 Conventional and Vacuum Drying Costs.

A model to estimate drying costs was created based on studies of the wood drying economics discussed in the literature (Section 2.7). The proposed model includes variables that estimate the total cost of a drying operation, which means costs regarding the price of land, buildings, kilns and equipment, lighting, fencing, drainage installation, air-drying area, maintenance, road constructions, labor, and electricity.

Data for each cost (fixed or variable) involved in conventional drying was collected during visits to the flooring manufacturers as outlined in section 3.1. Data was supplied by the production managers at each company. While each company was able to provide some of the data, none could provide all the cost data necessary. For example, one of the company's drying operations was not only used for flooring but also for lumber sold on the open market and the company could not separate their drying costs respective to flooring and lumber sales. Another example was trying to separate electrical usage between drying costs and the flooring manufacturing (fan rating, Kiln Kw, fuel consumption). Also, none of the companies kept records of the costs of piles, bolsters, maintenance, or depreciation of the equipment. Table 13 presents the information that each company was able to answer and provide in the data collection instrument.

Table 13. Data Collected from three flooring manufactures regarding Drying Costs

FINANCE VARIABLES	**Company able to answer**
Direct investments (total costs)	
Buildings, sheds, etc.	Plant D and E
Kiln (including, auxiliary equipment, boiler, installation)	none
Stickers	Plant D and E
Pile roofs	Plant E
Pile bases, bolsters	Plant D and E
Depreciation period for direct investments (years)	
Buildings, sheds, etc.	none
Kiln, auxiliary equipment (including boiler)	none
Stickers	none
Pile roofs	none
Pile bases, bolsters	none
Drying yard investments (Total costs)	
Temporary road construction (includes drying alleys)	Plant D
Fences	none
Lighting systems	none

Drainage systems	none
Sprinkler systems	none
Depreciation period for drying yard investments	
Fences	none
Lighting systems	none
Sprinkler systems	none
Storage sheds for stickers, dried lumber, etc.	none
OTHER FINANCE VARIABLES(If applicable)	
Maintenance of kilns and boiler ($).	none
Maintenance and repair of yard ($)	none
Snow removal ($/yr)	none
Land area (ft2)	
Air drying area (include space between the piles) ($/Acre)	Plant C,D,E
Road area ($/Acre)	Plant C,D,E
Area for buildings, kiln, boiler, etc. ($/Acre)	Plant C,D,E
Land value ($/Acre)	Plant D
Annual interest rate (%)	Plant D
Tax rate to be applied to the total of taxable values (%)	Plant D
Insurance rate applied to the total of insurable values (%)	Plant D

Continue Table 13

Direct investments (total costs)	
CAPACITY VARIABLES	
Average price of lumber ($/Mbf)	none
Average drying degrades based on lumber value (percent as decimal)	Plant C
Average daily volume of lumber on yard and in kilns on any given day (MBF)	Plant C, D, E
Total capacity of kilns	Plant C, D, E
Number of Kilns	Plant C, D, E
Operational year	Plant C, D, E
Annual throughput (Mbf/yr)	Plant C, D, E
Run times	Plant C, D, E
Kiln cycles per year	Plant C, D, E
Average length of kiln run (include loading and unloading time)	Plant C, D, E
Number of fans	Plant D
Fan rating (kW)	none
Air drying time (weeks)	Plant C, D, E

Final Drying time (hrs)	Plant C, D, E
Volume air dry yard (MBF)	Plant C, D, E
Maximum drying temperature (F)	Plant C, D, E
Minimum drying temperature (F)	Plant C, D, E
OPERATIONAL VARIABLES	
Forklift wage ($/yr)	Plant D and E
Lumber graders ($/yr)	Plant D and E
Wage for kiln operator and yard supervisor ($/yr)	Plant D and E
ENERGY COSTS	
Fuel consumption (hog waste) (tons/day)	Plant D
Fuel cost ($/ton)	Plant D
Annual electrical usage attributed to drying (kWh/yr)	none
Electrical cost ($/kWh)	Plant D
Initial MC (%)	Plant C, D, E
Final MC (%)	Plant C, D, E
Raw Material Cost ($/MBF)	none

Two case studies were developed to estimate the cost for drying using different drying methods. Plant C and D were chosen for each case study. Plant C dries wood for flooring and for selling dried lumber, while Plant D is an industry that only dries lumber for flooring production. Plant C was not able to provide the complete cost information for the flooring production solely, so a hypothetical case was developed. The hypothetical case consisted of an estimation of the parameters for drying only the lumber needed for flooring production. Some data had to be estimated as it was not available from the manufacturers. For example, the fence price was determined by using an approximation of the area (provided by the company) and an online estimator. The cost model for each case study was calculated for three scenarios: 1) conventional drying (air drying +kiln drying), 2) vacuum with air drying, and 3) vacuum with no air drying. The formulas that were used to calculate the costs are presented in Appendix II. Tables 14 and 15 show the total costs for each variable analyzed according to each scenario: conventional drying, vacuum with air drying, and vacuum with no air drying.

Table 14. Cost Values for Plant C for the Three Different Scenarios

FINANCE VARIABLES	Scenario		
Direct investments (total costs)	**Conventional**	**Vacuum with air drying**	**Vacuum with no air drying**
Buildings, sheds, etc.	$762,097	$387,505	$193,752
Kiln (including boiler, vacuum pump, material handling, auxiliary equipment)	$2,575,000	$3,938,550	$7,566,750
Stickers	$393,838	$1,182,384	$92,560
Pile roofs	$113,250	$340,000	*
Pile bases, bolsters	$146,772	$190,400	*
Depreciation period for direct investments (years)			
Buildings, sheds, etc.	20	20	20
Kiln, auxiliary equipment (including boiler)	20	10	10
Stickers	3	3	3
Pile roofs	5	5	*

Pile bases, bolsters	5	5	*
Drying yard investments (Total costs)			
Temporary road construction (includes drying alleys)	$120,000	$120,000	$120,000
Fences	$8,198	$9,191	*
Lighting systems	$1,377	$1,377	*
Drainage systems	$4,090	$4,090	*
Sprinkler systems	$2,520	$2,520	
Depreciation period for drying yard investments			
Fences	20	20	*
Lighting systems	20	20	*
Sprinkler systems	15	15	*
Storage sheds for stickers, dried lumber, etc.	20	10	*
OTHER FINANCE VARIABLES(If applicable)			
Maintenance of kilns and boiler ($).	$29,925	$29,925	$29,925
Maintenance and repair of yard ($)	$15,000	$15,000	*
Snow removal ($/yr)	$4,500	$4,500	*

Continue Table 14

Land area (ft2)			
Air drying area (include space between the piles) ($/Acre)	$175,000	$175,000	*
Road area ($/Acre)	$175,000	$175,000	*
Area for buildings, kiln, boiler, etc. ($/Acre)	$150,000	$150,000	$175,000
Land value ($/Acre)	$25,000	$25,000	$25,000
Annual interest rate (%)	9	9	9
Tax rate to be applied to the total of taxable values (%)	5	5	4
Insurance rate applied to the total of insurable values (%)	1.71	1.71	1.71
CAPACITY VARIABLES			
Average price of lumber ($/MBF)	$1,200	$1,200	$1,200
Average drying degrades based on lumber value (percent as decimal)	0.03	0.03	0.03
Total capacity of kilns	525000	157742	303350
Number of Kilns	7	13	25
Operational year	365	365	365
Annual throughput (MBF/yr.)	13,650	14,393	13,954
Run times (hrs.)	24	24	24
Kiln cycles per year	26	91.25	46

Average length of kiln run (days)	12	4	8
Number of fans	35	*	*
Fan rating (kW)	3.73	*	*
Air drying time (weeks)	6	6	*
Final Drying time (hrs)	295	96	192
Volume air dry stock (Mbf)	4,000	12,012	*
Maximum drying temperature (F)	180	180	180
Minimum drying temperature (F)	90	90	90
Raw material cost ($/MBF)	16,061,500	$39,779,935	$12,698,231

Continue Table 14

OPERATIONAL VARIABLES			
Forklift wage ($/yr)	$114,000	$114,000	$114,000
Lumber graders ($/yr)	$160,000	$160,000	*
Wage for kiln operator and yard supervisor ($/yr)	$67,000	$67,000	$33,500
Vacuum pump rating kw/1000bf)	*	1.5	1.5
Vacuum pump usage	*	20	20
Condenser fan rating	*	11	11
Condenser fan usage	*	25	25
ENERGY COSTS			
Fuel consumption (gal/day)	13.50	20	20
Fuel cost ($/gal)	35	$3.50	$3.50
Annual electrical usage attributed to drying (kW/year)	1383200	1197163.5	1160580
Electrical cost ($/kWh)	0.10	0.1	0.1
Initial MC (%)	20	20	70
Final MC (%)	8	8	8

Plant D provided the area of their storage building, which was 13,500 square feet. The volume of dried lumber that was stored in this building was 4.65 MMBF, and the cost/value of the building was $50/square foot. For plant C, the area of the storage building was calculated by establishing a relationship between the square feet and the volume of lumber dried in Plant D. The storage building area obtained for Plant C was 152,942 square feet for conventional drying, 3,875 square feet for vacuum with air drying, and 7,750 square feet for vacuum with no air drying. The price of the building was then multiplied by the total square feet of the building area.

The price of the kiln company A boiler of 75 HP was $125,000, auxiliary equipment was $ 2,500 and the concrete foundation for conventional drying was $ 35,000. The price of the kiln of 80,000 BF kiln capacity was $312,500 as provided by Plant D. The price of the kiln, auxiliary equipment and concrete foundation were summed and multiplied by the number of kilns that each case study used (for Plant C, 7 kilns). The value was then added to the price of the boiler.

Regarding vacuum drying costs, company A and B from section 4.1 provided information about: 1) price of the equipment and material handling, 2) cost of electricity(kW, BTU's, fuel consumption, and 3) kiln board feet capacity. However, the companies were not able to provide information about vacuum and condenser rate and price, and thermal loss. These values were obtained from a study conducted by Redman (2011) (see chapter 2).

The capacity of the vacuum kilns was 12.14 MBF. The number of kilns used in the model was estimated by the annual throughput for Plant C divided by the average drying rate (4 days for vacuum with air drying and 8 days for vacuum with no air drying); the obtained value corresponded to the number of loads per year. Then the number of cycles per year was multiplied by the capacity of the kiln, which referred to the throughput per year. Then the annual throughput per year for Plant C was divided by the estimated throughput with vacuum drying. A total of 13 vacuum kilns for the scenario of vacuum drying with air drying were obtained. The same steps were used to calculate the number for vacuum with no air drying, with the exception of using 8 days for drying times. A value of 25 kilns was obtained.

The cost of the chamber, material handling and boiler (12HP) were provided by company A: $298,350, $4000, and $8000 respectively. The chamber and material handling values were summed and multiplied by the number of kilns for each scenario of vacuum with air drying and vacuum with no air drying. The obtained value was then summed together to the price of the boiler.

Pile roofs, bolsters, base and stickers' costs were calculated using the cost information supplied by Plant E. An approximated number of piles were calculated for Plant C. A pile was estimated to be 12 feet long, containing approximately 8832 BF. The total volume or board foot presented in the air yard for each Plant C was divided by the total board feet presented in a pile. For Plant C a total of 214 piles were obtained. The estimated cost of a pile roof was $250. The pile roof cost was then multiplied by the number of piles for company C. The stickers had a price of $1.35/stick, so a number of 7 stickers per layer were calculated. The obtained value was then multiplied by the total number of layers (23) of each pack, and then by the total number of packs (4). Plant D provided a pile base and bolster cost of $8 and $11.5 respectively. A number of 6 bases per pile and 7 bolsters per pack were determined. The amount of bases and bolsters were multiplied by the price, and then by the total number of piles for Plant C.

Road construction costs were estimated using values obtained from Plant D, which were $120,000. An online estimator where the area and location of the property was placed on the input of the online estimator and an approximated cost was given. The area given by Plant C was 20 acres. The land price was given by Plant D and the value was of $25000/acre. The respective acres of each company were multiplied by $25000 and the land area cost was obtained.

The estimation of the air drying for vacuum drying was done because the drying rate is faster so the air drying will need more input to be able to load a kiln every 4 days. Volume was obtained by multiplying the chamber capacity (12.14 MBF) by the time it takes to be kiln dried (4 days), times the time it takes to be air dried (67 days). This value was then multiplied by the number of kilns, resulting in 42275 MBF. The pile estimation was done following the same procedures as in conventional drying. The obtained number of piles for Plant C was 628.The piles roofs, bases, and stickers were calculated by multiplying the respective number of piles by the price provided by Plant E.

Tax and insurance rates were based on information provided by Plant D. The price of lumber was obtained from the Hardwood Market Report 2013. The average daily volume of lumber on yard and in kilns on any given day (MBF), total capacity of kilns, number of Kilns, operational year, annual throughput (MBF/yr), run times (hrs.), kiln cycles per year, average length of kiln run (days), air drying time (weeks), final drying time (hrs), volume air dry stock (Mbf), maximum and minimum drying temperature (F) were provided by Plant C.

The number of fans and fan rate per load (KW) was estimated using information supplied by kiln company A. The total of kW per year for Plant C was estimated by multiplying the number of fans by the total number of kilns. Then, the fan rate per load was multiplied by the number of cycles per year and then by the total number of fans. The electrical cost was provided by Plant D ($0.10/kW) and it was multiplied by the kW per year for each company. Fuel consumption was given by Plant D and the formulas to estimate the BTU's are presented in Appendix II. The depreciation for fences, lightning systems, stickers were taken from the study proposed by MacMillen and Wengert (1978); the maintenance of the kiln, boiler and yard was taken from Fortin (2010). The wage salaries were estimated using information supplied by Plant D.

The electrical usage per load for vacuum drying was provided by Company A. The amount of kW/load was multiplied by the respective number of loads in each scenario (vacuum with air drying and no air drying); then, the obtained value was multiplied by the total number of kilns of each scenario. The electrical cost was obtained from Plant D ($0.10/kW) and it was multiplied by the total amount of kW/year. Vacuum drying costs with no air drying were estimated as described for conventional and vacuum air drying.

Plant D provided the wage salaries per year of their workers, and these were used as a base for the Plant C operators. The wage salaries correspond to two forklift works, two lumber graders, one kiln operator and one yard operator. In the case of vacuum drying with no air drying, only the kiln operator is considered. The maintenance cost was gathered from Fortin (1998). Raw material for conventional and vacuum drying was calculated by adding to the annual throughput the air drying volume to meet demand. The obtained value was multiplied by the cost of green lumber provided by the Hardwood Market Report ($910/MBF).

Table 15 Plant D Variables to Calculate Conventional Drying Costs.

FINANCE VARIABLES	Scenario		
Direct investments (total costs)	**Conventional**	**Vacuum with air drying**	**Vacuum with no air drying**
Buildings, sheds, etc.	$675,000	$440,347.00	$228,980.00
Kiln (including boiler, vacuum pump, material handling, auxiliary equipment)	$2,225,000	$3,333,850.00	$6,659,700.00
Stickers	$406,010	$1,397,126.00	$1,100.00
Pile roofs	$116,750	$401,750.00	*
Pile bases, bolsters	$139,164	$224,980.00	*
Depreciation period for direct investments (years)			
Buildings, sheds, etc.	$20	20	20
Kiln, auxiliary equipment (including boiler)	$20	10	10
Stickers	$3	3	3
Pile roofs	$5	5	*
Pile bases, bolsters	$5	5	*

Drying yard investments (Total costs)			
Temporary road construction (includes drying alleys)	$120,000	$120,000	$120,000
Fences	$9,191	$9,191.23	*
Lighting systems	$1,377	$1,376.90	*
Drainage systems	$4,090	$4,090.00	*
Sprinkler systems	$2,160	$4,680.00	*
Depreciation period for drying yard investments			
Fences	$20	20	*
Lighting systems	$20	20	*
Sprinkler systems	$15	15	*
Storage sheds for stickers, dried lumber, etc.	$20	10	*
OTHER FINANCE VARIABLES(If applicable)			
Maintenance of kilns and boiler ($).	$29,925	$29,925.00	$29,925
Maintenance and repair of yard ($)	$15,000	$15,000	*
Snow removal ($/yr)	$4,500	$4,500	*

Continue Table 15

Land area (ft2)			
Air drying area (include space between the piles) ($/Acre)	$100,000	$100,000	*
Road area ($/Acre)	$75,000	$75,000	*
Area for buildings, kiln, boiler, etc. ($/Acre)	$75,000	$75,000	$75,000
Land value ($/Acre)	$25,000	$25,000	$25,000
Annual interest rate (%)	9	9	9
Tax rate to be applied to the total of taxable values (%)	5	5	4
Insurance rate applied to the total of insurable values (%)	2	2	2
CAPACITY VARIABLES			
Average price of lumber ($/M bm)	$1,275	$1,275	$1,275
Average drying degrades based on lumber value (percent as decimal)	0.30	0.3	0.3
Average daily volume of lumber on yard and in kilns on any given day (M bm)	4000	4000	4000
Total capacity of kilns	480000	133485	266970
Number of Kilns	6	11	22
Operational year	365	365	365

Annual throughput (Mbf/yr)	12000	12000	12000
Run times (hr)	24	24	24
Kiln cycles per year	25	91.	46
Average length of kiln run (include loading and unloading time) (days)	12.30	4	8
Number of fans	35	*	*
Fan rating (kW)	5	*	*
Air drying time (weeks)	6	16	*
Final Drying time (hrs)	295	96	192
Volume air dry stock (Mbf)	4,125	14,197	*
Maximum drying temperature (F)	180	180	180
Minimum drying temperature (F)	105	105	105
Raw Material ($/MBF)	$14,673,750	$43,634,986	$11,174,443

Continue Table 15

OPERATIONAL VARIABLES	**Value**	Value	Value
Forklift wage ($/yr)	$114,000	$114,000	$114,000
Lumber graders ($/yr)	$160,000	$160,000	*
Wage for klin operator and yard supervisor ($/yr)	$67,000	$67,000	$33,500
Vacuum pump rating kw/1000bf)	*	1.5	1.5
Vacuum pump usage	*	20	20
Condenser fan rating	*	11	11
Condenser fan usage	*	25	25
ENERGY COSTS			
Fuel consumption (gal/day)	13.50	20	20
Fuel cost ($/gal)	35	$3.50	$3.50
Annual electrical usage attributed to drying (kW/year)	1845770	1012984	1021310
Electrical cost ($/kWh)	0.10	0.1	0.1
Initial MC (%)	20	20	70

Final MC (%)	8	8	8

Plant D provided the area of their storage building, which was 13,500 square feet. The volume of dried lumber that was stored in this building was of 4.65 MMBF, and the cost of the building was $50/square feet. For Plant D vacuum drying, the area of the storage building was calculated by doing a relation between square feet and volume of lumber dried of Plant D. The storage building area obtained for vacuum with air drying was 4,580 square feet, and for vacuum with no air drying 303,350 square feet. The price of the building was then multiplied by the total square feet of the building area.

The price of the kiln company A boiler of 75 HP was $125,000, auxiliary equipment was $2,500 and the concrete foundation for conventional drying was $35,000. The price of the kiln was provided by Plant D which corresponded to an 80,000 BF kiln capacity, and the price was $312500. The price of the kiln, auxiliary equipment and concrete foundation were summed and multiplied by the number of kilns at Plant D (6 kilns). The obtained value was then added the price of the boiler.

The capacity of the vacuum kilns was 12.14 MBF. The number of kilns used in the model was estimated by the annual throughput for Plant D divided by the average drying rate (4 days for vacuum with air drying and 8 days for vacuum with no air drying); the obtained value corresponded to the number of loads per year. Then the number of cycles per year was multiplied by the capacity of the kiln, which referred to the throughput per year. Then the annual throughput per year for Plant D was divided by the estimated throughput with vacuum drying. A total of 13 and 25 vacuum kilns for the scenarios of vacuum drying with air drying and vacuum with no air drying were obtained respectively.

Company A provided the vacuum drying costs for the chamber, material handling and boiler. The costs of the chamber, material handling and boiler (12HP) were given by company A: $298,350, $4000, and $8000 respectively. The chamber and material handling values were summed and multiplied by the number of kilns of for each scenario vacuum with air drying and vacuum with no air drying. The obtained value was then summed the price of the boiler.

Pile roofs, bolsters, base and stickers' costs were calculated using the cost information supplied by Plant E. An approximated number of piles were calculated for Plant D as described for Plant C. Plant D obtained a total of 467 piles. The pile roof cost ($250) was then multiplied by the number of piles for company D. For the stickers, the price was $1.35/stick, so it was calculated a number of 7 stickers per layer; the obtained value was then multiplied by the total number of layers (23 layers) of each pack, and then by the total number of packs (4 packs). Plant D provided a pile base and bolster cost of $8 and $11.5 respectively. It was determined a number of 6 bases per pile and 7 bolsters per pack. The amount of bases and bolsters were multiplied by the price, and then by the total number of piles for Plant D.

Plant D road construction costs were of $120,000. An online estimator where the area and location of the property was placed on the input of the online estimator and an approximated cost was given. The area given by Plant D was 6 acres respectively. The land price was given by Plant D and the value was of $25000/acre. The respective acres of each company were multiplied by $25000 and the land area cost was obtained.

The estimation of the air drying for vacuum drying was done because the drying rate is faster so the air drying will need more input to be able to load a kiln every 4 days. Volume was by multiplying the chamber capacity (12.14 MBF) by the time it takes to be kiln dried (4 days), times the time it takes to be air dried (67 days); the obtained value was then multiplied by the number of kilns, resulting in 35771 MBF. The pile estimation was done following the same procedures as in conventional drying. The obtained number of piles for Plant D was 742. It was calculated the piles roofs, bases, and stickers by multiplying the respective number of piles by the price provided by Plant E.

Tax and insurance rates were based on information provided by Plant D. The price of lumber was obtained from the Hardwood Market Report 2013. The average daily volume of lumber on yard and in kilns on any given day (MBF), total capacity of kilns, number of Kilns, operational year, annual throughput (MBF/yr), run times (hrs.), kiln cycles per year, average length of kiln run (days), air drying time (weeks), final drying time (hrs), volume air dry stock (Mbf), maximum and minimum drying temperature (F) were provided by Plant C.

The kW per year and electrical cost for Plant D were given by the company. The electrical cost ($0.10/kW) and was multiplied by the kW per year for each company. Fuel consumption was given by Plant D and the formulas to estimate the BTU's are presented in Appendix II. The depreciation for fences, lightning systems, stickers were taken from the study proposed by MacMillen and Wengert (1978), the maintenance of the kiln, boiler and yard was taken from Fortin (2010). The wage salaries were estimated using information supplied by Plant D.

The electrical usage per load for vacuum drying was provided by Company A. The amount of kW/load were multiplied by the respective number of loads of each scenario (vacuum with air drying and no air drying), then the obtained value was multiplied by the total number of kilns of each scenario. The electrical cost was obtained from Plant D ($0.10/kW) and it was multiplied by the total amount of kW/ year. Vacuum drying costs with no air drying were estimated as described for conventional and vacuum air drying.

Plant D provided the wage salary per year. The wage salaries corresponds for two forklift works, 2 lumber graders, one kiln operator and one yard operator. In the case of vacuum drying with no air drying, it is only considered the kiln operator. Raw material for conventional and vacuum drying was calculated by adding to the annual throughput the air drying volume to meet demand. The obtained value was multiplied by the cost of green lumber provided by the Hardwood Market Report ($910/MBF).

The formulas that were used to calculate the costs are presented in Appendix II. Table 16 shows the obtained values

Table 16. Total Costs for Plant C and D for Three Different Scenarios

Company	Drying scenario		
	Conventional	**Vacuum with air drying**	**Vacuum with no air drying**
C	$156/MBF	$349/MBF	$163/MBF
D	$160/MBF	$373/MBF	$164/MBF

It can be observed that vacuum with air drying obtained the highest cost ($349/MBF) in comparison with the other two scenarios: conventional drying and vacuum with no air drying. The differences in the costs can be due to the capital investment and raw material or inventory cost. The capital investment and inventory cost represented 8.26% and 83% respectively from the total costs, which make vacuum with air drying costs to be higher than conventional. In the case of Plant D, vacuum with air drying presented the higher cost values. Differences in the costs rates between the three scenarios were due to the capital investment and inventory costs, which represented a 7% and 97% respectively from the total costs. The inventory cost for vacuum with air drying is higher due to the kiln rate of 4 days. This means that there have to be lumber air dried every 4 days to fulfill the customer demand.

While these results clearly show that conventional drying has the lowest cost per MBF, they do not show which scenario and technology is most economically viable because the costs are for a fixed time period and not projected for a longer period of time. Such an analysis is presented in chapter 5 to determine the feasibility of the three scenarios.

4.4 Summary

In this chapter, it was determined that vacuum drying quality is slightly better than conventional drying, with less checking, end splits, drying stress and shrinkage. Vacuum drying times for 4/4 red oak average 8 days when it is dried from the green state and 4 days when it is air dried to 40% MC. Conventional drying takes a total average of 54 days from air drying (42 days) and kiln drying (12 days). Thus, vacuum drying is significantly quicker (92%) than conventional drying which may allow for improvements in cycle time, throughput and reduced inventory levels in the remaining manufacturing processes. From the three scenarios studied (conventional kiln, vacuum with air drying and vacuum with no air drying), for both plants C and D, vacuum drying with air drying obtained the highest cost, $349/MBF and $373/MBF respectively. The higher cost is due to the kilns capital investment and inventory cost, which represented 8.26% and 83%, and 7% and 97% of the total costs of vacuum with air drying respectively for Plant C and D. While vacuum drying has the highest cost per MBF, it is possible that over time it may prove to be a more feasible investment. It is also possible that for a manufacturing facility that dries its own lumber for consumption the reductions in inventory levels, work in process and lead times may offset the high capital costs.

CHAPTER 5

FEASIBILITY ANALYSIS FOR THE INVESTMENT OF CONVENTIONAL AND VACUUM DRYING

One of the objectives of the project is to determine by the use of a feasibility analysis (cash flow, net present value, and internal rate of return) differences between conventional and vacuum drying for 4/4 red oak lumber. The drying costs obtained in chapter 4 were used to perform the feasibility analysis. The cash flow was performed in Microsoft Excel. Net present value and internal rate of return were calculated using the formulas presented in chapter 3. The obtained values of NPV and IRR were used to compare conventional with vacuum drying and to determine which technology was more economically feasible. The analysis was conducted for a

20 year time period. According to Govett et. al(2006), 20 years is a good analysis period for drying investments due to the life expectations.

Some assumptions were made to be able to estimate the rest of the variables needed for the cost model. These assumptions are the following:

1. Sales increase rate is of 4% per year.
2. Bank businesses loans go from \$25000 to \$200000, and finance 80% of the requested value. For the company we will assume that a loan of \$200000 was made where the bank approved 80% corresponding to \$1600000 with an interest rate of 9%.

A cash flow spreadsheet was created to calculate the net present value and internal rate of return to see which technology was more feasible. According to Rodgers (2011) a cash flow is composed of three essential elements: a) Operating activities, b) investing activities, and c) financing activities. The cost information for each of the elements that compose a cash flow was gathered from the cost analysis in chapter 4. The methodology from Keown et. al (2006) was used: The operating activities referred to operational, maintenance, land, and energy costs. The investing activities were the costs of assets like kilns, buildings, etc., stickers and their respective depreciation. The financing activity was referred to the bank loan and the interest rate. Section 3.2 describes in more detail the methods to create the cash flow.

5.1 Plant C Feasibility Analysis

The net cash flow for plant C for conventional drying, vacuum with air drying and vacuum with no air drying are shown in Tables 17, 18, and 19 respectively. It can be seen that at the year “0” the net cash flow for the three cases is negative, but then while the years increase the net cash flow becomes positive. Generally when a company is starting up a business, they have at the beginning negative cash flows from operations and investing activities, while positive cash flows from financing activities. This is due to the inventories, capture of new costumers, purchase of materials and equipment (assets) that are done when the business is established (Comiskey and Mulford 1993).

Table 17. Net Cash Flow for Conventional Drying for Plant C

cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		16,380,000	17,035,200	17,716,608	18,425,272	19,162,283	19,928,775	20,725,926	21,554,963	22,417,161	23,313,847	24,246,401	25,216,257	26,224,908	27,273,904	28,364,860	29,499,455	30,679,433	31,906,610	33,182,875	34,510,190
(-) Costs		16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231	16,615,231
(-) tax		-20,977	31,439	85,951	142,645	201,605	262,925	326,697	393,020	461,996	533,731	608,335	685,923	766,615	850,535	937,812	1,028,579	1,122,977	1,221,152	1,323,253	1,429,438
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	-4,627,142	-532,159	70,625	697,521	1,349,492	2,027,542	2,732,714	3,466,093	4,546,712	5,339,934	6,164,886	7,022,835	7,915,103	8,843,061	9,808,138	10,811,817	11,855,644	12,941,224	14,070,227	15,244,391	16,465,520

Table 18 Net Cash Flow for Vacuum with Air Drying for Plant C

cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		16,380,000	17,035,200	17,716,608	18,425,272	19,162,283	19,928,775	20,725,926	21,554,963	22,417,161	23,313,847	24,246,401	25,216,257	26,224,908	27,273,904	28,364,860	29,499,455	30,679,433	31,906,610	33,182,875	34,510,190
(-) Costs		41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832	41,040,832
(-) tax		-1,978,492	-1,926,076	-1,871,563	-1,814,870	-1,755,909	-1,694,590	-1,630,818	-1,564,495	-1,495,519	-1,423,784	-1,349,180	-1,271,591	-1,190,899	-1,106,980	-1,019,703	-928,936	-834,537	-736,363	-634,262	-528,077
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	-6,676,017	-23,000,245	-22,397,461	-21,770,566	-21,118,594	-20,440,544	-19,735,372	-19,001,994	-17,921,375	-17,128,152	-16,303,201	-15,445,251	-14,552,983	-13,625,025	-12,659,948	-11,656,269	-10,612,442	-9,526,862	-8,397,859	-7,223,696	-6,002,566

Table 19 Net Cash Flow for Vacuum with no Air Drying for Plant C

cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		16,380,000	17,035,200	17,716,608	18,425,272	19,162,283	19,928,775	20,725,926	21,554,963	22,417,161	23,313,847	24,246,401	25,216,257	26,224,908	27,273,904	28,364,860	29,499,455	30,679,433	31,906,610	33,182,875	34,510,190
(-) Costs		14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825	14,386,825
(-) tax		154,684	207,100	261,613	318,306	377,267	438,586	502,358	568,681	637,657	709,392	783,997	861,585	942,277	1,026,197	1,113,473	1,204,241	1,298,639	1,396,813	1,498,914	1,605,100
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	1,520,586	1,520,586	2,123,370	2,750,265	3,402,236	4,080,286	4,785,458	5,518,837	6,599,456	7,392,679	8,217,630	9,075,580	9,967,847	10,895,806	11,860,882	12,864,562	13,908,389	14,993,969	16,122,972	17,297,135	18,518,265

Newnan and Lavelle (1998) established three major economic analysis techniques to determine the economic viability of a project, which are: cash flow net present value, and internal rate of return. The net present value is a method used to compare costs and benefits by deducting them to present values over a determinate project life. The internal rate of return is described as the discount rate at which the NPV is equal to zero, and the discounted cash flow equals the initial investment cost (Lang and Merino 1993). The net present value (NPV) and the internal rate of return (IRR) were calculated using the obtained values from the net cash flow for each scenario: conventional, vacuum with air drying, vacuum with no air drying. Results are presented in Table 20.

Table 20. Net Present Value (NPV) and Internal Rate of Return (IRR) For Plant C

Scenario	**Plant C**	
	NPV	**IRR**
Conventional Drying	$17,039,064	33%
Vacuum Drying with Air Drying	-$125,645,009	-16%
Vacuum without Air Drying	$26,553,430	40%

The net present value can be positive or negative, a positive NPV indicates that the company's benefits are greater than the costs; while a negative represents that costs are greater than benefits. It can be said that for the study conventional drying and vacuum with no air drying are economic feasible. A project is considered economically feasible if NPV is positive. (Newnan and Lavelle 1998). However, if we compare these two scenarios, vacuum with no air drying is more economically viable than conventional drying, due to the high value of NPV reported for vacuum with no drying. A higher NPV will be more feasible, if more than one NPV is compared (Newnan and Lavelle 1998). However, vacuum with air drying obtained a negative NPV, which indicates that this scenario is not feasible. The main difference between the three scenarios is the inventory cost that is needed at each scenario. Vacuum with air drying kiln rates are faster (4 days), which means that lumber the air drying yard should be bigger to fulfill the loading of the kilns every 4 days. This increases the inventory and air drying costs.

Regarding the IRR, values of 33% and 40% for conventional and vacuum with no air drying were obtained respectively for Plant C. It can be said that the two scenarios are economically feasible at a discount rate of 15%. When the NPV is positive, the IRR will be greater than the discount rate; while when the NPV is negative it will be less than the discount rate (Lang and Merino 1993). Vacuum with no air drying obtained a higher IRR, which means that it is more viable than conventional drying. The IRR for vacuum with air drying was negative, due to the negative NPV, which indicates that this scenario is not feasible.

5.2 PLANT D FEASIBILITY ANALYSIS

A feasibility analysis was also conducted for Plant D. A cash flow analysis was created for the same scenarios mentioned in Plant C analysis (section 5.1). The net cash flows for the three scenarios were obtained from the cash flow statement.

It can be seen in Table 21 and 23 that for the three scenarios (conventional, vacuum with air drying, vacuum with no air drying) the net cash flow value at the year "0" was negative, and as the period of years increased, the net cash flows turned into positive values. This behavior can be explained by Rodgers (2011) who established that after a company is starting up, the firm goes into a growth phase, where the operating activities gain improvement and which is shown by positive net profits. However, the company's investing activities will still show a negative cash flow because the firm is still adding capacity and consuming external capital. Then, once the company is finally established or matured, the cash flow will be positive, reflecting the operating activities. A similar behavior, as described by Rodgers (2011), can be seen in table 21 and 23. After year 1, profit growth can be seen, which means that some of the debt and dividends are being paid off.

After the cash flow was computed, the net present value and the internal rate of return were calculated by using the values obtained from the net cash flow analysis. Then, the values between the three scenarios were compared to determine which scenario was best. Results are presented in Tables 21, 22, and 23.

Table 21. Net Cash Flow for Conventional for Plant D

Cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		15,300,000	15,912,000	16,548,480	17,210,419	17,898,836	18,614,789	19,359,381	20,133,756	20,939,106	21,776,671	22,647,738	23,553,647	24,495,793	25,475,625	26,494,650	27,554,436	28,656,613	29,802,878	30,994,993	32,234,792
(-) Costs		15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506	15,264,506
(-) tax		625	49,585	100,503	153,458	208,532	265,808	325,375	387,325	451,753	518,759	588,444	660,917	736,288	814,675	896,197	980,980	1,069,154	1,160,855	1,256,224	1,355,408
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	-3,948,742	-283,035	280,005	865,566	1,474,550	2,107,894	2,766,571	3,451,595	4,481,925	5,222,847	5,993,406	6,794,788	7,628,225	8,494,999	9,396,444	10,333,947	11,308,950	12,322,953	13,377,517	14,474,263	15,614,878

Table 22 Net Cash Flow for Vacuum with Air Drying for Plant D

Cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		15,300,000	15,912,000	16,548,480	17,210,419	17,898,836	18,614,789	19,359,381	20,133,756	20,939,106	21,776,671	22,647,738	23,553,647	24,495,793	25,475,625	26,494,650	27,554,436	28,656,613	29,802,878	30,994,993	32,234,792
(-) Costs		44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399	44,773,399
(-) tax		-2,364,520	-2,315,560	-2,264,641	-2,211,686	-2,156,613	-2,099,337	-2,039,769	-1,977,819	-1,913,391	-1,846,386	-1,776,701	-1,704,228	-1,628,856	-1,550,470	-1,468,948	-1,384,165	-1,295,991	-1,204,290	-1,108,920	-1,009,736
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	-6,580,724	-27,426,784	-26,863,744	-26,278,182	-25,669,198	-25,035,854	-24,377,177	-23,692,153	-22,661,823	-21,920,901	-21,150,342	-20,348,960	-19,515,523	-18,648,749	-17,747,304	-16,809,801	-15,834,798	-14,820,795	-13,766,231	-12,669,485	-11,528,870

Table 23 Net Cash Flow for Vacuum with no Air Drying for Plant D

Cash flow	year 0	year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
(+) Sales		15,300,000	15,912,000	16,548,480	17,210,419	17,898,836	18,614,789	19,359,381	20,133,756	20,939,106	21,776,671	22,647,738	23,553,647	24,495,793	25,475,625	26,494,650	27,554,436	28,656,613	29,802,878	30,994,993	32,234,792
(-) Costs		12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602	12,735,602
(-) tax		199,895	248,855	299,773	352,728	407,802	465,078	524,645	586,595	651,023	718,029	787,714	860,187	935,558	1,013,945	1,095,467	1,180,250	1,268,424	1,360,125	1,455,494	1,554,678
(-) interest		144,000	128,349	111,289	92,693	72,424	50,331	26,249													
(-)Amortization		173,905	189,556	206,616	225,212	245,481	267,574	291,656													
Net cash flow	-8,111,657	2,046,599	2,609,639	3,195,200	3,804,184	4,437,528	5,096,205	5,781,229	6,811,559	7,552,481	8,323,040	9,124,422	9,957,859	10,824,633	11,726,078	12,663,581	13,638,584	14,652,587	15,707,151	16,803,897	17,944,512

Table 24. Net Present Value (NPV) and Internal Rate of Return (IRR) for Plant D

Scenario	Plant D	
	NPV	IIR
Conventional Drying	$17,672,640	37%
Vacuum Drying with Air Drying	-$154,861,059	-13%
Vacuum without Air Drying	$29,205,867	43%

The NPVs for conventional drying and vacuum without air drying were positive and larger than one. A positive NPV indicates that the company's benefits are greater than the costs, so it can be said that the two scenarios are feasible. However, the NPV of vacuum with no air drying was highest making this the scenario with most economic viability. The NPV for vacuum with air drying was negative, thus smaller than one, which indicates that the scenario is not feasible. The respective values of IRR for conventional and vacuum without air drying were the following: 37% and 43%. At a discount rate of the 15% it can be seen that the obtained IRR for conventional and vacuum without air drying, makes the two scenarios feasible. According to the literature review, when the IRR is larger than the discount rate, the project is considered as feasible (Zhang 2009). However, vacuum with no air drying obtained the highest IRR percent, making it the best scenario for investment.

However, for vacuum with air drying the IRR was negative (-13%) due to negative value of the NPV, which indicates that the costs are higher than the benefits. Thus, vacuum with air drying is not feasible.

5.3 Summary

The NPVs for conventional drying, vacuum drying with air drying and vacuum drying with no air drying for the case of Plant C were respectively: $17,039,064, -$125,645,009, and $26,553,430. The NPVs for Plant D for conventional drying, vacuum drying with air drying and vacuum drying with no air drying were respectively: $17,672,640, -$154,861,059 and $29,205,867. The obtained values for the IIR for Plant C were: 33%, -16%, and 40% for conventional drying, vacuum drying with air drying and vacuum drying with no air drying, respectively. The IRR values for Plant D were 37%, -13%, and 43% for conventional drying, vacuum drying with air drying and vacuum drying with no air drying, respectively.

The two scenarios evaluated in the feasibility analysis (conventional and vacuum with no air drying) were cost effective in terms of net present value and internal rate of return. However, vacuum with no air drying had higher values of NPV and IRR, which means that, is more feasible or more economically viable than conventional drying. The scenario of vacuum with air drying was not economically feasible in terms of NPV and IRR. The capital costs of the vacuum kiln, boiler and auxiliary equipment, and raw material costs were the parameters that impacted the total costs among the three different scenarios. For plant C the capital investment of the kiln, boiler, and auxiliary equipment for vacuum with air drying was 23% higher than in conventional drying; and vacuum with no air drying was 61% higher than in conventional drying. Vacuum with no air drying required 50% more kiln capacity than vacuum with air drying. For plant D the total capital investment of the kilns, boiler and auxiliary equipment for vacuum with air drying was 44% higher than in conventional drying and vacuum with no air drying was 71% higher than in conventional drying It can be seen that vacuum with no air drying is more economically feasible regarding NPV, IRR, and inventory cost.

Table **25**). In terms of inventory cost, vacuum with air drying was 60% more than in conventional for Plant C; while for Plant D, vacuum with air drying inventory cost was 66% more than conventional drying. It can be seen that vacuum with no air drying is more economically feasible regarding NPV, IRR, and inventory cost.

Table 25 Capital Cost Investments for Plant C and D

Parameter	Plant C			Plant D		
	conventional	vacuum with air drying	vacuum with no air drying	conventional	vacuum with air drying	vacuum with no air drying
Kiln equipment	$2,575,000	$3,333,850	$6,659,700	$2,225,000	$3,938,550	$7,566,750
Inventory Cost	16,061,500	39,779,935	12,698,231	14,673,750	43,634,986	11,174,443

CHAPTER 6

CURRENT STATE VALUE STREAM MAPS FOR PLANT C AND D

This chapter presents the value stream maps developed from Plant C and D using data collected at each facility. For each facility, only one production line was chosen to develop a value stream map. The selection of the production line was based on the product with the greatest demand. Cycle times, changeover times, batch sizes, number of employees, availability of machines, inventory levels, and shipment data was collected by using the methodology of Shook and Rother (2003) as discussed in section 3.3.1. Then, the different processes were graphically shown in a current state value stream map (VSM) using Visio 2013. The VSMs created in this section will serve as key for the future state maps of the respective manufactures in study.

6.1 PLANT C

Plant C main flooring products consist of 2.25” and 3.25” red and white oak pre-finished and un-finished flooring. They have two flooring production lines; however, only one production line was selected: 3.25” prefinished flooring. The production line consists of 7 processes which are: grading and stacking, air drying, kiln drying, surface planner, rip saw, moulder, and pre-finishing.

Customer orders for pre-finished floor are received primarily via email (pdf) to designated incoming order email address. Lumber orders are placed either by email (pdf) or fax. In both cases, flooring and lumber, there can be phone and/or email conversation regarding availability and lead times prior to order submission. Customer demand for 3.25” pre-finished flooring is 325.5 MBF on average per month. Plant C has from 85 to 105 customers that vary with seasonality of demand.

The company works 20 days per month. Shifts are 8.5 hours per day, with 30 minutes for lunch and 2 breaks of 10 minutes each. An optimized program called LISA is used to control and schedule production decisions. For example, kiln drying operations are scheduled weekly, while flooring production is scheduled daily. Shipment to customers is made daily by truck. Shipments from suppliers are also made by truck and are made daily. Orders are placed by email and fax. Also, the company can vary their production scheduling depending on availability of material, competitiveness in the market and inventory. Data required to the VSM of this production line was collected as mentioned in section 3.3.3. Data collected from each process in the production line is presented in Table 26.

Table 26. Parameters observed and reported by the company for each Workstation in the 3.25" wide Red Oak Prefinished Line Production for Plant C.

Process parameters	**Process**					
	Air Drying	**Kiln Drying**	**Surface Planner**	**Rip Saw**	**Moulder**	**Pre-Finishing**
Number of Machines	0	7	1	1	1	1
Batch size	variable	75,000 BF	1,200 BF	1,100 BF	850 BF	850 BF
Process time	6 weeks	12 days	0.83 sec/BF	1.71 sec/BF	2.05 sec/BF	1.2 sec/BF
Number of employees	1	1	7	2	11	15
Changeover time	not applicable	180 min	5 minutes	5 min	5 min	8 minutes
Inventory	1.89 MMBF	717.8MBF	143.5 MBF	470.6 MBF	333.5 MBF	245.3 MBF
Quality	85%	97.50%	97.50%	97.50%	97.50%	97.50%
Yield	100%	97%	100%	80%	63%	98.50%
Uptime machine	not applicable	24 hours	98.90%	98.90%	98.90%	97.60%

6.1.1 Plant C Current State Value Stream Map

A value stream map was developed to visually present the processes involved in the manufacturing of 3.25” red oak pre-finished flooring. Symbols proposed by Apel et. al (2007) were used to map each process. Inventory levels were calculated in days by dividing the amount of inventory by the daily demand, with the purpose to calculate the lead times. Figure 8 shows the value stream map for Plant C.

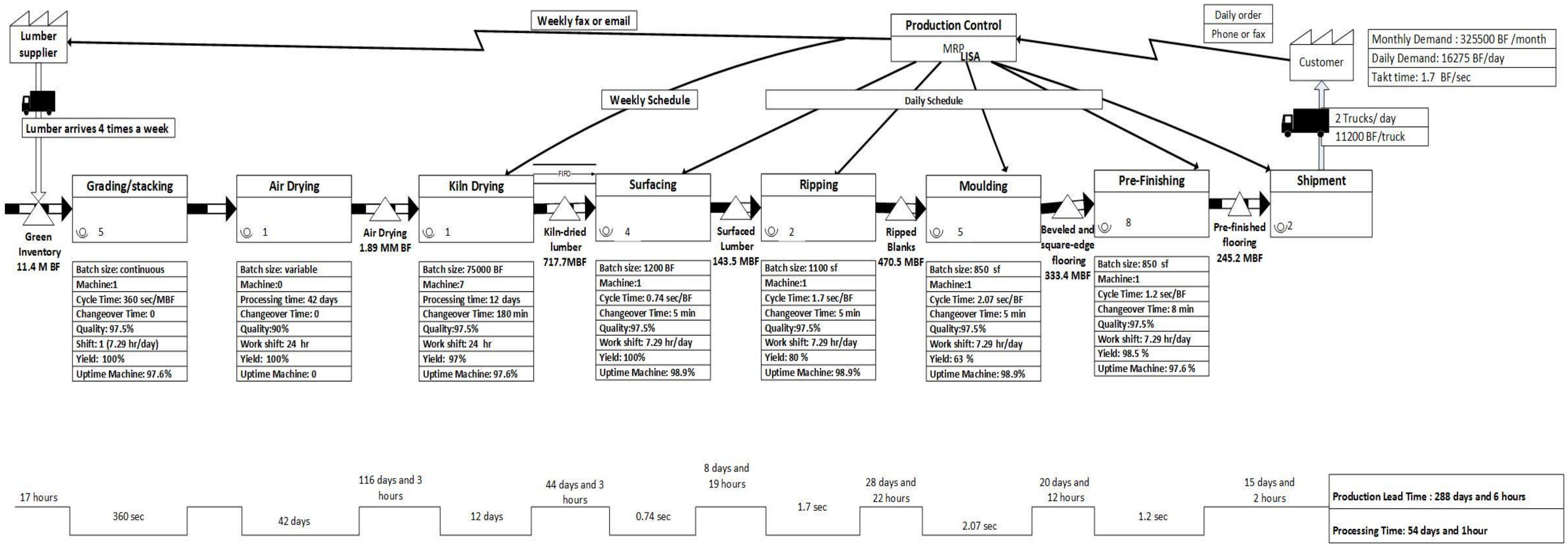


Figure 8. Current value stream map for the pre-finished line in plant C

Plant C has a lean manufacturing concept called cell manufacturing in their production line. In a study performed by Hyer and Brown (1999), cell manufacturing was described as: "Dedicating equipment, and materials to a family of parts or products with similar processing requirements by creating a work flow where tasks and those who perform them are closely connected in terms of time, space and information." Plant C has re-arranged their line production and grouped processes that are common in function and time. The process of chopping, moulding, end matching, grading and nesting were re-arranged into a cellular line with the purpose of reducing inventory and work in process. The cellular line that contains all the mentioned processes is named Moulding.

As shown in Figure 8, manufacturing processes consist of grading and stacking, air drying, kiln drying, surface planning, ripping into blanks, moulding and pre-finishing line. Lumber comes from both external suppliers and internally from their own facilities, and is graded and stacked. Lumber then goes to the air drying for 6 weeks until the moisture content reaches 20 % and then to the kiln drying operation and dried to 8% of moisture content. After the lumber is dried some, it goes to a storage shed (inventory) and into the production line. First, lumber enters into the surface planer which planes the boards to a consistent thickness throughout their length on both surfaces. After the lumber is planed, it goes to the rip saws were it is cut into the dimension standards of the company. Then the ripped blanks go through the moulder line where the four sides of the blank are shaped or moulded into flooring. Any remaining knots, bows, and other defects in the profiled board are cut out with the Chop Saw. The four sided board enters the end matcher which profiles the board at the 2 remaining ends, producing a tongue and a groove, and then it is graded for quality. After grading, flooring goes through the prefinished line where it is micro-beveled and sanded; and then is nested and bundled with plastic strap and piled onto standard sized pallets.

Air drying and kiln drying processing times were 42 and 12 days respectively. Cycle times for the surface planner, rip saw, moulder and pre-finishing machines were 0.74, 1.7, 2.05, 1.2 sec/BF respectively. It can be seen that air drying and kiln drying are the bottleneck processes of the production lines because their processing times are higher than takt time (1.7 sec/BF). The amount of inventory stacked in the air drying and kiln drying can be due to their lead times. The company needs to have dried lumber for 54 days to be able to supply the flooring production line. The planner, rip saw, and pre-finishing cycle times were lower than takt time (1.7 sec/MBF) which indicate that they are not bottlenecks. The cycle times are lower to ensure that the production rate can meet the customer's demand. Also, the lower cycle times indicate that the machines can produce faster than demand which leads to the accumulation of WIP between each process. However, the inventories do not mean that this was necessarily needed between each process step.

According to the production manager at Plant C, the average yield of the surface planer, rip saw, moulders and pre-finished lines are on average 100%, 80%, 63% and 98.5% respectively. The time line shown in Figure 8 represents the inventory values as lead times, calculated by dividing the inventory levels into the daily demand. Value added times were considered to be the processing (air and kiln drying) and cycle times of the machines. The total production lead time was the sum of the top and bottom times in the timeline. For example, the drying operation total lead time for Plant C was 288 days, in where 54 days corresponded from the air and kiln drying and 234 days were related to the waiting WIP.

As shown in Figure 8, the total lead time from purchased lumber to customer delivery is 288 days. Only during 19 percent (54 days) of this lead time, lumber is being processed toward customer delivery. The majority of this lead time (56 percent) is tied up in lumber WIP associated with the drying process (116 days of air dried lumber waiting to be kiln dried and 44 days of kiln dried lumber waiting to be processed into customer orders). Once lumber enters into flooring production, 73 days of various forms of work-in-process inventory are observed (25 percent of the total lead time). In costs terms, the 234 days of the waiting inventory can represent a cost of $3,857,263 to Plant C.

6.2 PLANT D

Plant D is a family business that produces mostly unfinished and prefinished 2.25” and 3.25” red and white oak flooring. The production line of study is 3.25”’’ red oak flooring. Customer orders of 3.25” un-finished red oak flooring are received primarily via fax and email every two weeks. Lumber orders are placed either by email (pdf) or fax. Customer demand of red oak 3.25” is 50 MSF on average per day (50% goes to the unfinished line and 50% to the finished line). Plant D has 20 customers; however the number can vary with seasonality of demand. A projection of demand in a year was not able to be provided by the company, so the actual value of demand for a period of a month was used as given by the project manager.

Raw material is purchased green. Lumber arrives on 11 trucks per day with 7500 bf each. Shipment is done by 12 trucks per week approximately with 20 pallets each in which 20% corresponds to prefinished product and the 80 % to unfinished.

The company works 22 days per month. Work shifts are 9 hours per day, with 30 minutes for lunch and 2 breaks of 10 minutes each. The company does not use any optimized program, their production is performed manually and it is scheduled daily. Data from one flooring line production was collected to develop the VSM as mentioned in section 3.3.3, and is presented in Table 27.

Table 27. Parameters for each workstation in the 3.25” un-finished line production for plant d

Process parameters	Process								
	Grading	**Air Dying**	**Kiln Drying**	**Rip Saw**	**Knot Machine**	**Floor Machine**	**End matchers**	**Grading**	**Nesting/ Bundling**
Number of Machines	1	0	6	1	10	3	10	5	5
Batch size	continuo us	variable	77500 BF	90,000 BF	78,000 BF	65,000 BF	65,000 BF	57,000 BF	57,000 BF
Process time	360 sec/MBF	6 weeks	12 days	360 sec/MBF	377 sec/MBF	452 sec/MBF	452 sec/MBF	516 sec/MBF	516 sec/MBF
Number of employees	6	1	2	4	12	4	12	10	16
Changeover time	1 min	0	3 hours	5 min	5 minutes	2 minutes	2 minutes	2 minutes	2 minutes
Inventory	2 MBF	3.89 MMBF	465 MBF	200 BF	33.5 MBF	1 MBF	0	0	0
Quality	95%	97%	95%	not applicable	not applicable	85%	95%	99%	95%
Yield	100%	97%	95%	87%	83%	98%	88%	not applicable	not applicable
Uptime machine	90%	0	98%	95%	90%	95%	95%	95%	99%

6.2.1 PLANT D CURRENT VALUE STREAM MAP

A value stream map was developed to visually present the processes involved in the manufacturing of 3.25” red oak unfinished flooring. Section 3.3.1 describes how the product selection was performed. Data in Table 27 were placed inside the symbols proposed by Apel et. al(2007) (Figure 5). Inventory levels were calculated in days by divining the amount of inventory by the daily demand, with the purpose to calculate the lead times. Figure 9 shows the current value stream map for Plant D.

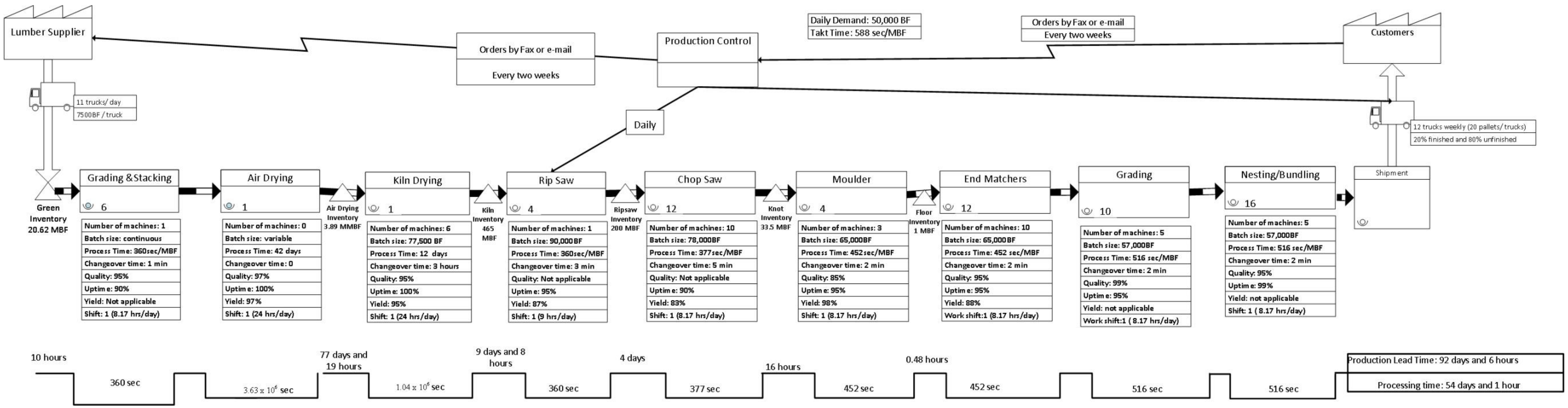


Figure 9. Current value stream map for the un-finished line in plant D

Plant D manufacturing processes consist of graders and stacking, air drying, kiln drying, rip saws, chop saw, moulder, end matchers, grading and nesting/bundling. Lumber comes from the suppliers, and is graded and stacked to be air dried. When the lumber reaches 20% moisture content, it goes through the kiln drying process to be dried to 7-8% moisture content during 12 days. After the lumber is dried, it goes through the rip saw machine, and then to the chop saw where any large defects presented in the boards are removed, so the quality can be improved. After the chop saw, the boards are sent to moulder, where the pieces are moulded into flooring and stamped with the company logo. Then, the flooring goes through the end matchers to be squared and acquire a UV sealer. After the end matchers, the floor boards go through another grading process and then to the nesting machine where they are bundled and ready for shipment.

In the case of air drying and kiln drying, processing times were 42 and 12 days respectively. Processing times are higher than takt time which makes these two processes bottlenecks of the operation. The company needs to have dried lumber for 42 days so they can supply the flooring production line which leads to higher inventories in the air and kiln drying processes. The takt time obtained for plant D was 588 sec/MBF. Cycle times obtained for the rip saw, chop saw, flooring, end matchers, grading and nestling/bundling were 360, 377, 452, 452, 516 and 516 sec/MBF respectively. The obtained cycle times are lower than takt time so the company does not over or under produce; and to ensure that the customer's demand can be met. The rip saw cycle time indicates that the machine produces faster than demand, which led to inventory between the rip saw and chop saw. The same situation can be seen for the chop saw. The average yield of the rip saw, chop saw, moulders, and end matchers are on average 87%, 83%, 98%, and 88% respectively.

The time line shown in figure 9 represents the lead times of the non-value added times(WIP) that are presented in the manufacturing process of flooring at Plant D. The inventory was calculated as a lead time by dividing the inventory levels by the daily demand. Value added times were considered to be the processing time of the machines. The total production lead times was determined by summing up the upper and bottom values of the timeline.

It was obtained that the drying operation total lead time for Plant D was 141 days in where 54 days were obtained from the air and kiln drying process and 87 days to the waiting WIP in these two processes.

The total lead time from purchased lumber to customer delivery was 141 days, in which 38% (54 days) represents lumber that has been processed. It can be seen in Figure 11 that most of the lead time (62 %) is related to the drying process, in which 77 days of air dried lumber is waiting to be kiln dried, and 9 days of lumber waiting to be processed. Once lumber enters into flooring production, 7 days of various forms of work-in-process inventory are observed (5 percent of the total lead time). In costs terms, the 141 days of the waiting inventory can represent a cost of $4,820,725 to Plant D.

6.3 Plant C and D Current State Value Stream Map Analysis

As shown in Figure 8 and Figure 9, for both Plant C and D, air drying presented the largest WIP which takes approximately 6 weeks. The second operation with largest inventory was kiln drying where approximately 12 days are needed to dry the lumber. Basically, the reason for the high inventory in the drying operation is that 6 weeks are needed (for both companies) for air drying and then 12 days (for both companies) to dry a batch of lumber. The companies need to maintain at least 42 days of air dried + kiln dried inventory of its various grades and species to feed the rest of the process and meet varying customer demand while waiting for more to be processed. For Plant C and D, the air drying and kiln drying inventory held is a function of their drying cycle lead times and batch size constraints. If the drying lead time could be reduced, it could be possibly reduce costs by reducing inventory.

The time line presented at the bottom of Figure 8 and Figure **9** represents the time elapsed from when the lumber first arrives to when the finished products are delivered to the costumers. Also, scheduling is basically a push system that simultaneously schedules the rip saw and the shipment. In the case of Plant C all the different processes are scheduled at the same time. Scheduling production at several processing points is not ideal because it tends to disconnect process flow and create more inventories and consequently more work for the production management to coordinate.

6.4 SUMMARY

The value stream maps for Plant C and D show the different processes that are involved in the flooring production and their associated production line inventories, cycle times, bath sizes of each machine, arrival of raw material, shipment of finished goods, change over time of the machines, yield at each process, number of employees, and others.

The value stream map for Plant C indicates that air drying with 1.89 MMBF and kiln drying with 717.7 MBF were the activities with highest values of WIP. For Plant D the values of WIP for air drying and kiln drying were 3.89 MMBF and 465MBF respectively. A possible cause of the amount of inventory produced in the air drying and kiln drying can be due to the long lead times of each process (42 days and 12 days respectively). One way to reduce inventory in the production line of both companies is by using a different drying technology with shortened lead times, and capacity to achieve the desired demand.

CHAPTER 7

PLANT C AND D SIMULATION AND FUTURE STATE MAP

In chapter 6, it was determined that for the two flooring manufactures the inventory in the drying operation had the greatest impact on lead times. Inventory reduction can help to smooth production flow and minimize costs. Vacuum drying has the potential to dry lumber faster, which can reduce the inventories. One of the objectives of the project is to demonstrate how vacuum drying can impact the work in process, throughput and cycle time for a flooring manufacturer.

This chapter presents the results of Little's Law, simulation, and future state map for Plant C and D. Little's Law was used to determine if the parts of the flooring production lines from Plant C and D VSMs were working efficiently. Little's Law was also used to estimate the WIP for the simulation models. The simulations were performed based on the VSMs, and they were addressed for three different scenarios: 1) conventional drying 2) vacuum drying including air drying, 3) vacuum drying without air drying. The obtained results from the simulation were then compared with Little's Law to determine which scenario was the best and, with this, to develop the future state map of both flooring manufactures (Plant C and D). Figure 10 shows a brief summary of the steps that were used to build the simulation models.

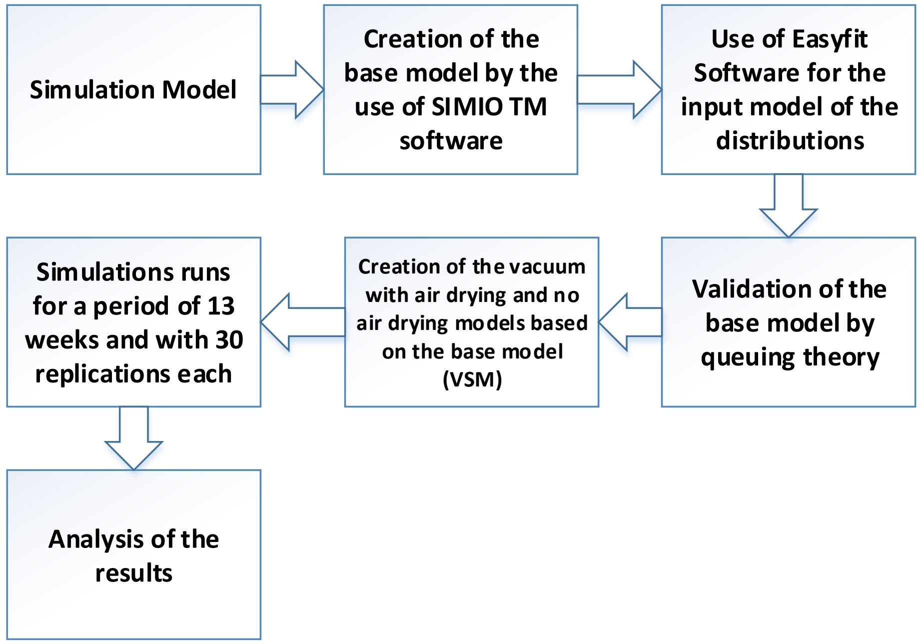


Figure 10. Steps used to develop the simulation models

7.1 Plant C and D Production Performance Given by Little's Law Analysis

Little's Law is used by industrial engineers to predict system behavior and validate operational improvements in a variety of factory settings. Little's Law establishes three comparison cases: the practical case, the best performance case, and the worst performance case, which were discussed in section 2.11 of the literature review.

Little's Law was used to analyze the production performance (how efficiently a production line is) of the two case studies. First the average process rate, which is the number of units that can be produced in certain period of time (in our case MBF/min) was calculated at each workstation. Then the bottleneck rate (r_b) and raw process time (T_0) were calculated. The bottleneck rate (r_b) is the rate (parts per unit) of the workstation having the longest utilization. Raw process time (T0) is the sum of the long term average process time of each workstation. The results are presented in

Table **28. AVERAGE PROCESS RATE AND TIME AT EACH STATION FOR PLANT** (Plant C) and 29 (Plant B).

Table 28. Average Process Rate and Time at Each Station for Plant C

Process	Rate (MBF/sec)	Time (sec)
Grading	0.0028	360
Air drying	0.00227	3628800
Kiln drying	0.00045	1036800
Ripsaw	0.00278	360
Knot Machine	0.0027	376.8
Floor Machine	0.0022	452.4
End Matchers	0.0221	452.4
Grading	0.0019	516
Nesting	0.0019	516
r_b, T_0	**0.00**	**4668633.6**

Table 29. Average process rate and time at each station for plant D

Process	Rate (MBF/min)	Time (min)
Grading stacking	0.0028	360
Air Drying	0.0052	3628800
Drying Kiln	0.0001	7257600
Surface Planner	0.2000	0.74
Rip Saw	1.9200	1.71
Moulder	0.0339	2.05
Pre-finishing	0.0195	1.2
r_b, T_0	0.0052	10886765

The bottleneck process (r_b) is air drying because it has the smallest value of rate (0.01 MBF/min), which means that air drying is the process with the highest production times. However, this activity was not considered as the bottleneck of the processing line because air drying is a process in where the factors that affects drying (temperature, relative humidity and air flow) cannot be controlled. As a result, no improvements can be done to the operation to significantly increase the drying rate. Kiln drying then becomes the bottleneck of the process because it has the second lowest production rate (0.03 MBF/min).

Table 28. **AVERAGE PROCESS RATE AND TIME AT EACH STATION FOR PLANT**and 29 shows the obtained values for r_b and T_0 that were used to compute the Critical WIP as referred as in section 3.3.4. According to Hopp (2010) the critical WIP (WIP_0) "is the WIP level for which a line with given r_b and T_0 achieves maximum throughput (rb) with minimum cycle time (T_0)." The obtained WIP_0 for plant C and D was 563 MBF and 2,094 MBF respectively. The total WIP of the VSMs was calculated by summing up the WIP at each process. The obtained value was then compared to the $WIP_{0.}$ Table 30 presents the comparison of the WIP_0 and the total measured values of the system (Based on the VSM).

Table 30. Comparison of measured and critical WIP (WIP_0) for plant c and d

Plant	WIP (MBF)	
	VSM WIP	WIP_0
C	3,812	563
D	4,610	2,094

As it is shown in Table 30 both companies use more inventory than what should be needed as suggested by Little's Law. Specifically, Plant C VSM WIP is 14% more than the critical WIP, and at Plant D VSM WIP is 45% more than the Critical WIP. The higher amount of inventory at each plant (C and D) can be due to the availability of the raw material during the year. When raw material is available, companies usually tend to buy more lumber to prevent lumber shortage in the following months. Also, when raw material prices are cheaper, companies take advantage of lower prices and buy more lumber. With Little's Law it can be seen that having more inventory than the Critical WIP does not make throughput to increase, just the costs (see chapter 2).

Little's Law was used to calculate the throughput value for the worst practical case using the equation 5. The worst practical case is one of the three scenarios that Little's Law uses to determine if a production line is working efficiently or not. It was calculated that throughput should be 7.95 MBF/day and 11.93 MBF/day for Plant C and D respectively. However, the measured values indicate that the system produces 16.275 MBF/day and 50 MBF/day for Plant C and D. The measured values are higher than the values suggested by Little's Law. According to Little's Law if the measured values are lower than those suggested by the practical worst case, it means that the production if not working efficiently; but if the measured values are higher than the ones suggested by Little's Law the production line is working efficiently. Both companies (C and D) produce more throughput than the values given by Little's Law, therefore the results show that both companies have a good performance.

7.2 Simulation Results

Simulation was used to model one production line for Plant C and D obtained in section 6. The purpose of the simulation was to simulate the actual system, and with this, to derive two new models using the same processes but changing the conventional drying operation to vacuum drying and air drying and vacuum drying.

The model was run for a period of 13 weeks for both companies to represent an approximation of the amount of inventory they had in their production according to the time line of their respective VSM. Validation of the simulation model consisted of comparing the cycle times and throughput of the simulation with the values from the production line. Simio™ software establishes as a minimum of 30 replications to obtain statistics of the results. The obtained results are shown in

TABLE 31 and 32 for Plant D.

Table 31. Comparison of parameters between plant C value stream map and simulation model

Company	Cycle Time	
	VSM	**Simio^{TM} Model**
Surface Planner (sec/MBF)	0.74	0.73 ± 0.20
Rip Saw (sec/MBF)	1.71	1.71 ± 1.8
Moulder (sec/MBF)	2.05	2.00 ± 0.63
Finishing (sec/MBF)	1.20	1.25 ± 0.20
Air Drying (weeks)	6.00	6.00 ± 5.99
Drying (days)	12.30 days	12.14 days ± 12 days

Table 32. Comparison of parameters between plant D value stream map and simulation model

Process	Cycle time	
	VSM	**Simio^{TM} Model**
Drying (days)	12	12.10 ± 12
Rip Saw (min/MBF)	6	6.15 ±6
Knot machine (min/MBF)	6.28	6.27 ± 6.26
Flooring machine (min/MBF)	7.54	7.53 ±7.51
End matchers (min/MBF)	7.54	7.51 ±7.50
Grading (min/MBF)	8.6	8.4 ±8.6
Nesting (min/MBF)	8.6	8.6 ± 8.2

The values obtained from the simulation model are not statistically different from the values for the value stream map. Similarities can be determined by the confidence interval of each process' cycle times. For example, 7.53 ± 7.51 with α of 95% indicates that the value can vary from 7.52 to 7.54 min/MBF; no values were found outside the confidence interval. Differences between the model and the VSM can be product of sampling error. Kelton et. al (2011) explains sampling error as follows: "the simulation model results match the expectation in probabilistic sense, but we either haven't run the model long enough or for enough replications." However, the confidence intervals of the values showed that they are not statistically different, so they were considered appropriate for the simulation. Also, throughput was compared for the model and VSM. An approximate throughput of 1,057,000 BF for Plant C and 3,249,300 BF for Plant D (Table 33) was obtained. Differences were not considered statistically different according to the confidence intervals obtained for each parameter. For example, the throughput of Plant C was 1,057,000 BF with a confidence interval of ±1, which means that the throughput can vary from 1,056,000 to 1,058,000. Differences between the values can be product of the variability and randomness of the simulation software.

Table 33. Throughput comparison between VSM and Simio™ model

Company	Throughput	
	VSM	Model
Plant C	1,057,875 BF	1,057,000 BF
Plant D	3,250,000 BF	3,249,300 BF

After validating the base model, two new models were derived from the base model: air drying with vacuum drying (case A) and vacuum drying without air drying (case B).

Little's Law worst practical case was used to compare the results from Plant C and D. Equation 4 and 5 of Little's Law formula was applied for both cases A and B with the objective to calculate the WIP_0 and determine if the production lines were working efficiently by using vacuum drying. If the WIP are lower than the WIP0 it means that the production line is not working efficiently (worst case); and if the WIP is higher than the WIP0 (best case) it means that the line is working well. Then r_b and T_0, and W_0 was predicted for each case for both plants C and D as described in section 3.3.4.

The obtained WIP_0 was used as the basis for the inventory of the models case A and case B. However, the WIP_0 is a total inventory, which means that it does not specify what amount corresponds to each process. A total WIP for each VSM (base model) was calculated by summing up the WIPs of each process. A proportion was computed by dividing the WIP at each process by the total amount of WIP. The obtained proportions for each station were applied to the WIP_0 to calculate the corresponding amount of WIP at each process. The obtained values were then project for the 13 weeks that the simulation was going to be run.

Table 34. Critical WIP (WIP_0) for each station for case A (vacuum with air drying) for plant c determined by Little's Law

Process	WIP (MBF)	
	WIP_0	**13 week**
Air Drying	140.22	9114.59
Drying Kiln	53.25"	3461.13
Surface Planner	10.65	692.03
Rip Saw	34.91	2269
Moulder	24.74	1607.83
Pre-finishing	18.19	1182.49

Table 35. Critical WIP (WIP_0) for each station for case B (vacuum with no air drying) for plant C determined by Little's Law.

Process	WIP (MBF)	
	WIP_0	**13 week**
Vacuum Kiln	112.75	7328.50
Surface Planner	22.54	1465.29
Rip Saw	73.91	4804.32

Moulder	52.38	3404.38
Pre-finishing	38.52	2503.76

7.2.1 Case A and B results for Plant C

As mentioned in the above section, Little's Law was used to determine the Critical WIP for case A (vacuum with air drying) and case B (vacuum with no air drying). The Critical WIP is a total value; it does not specify the amount of WIP that corresponds to each process. To determine the WIP that corresponded to each process, for the simulations, a proportion was then gathered by dividing the WIP from each process from the VSMs by the total WIP. This proportion was multiplied to the simulation's WIP_0, and the value was used as the correspondent WIP for the different process at the production line. Simulations were run for a period of 13 weeks to represent the lead time obtained from the time line of each VSM. Every scenario (vacuum with air drying and no air drying) had 30 replications. According to Kelton et. al (2001), 30 replications is the minimum number to get statistic parameters (mean, confidence interval, and others). The obtained values for case A and B for Plant C with a 95% of confidence are summarized in Table 36.

Table 36. Comparison of the Throughput, WIP, and Cycle Time for Case A and B for Plant C

Variables	**VSM C**	**Simulation Models**			
		Plant C			
		Case A	**CI***	**Case B**	**CI***
Throughput (MBF)	1057	1057	± 1029.19	1074.03	± 1000
WIP (MBF)	3811	1957.27	± 1815.37	595.57	± 556
CT (days)	233	30	± 28.64	10.67	± 10.5

**CI: Confidence Interval*

The simulation models were used to demonstrate how vacuum drying could influence the throughput, WIP, and cycle time of one part of Plant C. The desired throughput was met using vacuum drying while WIP and cycle times were reduced. WIP and cycle time reductions from case A were respectively 48% and 87% less than conventional drying Plant C (VSM C). WIP and cycle time from case B were respectively 84% and 95% less than conventional drying Plant C (VSM C). The obtained values from case B were chosen to create the future state map, because they presented the best results of WIP and cycle time, while meeting the customers desired demand. Thus, the obtained values from Case B can more positively improve the part of the production line.

7.2.2 Case A and B for Plant D

Little's Law was used to determine the WIP_0 for case A (vacuum with air drying) and case B (vacuum with no air drying). The critical WIP gives a total number of WIP does not specify the amount that corresponds to each process. A proportion from the base model (VSM for Plant D) was determined by dividing the WIP of each process by the total WIP (the sum up of WIP at each process). The obtained value was projected for a period of 13 weeks. The two scenarios were run with 30 replications each. The obtained values are summarized in .

Table 37 with a 95% of confidence.

Table 37. Comparison of Throughput, WIP, and Cycle Time for Case A and B for Plant D

Variables	VSM C	Simulation Models			
		Plant D			
		Case A	CI*	Case B	CI*
Throughput (MBF)	1057	3245.07	± 3239	3240.08	± 3088
WIP (MBF)	3811	2602.98	± 2479	327	± 311
CT (days)	233	45.11	± 44.99	8.33	± 8.31

It can be observed that for Plant D, the obtained WIP and cycle time for case A were 43% and 51% lower than conventional drying. The obtained WIP and cycle time for case B were 92% and 90% lower than conventional drying. These values show how vacuum drying can reduce WIP and cycle time by meeting the desired customer demand, which can help the hardwood industry, be more competitive.

7.3 Plant C and D Future State Value Stream Map

One of the objectives of the project is to determine how vacuum drying can impact the TH, CT and WIP of a flooring line production. According to the value stream maps mentioned in chapter 7, the drying process is the one that produced more inventories due to its lead time to dry lumber. According to the literature review in section 2.4, vacuum technology reduces the drying time of conventional technology by almost half, with the same quality and similar cost values as conventional. Due to this, one of the objectives of the research is to see how the WIP, throughput and cycle time can be impacted in the process.

Simulation results presented in Table 36 and 37 in section 7.2. Showed that vacuum drying can reduce lead times, inventory and meet desired demand. The future state map for Plant C and D presents improvement in their lead times and inventory levels of the line production by using vacuum drying. For the future state, case B presented better results than Case A as shown in table 36 and 37 of section 7.2, and it was chosen as the scenario for the future state improvements for Plant C and D.

The total lead times were reduced from 288 days to 8 hours and 4.03 min, which corresponded to a 96% reduction. Processing times of 54 days and 1 hour were reduced to 1 hour and 30 min, which represents a 98% reduction. Throughput met the daily demand of 1057 MBF. This means that costumer products are delivered on time.

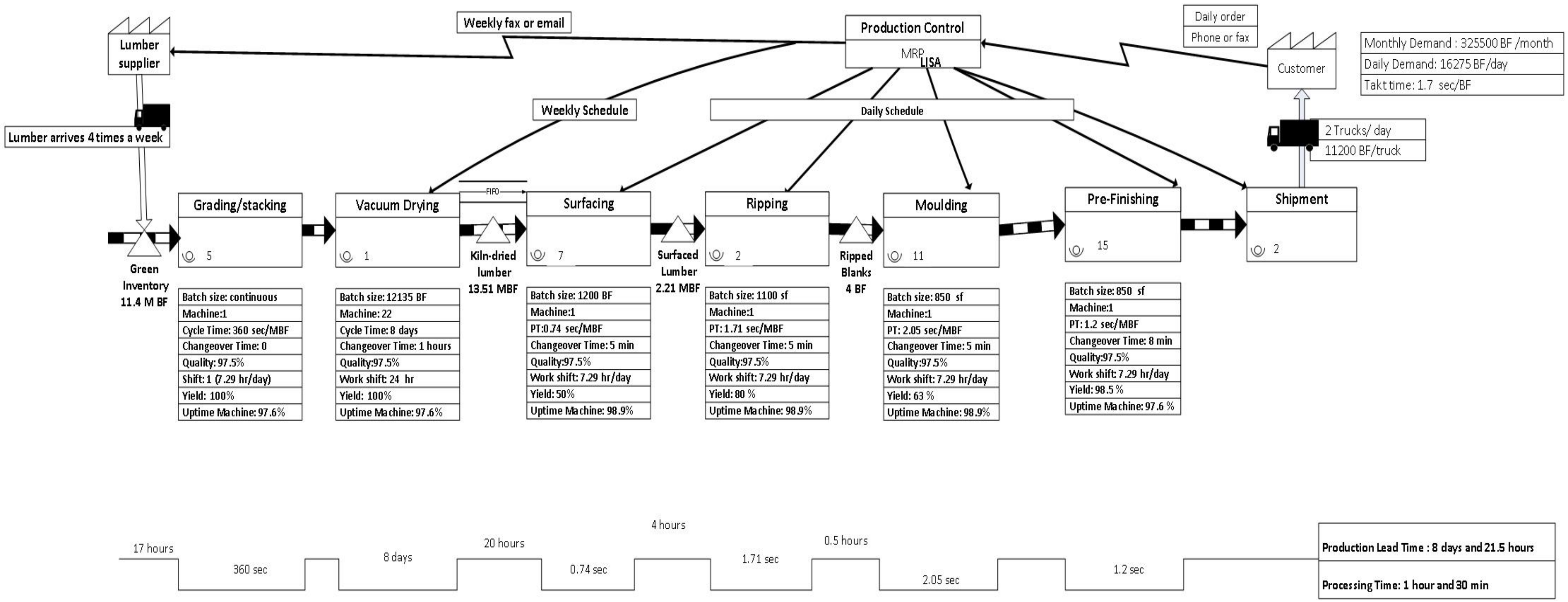


Figure 11. Future State Map for Plant C

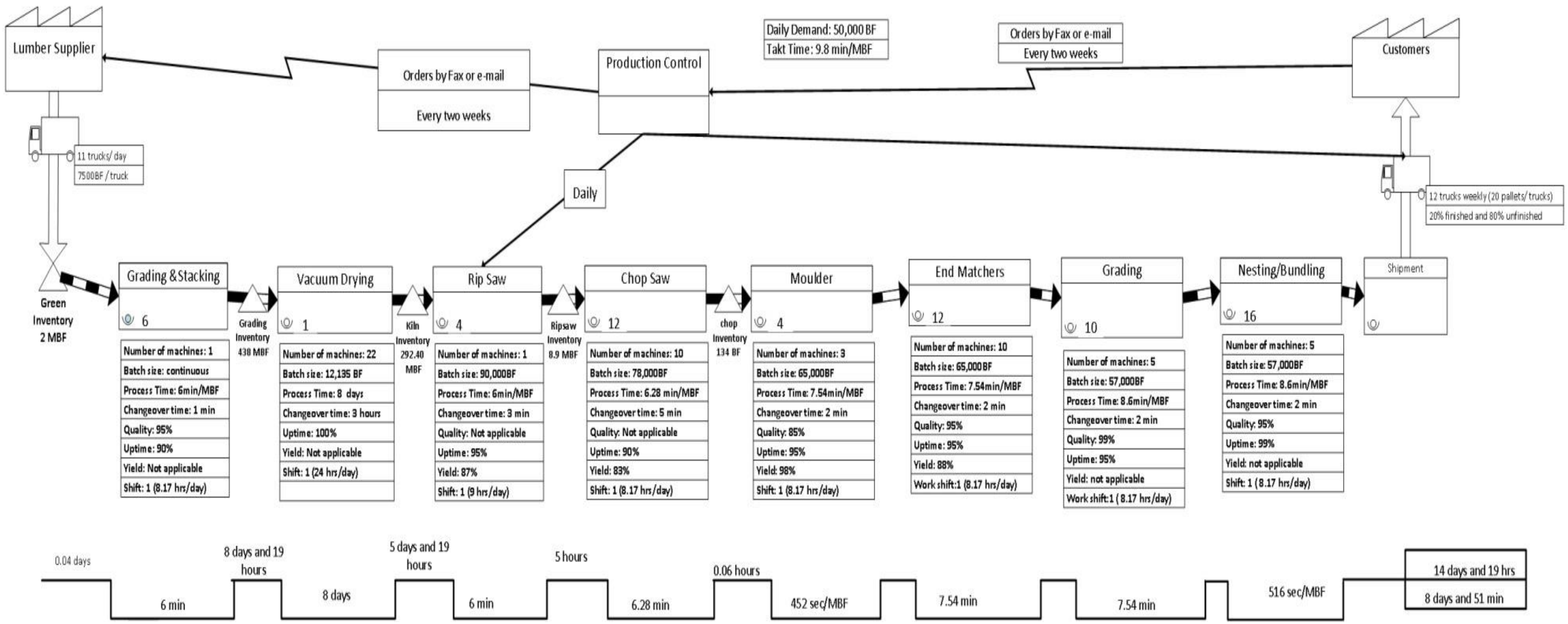


Figure 12. Future State Map for Plant D

Figure 12 shows how vacuum drying impacted the line production. Kiln drying inventory was reduced from 8.25 MMBF to 292.40 MBF, a 96% reduction. Rip Saw inventory was reduced from 400 MBF to 8.9 MBF, a 98% reduction. Inventories in knot machine and flooring were non-existent in the simulation. Also, inventories for shipment where reduced completely because the company is meeting daily demand.

As shown in Figure 11 and 12, the total lead time from purchased lumber to customer delivery is 9 and 19 days for Plant C and D, respectively. The obtained production lead times are less than in conventional drying (288 for Plant C and 141 for Plant D). The conventional drying rate for Plant C and D was of 54 days, which dropped to 8 days with vacuum drying. Inventory lead time for the drying operation for Plant C and D was 160 days and 86 days, which decreased to 20 hours and 5 days.

These results can enhance the importance of vacuum drying in the improvement of hardwood manufacturing by: 1) reducing inventory by 97% on average, 2) meeting desired throughput and 3) reducing cycle times by 85%.

7.4 Inventory Cost for Plant C and D

To further investigate the impact of using vacuum drying versus conventional drying, an estimation of the inventory cost for both case studies was done. The methodology used was proposed by Keown et. al (2006). Table 38 indicates the WIP values obtained from the VSMs and the simulation model for an approximate period of 4 months for the drying operation. These WIP values were used to determine the cost of inventory.

Table 38. WIP Values Obtained from the VSMS and Simulation Models for Plant C and D regarding drying operation.

Variables	VSM C	VSM D	Simulation Model	
			Plant C	Plant D
			Case B	Case B
WIP (MBF)	4000	4355	220	223

The time period of analysis was calculated for each case (Conventional of Plant C and D, and vacuum with no air drying of Plant C and D), which corresponded to 4 months. Second, the values of the beginning inventory were calculated by multiplying the WIP from Table 38 by the price of $910/MBF obtained from the Hardwood market report 2013. Third, the inventory purchase in the last month was estimated. For this the values from Table 38, which corresponded to 4 months or 13 weeks, were divided by 4 to obtain the total amount of WIP for a month, and then the values were multiplied by the price from the Hardwood Market Report ($910/MBF). Fourth, the inventory at the end of the period was calculated, in which one week was considered as the end of the period, and the WIP was multiplied by the price of the Hardwood Market Report 2013. The total cost of inventory was determined by the following formula:

The Cost of Inventory = Beginning Inventory + Inventory Purchases - Ending Inventory

Where,

Beginning inventory: is the value of the inventory at the beginning of the time period

Inventory purchases: is the inventory cost for the total time of period

Ending inventory: is the inventory value at the end of the time period

Table 39 presents the costs of inventory of the drying operation for each scenario of Plant C and D. It can be seen that for a period of 13 weeks (approximately 4 months) Plant C and D can save

$1,761,760/MBF and $2,171,207/MBF if they use vacuum drying technology with no air drying. A projection for a year was then done to determine the cost inventory savings for both companies. Plant C's inventory cost projection for a year would obtain the following results: $7,166,250/MBF for conventional drying and $ 1,880,970/MBF for vacuum with no air drying. This means that Plant C could save $5,285,280/MBF per year. The inventory cost projection for a year for plant D was $8,514,870 for conventional drying and $2,001,249. According to the obtained values, Plant D can save $ 6, 513, 621 per year. The cost inventory savings that both companies have agrees with the feasibility analysis in chapter 5, in where the NPVs and IRR of vacuum with no air drying were higher than conventional drying, making this scenario more economically feasible.

Table 39. Comparison between Conventional and Vacuum Drying Inventory Cost for Plant C and D for a period of 4 months

Parameter	Plant C			Plant D		
	Conventional	Vacuum with air drying	Vacuum with no air drying	Conventional	Vacuum with air drying	Vacuum with no air drying
Kiln equipment	$2,575,000	$3,333,850	$6,659,700	$2,225,000	$3,938,550	$7,566,750
Inventory Cost	$2,388,750	-	$626,990	$2,838,290	-	$657,083

The results agree with Apel et. al (2007), which established that reducing drying times will allow the industry to dry lumber in a faster way. The reduction in drying times will mean a reduction in cost performance, an increase in earnings, and a competitive advantage for the industry (Apel et. al2007).

7.5 SUMMARY

The simulation models presented how vacuum drying can influence the throughput, WIP, and cycle time of one part of Plant C and D flooring production lines. Table 40 presents a summary of the obtained results for both case studies. WIP and cycle time from case A were respectively 48% and 87% less than conventional drying Plant C. WIP and cycle time from case B were respectively 84% and 95% less than conventional drying in Plant C. For Plant D, the obtained WIP and cycle time for case A were 43% and 51% lower than conventional drying. For Plant D, the obtained WIP and cycle time for case B were 92% and 90% lower than conventional drying.

Table 40 Parameters obtained from the Simulation for Case A and B for both Case Studies

Variables	**VSM C**	**VSM D**	**Simulation Models**			
			Plant C		**Plant D**	
			Case A	**Case B**	**Case A**	**Case B**
Throughput (MBF)	1057	3250	1057	1074.03	3240.07	3240.08
WIP (MBF)	3811	4610	1957.27	595.57	2602.98	327
CT (days)	233	92	30	10.67	45.11	8.33

Industry costs are not only the capital cost of equipment, material handling, and storage required to manufacture products with large lead times, but also the opportunity cost associated with CT related to lost sales and higher finished goods inventory. For example, orders placed for products with lower CT have a greater probability of being filled before the orders expire or change. Also, associating a dollar value to cycle time often highlights the true impact of manufacturing time on total cost to the company (Rust 2008).

The reduction of WIP represented a drying cost saving of 73% and 76% for Plant C and D, respectively. The cost savings in WIP makes vacuum with no air drying scenario more feasible than conventional drying. The results of costs reduction, faster drying rates, and similar quality to conventional drying leads vacuum drying like a potential technology to make flooring manufactures more competitive in the market.

CHAPTER 8

OVERALL SUMMARY, CONCLUSIONS AND FUTURE WORK

8.1 OVERALL SUMMARY

As secondary wood products try to increase their competitiveness, many are moving towards leaner manufacturing processes. Lumber drying, typically a large-batch process, is a monumental barrier against sustainable lean improvement. Vacuum drying has been shown to reduce drying; therefore, it might be the technology that can help U.S hardwood industries to become leaner and more competitive in the market.

This project analyzed differences in quality, drying times and costs between conventional and vacuum drying. It also determined whether vacuum drying can be an economically viable operation. Finally, it analyzed the impact of vacuum drying regarding cycle time, throughput and WIP in two flooring manufacturers.

Companies that sell and use vacuum drying and three flooring manufactures that use conventional drying were contacted to gather information about quality, drying times and costs. Data collection instruments were mailed to the companies to gather the information from quality, and for drying times and costs some were mailed and others were asked directly to the production manager.

Two case studies were developed to determine the feasibility of conventional and vacuum drying. Three scenarios (conventional, vacuum with air drying, vacuum with no air drying) for both case studies were created to determine the feasibility of conventional and vacuum drying. Costs obtained from the first analysis were the basis for the model.

A value stream map was created for both case studies to graphically draw one part of their line production. Then, simulation was used to model the VSM of each company with the objective to see how vacuum drying can affect cycle time, throughput and WIP.

The obtained results demonstrated that vacuum drying has the potential to achieve shorter drying times, drying smaller loads, and achieving at least the same drying quality as conventional drying, while servicing the market more efficiently. All these potential benefits, can help sustain a more effective hardwood supply chain in the U.S.

8.2 Conclusions

The conclusions of the project can be listed according to the three objectives proposed.

9.2.1 To estimate conventional and vacuum drying times, quality, and costs for drying 4/4 red oak lumber

1. According to the information from Company A and B and from literature, vacuum drying results in less check, end splits, drying stress and total shrinkage than conventional drying.

2. According to the information from company A and B and literature, vacuum drying times with air drying were 67% less than conventional; and vacuum with no air drying times were 70% less than conventional drying.
3. For the production lines studied, vacuum drying with air drying resulted in the highest drying cost, $349/MBF and $373/MBF respectively for both Plants C and D. The higher cost was due mainly to the capital investment of the dry kilns and inventory, which represented 8.26% and 83%, and 7% and 97% of the total costs of vacuum with air drying of Plant C and D respectively.

9.2.2 To determine by the use of feasibility analysis (cash flow, net present value, and internal rate of return) differences between conventional and vacuum drying for 4/4 red oak lumber

1. Conventional drying and vacuum with no air drying scenarios were feasible for both companies studied; vacuum with no air drying was more feasible than conventional drying due to their respective values of NPV and IRR. Vacuum with air drying had negative values of NPV and IRR, which makes the scenario not economically viable.

2. The capital costs of the vacuum kilns and raw material costs were the parameters that impacted the total costs among the three different scenarios. For plant C the capital investment of the kilns of vacuum with air drying was 23% higher than in conventional drying; and vacuum with no air drying was 61% higher than in conventional drying. For plant D the total capital investment of the kilns of vacuum with air drying was 44% higher than in conventional drying and vacuum with no air drying was 71% higher than in conventional drying. In terms of inventory cost, vacuum with air drying was 60% more than in conventional for Plant C; while for Plant D, vacuum with air drying inventory cost was 66% more than conventional drying.

9.2.3 To determine if the high capital cost of vacuum drying equipment can be justified with the reduction of WIP and cycle time, and by meeting the desired throughput through two case studies in flooring manufacture.

1. Vacuum drying can reduce WIP and CT while meeting desired throughput for a part of flooring production line.

2. Cycle times from case A and B respectively were 87% and 95% less than conventional drying for Plant C. WIP from case A and B were 48% and 84% less than conventional drying for Plant C.

3. Cycle times from case A and B were respectively 51% and 90% less than conventional drying for Plant D. WIP from case A and B were 43% and 92% less than conventional drying for Plant D.

4. For the production lines studied, vacuum drying technology could meet customer demand while reducing WIP and cycle times. The reduction of WIP for a year represented a cost saving of 73% and 76% for Plant C and D, respectively.

5. Vacuum drying would result in Plant C and D saving $5,285,280/MBF and $6,513,621/MBF in inventory respectively.

6. The cost savings from a reduction in WIP makes vacuum with no air drying scenario more feasible than conventional drying for the production lines studied. The reduction in capital and inventory costs, faster drying rates, and similar quality to conventional drying makes vacuum drying like a potential technology available for improvement of the competitiveness for flooring manufacturers.

8.3 Study limitations

The project presented several limitations in each objective that was analyzed. The limitations were the following:

1. The study specifically assessed one single line production of two flooring manufactures, and the results gathered may not reflect the rest of the hardwood industry.

2. The companies that collaborated in the project do not quantify or track lumber quality, and do not record all of their drying costs which complicates data gathering and estimation of the costs.

3. Future state map was based on average customer demand and results from the simulation, seasonal demand variation may not be reflected in the inventory levels.

8.4 Future Work

Based on the previous chapters, some recommendations for future work are the following:

1. A cost analysis for a furniture company to determine if vacuum drying can be feasible, and can impact the WIP, TH, and CT of the company.
2. To use the methodology of this project but applied for the entire company and including seasonal variation.

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APPENDIX A – COMPARISON OF THE ECONOMIC DRYING MODELS

	Models						
Variables	**Holmes and Bilek 19831**	**McMillen and Wenegert 1978**	**Redman 2011**	**Fortin 2010**	**Rebb 2011**	**Govett et. al2006**	**Suggested Model**
FIXED COSTS							
DIRECT INVESTMENTS							
Buildings, sheds, etc.	x	X	x	X	X		x
Kiln, auxiliary equipment (including boiler)	x	X		X	X	x	x
Stickers		X		X	X	x	x
Pile roofs	x	X				x	x
Pile bases, bolsters	x	X				x	x
DEPRECIATION FOR DIRECCT INVESTMENTS							
Buildings, sheds, etc.	x	X	X	X	x		x
Kiln, auxiliary equipment (including boiler)	x	X		X	x	x	x
Stickers		X		X	x		x
Pile roofs	x	X			x		x
Pile bases, bolsters	x	X					x
DRYING YARD INVESTMENTS	x	X				x	
Storage sheds for stickers, dried lumber, etc.	x	X		X			x
Quantity of wood dried annually (MBF)	x	X		X		x	x
Permanent road construction, rail access, etc.		X					
Temporary road construction (includes drying alleys)		X					
Fences	x	X					x
Lighting systems	x	X					x
Drainage systems	x	X					x
Sprinkler systems		X					x

[1]*DEP by Holmes and Bilek (1983)*

[2]*Drying Eastern Hardwood Lumber by McMillen and Wegert (1978)*

[3]*Evaluation of super-heated steam vacuum drying viability and development of a predictive drying model for four Australian hardwood species by Redman (2011)*

[4]*Calculating Drying Costs by Fortin (2010)*

[5]*Fuels Calculator by Rebb (2011)*

[6]*DRYFEAS by Govett et. al (2006).*

Continue of Appendix A.

	Models						
Variables	**Holmes and Bilek 19831**	**McMillen and Wenegert 1978**	**Redman 2011**	**Fortin 2010**	**Rebb 2011**	**Govett et. al2006**	**Suggeste d Model**
FIXED COSTS							
DEPRECIATION FOR DRYING YARD INVESTMENTS							
Storage sheds for stickers, dried lumber, etc.	x	X		x			x
Permanent road construction, rail access, etc.		X					
Temporary road construction (includes drying alleys)		X					
Fences	x	X					x
Lighting systems		X					x
Drainage systems	x	X					x
Sprinkler systems		X					x
OTHER YARD INVESTMENTS							
Plus snow removal ($/yr)		X		X			
Plus yard cleaning ($/yr) (64)		X		X		X	x
Plus annual lighting expense (bulbs and electricity) ($/yr)		X					x
Land area (ft2)		X				X	x
Air drying area (include space between the piles)		X				X	x
Road area		X					x
Area for buildings, kiln, boiler, etc.		X					x
Land value ($/ft2)	x	X					x
Loan		X				X	
Borrowing rate	x	X				X	
reinvestment rate	x	X				X	
Inventory tax	x	X		X		X	x
Taxable values ($)	x	X		X		X	x
Insurable values ($)	x	X		X	X	X	x
Tax rate to be applied to the total of taxable values.		X		X		X	x
Insurance rate applied to the total of Insurable values (percent as decimal)	x	X		X		X	x
Annual interest rate (percent as decimal)	x	X	x	X	X	x	x

[1]*DEP by Holmes and Bilek (1983)* [2]*Drying Eastern Hardwood Lumber by McMillen and Wegert (1978)*

[3]*Evaluation of super-heated steam vacuum drying viability and development of a predictive drying model for four Australian hardwood species by Redman (2011)*

[4]*Calculating Drying Costs by Fortin (2010)* [5]*Fuels Calculator by Rebb (2011)* [6]*DRYFEAS by Govett et. al(2006).*

Continue of Appendix A.

Variables	Models						
	Holmes and Bilek 19831	McMillen and Wenegert 1978	Redman 2011	Fortin 2010	Rebb 2011	Govett et. al2006	Suggested Model
VARIABLE COSTS							
CAPACITY VARIABLES							
Average price of lumber ($/Mbf)	x	x	X	x		X	x
Average drying degrades based on lumber value (percent as decimal)		x		x		X	x
Average daily volume of lumber on yard and in kilns on any given day (MBF)	X	x	X			X	x
Total capacity of kilns	x	x	X	x	x	X	x
Number of Kilns	x	x	X			X	x
Operational year	x	x	X	x		X	x
Run times				x			x
Average length of kiln run (include loading and unloading time)	x	x				X	x
Green lumber price						X	x
Average number of days lumber item is held in predryer						X	x
Average number of days lumber item is held in air drying						X	x
Average number of days item is held after kiln drying						X	x
Capital cost for green lumber inventory						X	x
Total gross margin for item						X	
Predryer "rated" size in mbf when loaded with 4/4 lumber						X	
Expected predryer downtime days per year (e.g. maintenance)						X	x
Calculated number of days predryer is available/year						X	x
Wood residues				x			x
kiln residence time					X		x
OPERATIONAL VARIABLES							
Forklift time (MBF/hr)	x	x		x			x
Hourly forklift cost (include machines cost, labor, and fringe benefits) ($/hr)	x	x		x			x
Stacking time (MBF/hr)		x		x			x
Hourly stacking cost (include machinery, labor, and fringe benefits ($/hr)		x		x			x
Time spent each day observing and running kilns, boilers, etc. (hr).		x				X	x
Hourly wage rate and fringe benefits for kiln operator and auxiliary equipment including boiler ($/hr).	x	x				X	x
Annual throughput	x		X	X	x	X	x
Annual office costs attributed to drying (in dollars)	x	x		X		X	x
Average # of production employees used 1st shift						X	
Average # of production employees used 2nd shift						X	
Average # of production employees used 3rd shift						X	
Average # of production employees used 4th shift						X	
Average # of days (not including overtime) that an employee works per year						X	
Fringe benefits for overtime hours a % of the overtime hourly wage	x					X	x
Maintenance of kilns and boiler (in dollars).	x	X		X	x	X	x
Maintenance and repair of yard	x	X		X		X	x

[1]DEP by Holmes and Bilek (1983) [2]Drying Eastern Hardwood Lumber by McMillen and Wegert (1978) [3]Evaluation of super-heated steam vacuum drying viability and development of a predictive drying model for four Australian hardwood species by Redman (2011) [4]Calculating Drying Costs by Fortin (2010) [5]Fuels Calculator by Rebb (2011) [6]DRYFEAS by Govett et. al(2006).

Continue of Appendix A.

	Models						
Variables	**Holmes and Bilek 19831**	**McMillen and Wenegert 1978**	**Redman 2011**	**Fortin 2010**	**Rebb 2011**	**Govett et. al2006**	**Suggested Model**
			Fixed Costs				
ENERGY COSTS							
Annual fuel consumption (gal or 1000 ft3)		X				X	x
Fuel cost ($/gal)	x	X				X	x
Annual electrical usage attributed to drying (kWh)		X	x	X	X		x
Electrical cost ($/kWh)	x	X	x	X	X	x	x
Cost of heat		X	x	X	x		x
Initial MC	x	X	x	X	x	x	x
Specific heat of water			x	X			x
Heat of vaporization			x	X			x
Final MC	x	X	x	X	x	x	x
Kiln cycles per year		X	x			x	x
Vacuum pump rating			x				x
Vacuum pump usage			x				x
Drying time		X	x	X			x
Condenser fan rating			x				x
Condenser fan usage			x				x
Air drying and Air Flow			x				x
Number of fans			x				x
Fan rating			x				x
Air drying time (weeks)			x				x
Final drying time (hrs)		X	x				x
Wood basic density (kg/m3)			x				x
Volume air dry stock			x				x
Cost of dry stock interest			x				x
Maximum drying temperature			x				x
Minimum drying temperature			x				x
Thermal loss			x				x
Steam					x		x

[1]DEP by Holmes and Bilek (1983) *[2]Drying Eastern Hardwood Lumber by McMillen and Wegert (1978)*

[3]Evaluation of super-heated steam vacuum drying viability and development of a predictive drying model for four Australian hardwood species by Redman (2011)

[4]Calculating Drying Costs by Fortin (2010) *[5]Fuels Calculator by Rebb (2011)* *[6]DRYFEAS by Govett et. al(2006).*

APPENDIX B. VARIABLES AND FORMULAS USED TO OBTAIN VACUUM AND CONVENTIONAL DRYING COSTS (REDMAN 2011).

FINANCE CALCULATIONS

Total direct investments

1. $Total\ direct\ investments(\$) = buidings, sheds\ (\$) + kiln\ equipment\ (\$) + stickers\ (\$) + pile\ roofs\ (\$) + pile\ bases, bolsters\ (\$)$

Total Depreciation for direct investment

2. $depreciation\ in\ direct\ investments\left(\frac{\$}{M\ bm}\right) = \left[\left(\frac{Buildings\ ,sheds\ (\$)}{C}\right) + \left(\frac{Kiln\ auxiliary\ equipment\ (\$)}{C}\right) + \left(\frac{Stickers\ (\$)}{C}\right) + \left(\frac{Pile\ roofs}{C}\right) + \left(\frac{Pile\ bases,bolsters\ (\$)}{C}\right)\right]$

Where C = to each direct investment depreciation (years) *Quantity of wood dried annually (M bm)

Interest on direct investment

3. $Interest\ on\ direct\ investment\ \left(\frac{\$}{M\ bm}\right) = \frac{Total\ direct\ investment\ (\$)}{(Annual\ interest\ rate\ (\%)*Quantity\ of\ wood\ dried\ annually\ (M\ bm))}$

Air drying

- *Drying yard investments*

4. $Total\ drying\ yard\ investments\ (\$) = storage\ sheds\ for\ stickers, dried\ lumber\ (\$) + Permanent\ road\ construction\ (\$) + temporary\ road\ construction\ (\$) + Fences\ (\$) + ligtning\ systms\ (\$) + drainage\ systems\ (\$) + sprinkler\ systems\ (\$)$

- *Air Drying yard depreciation*

5. $Total\ air\ drying\ yard\ depreciation\left(\frac{\$}{M\ bm}\right) = \left[\left(\frac{storage\ sheds\ for\ stickers,dried\ lumber\ (\$)}{C}\right) + \left(\frac{permanent\ road\ contruction\ (\$)}{C}\right) + \left(\frac{Temporary\ road\ construction\ (\$)}{C}\right) + \left(\frac{Fences}{C}\right) + \left(\frac{Ligtning\ systems\ (\$)}{C}\right) + \left(\frac{drainage\ systems\ (\$)}{C}\right) + \left(\frac{Sprinkler\ systems\ (\$)}{C}\right)\right]$

Where C = to each direct investment depreciation (years) *Quantity of wood dried annually (M bm)

- *Interest on air drying yard investments*

6. $Interest\ on\ air\ drying\ investment\ \left(\frac{\$}{M\ bm}\right) =$

$$\frac{Total\ air\ drying\ yard\ investment\ (\$)}{(Annual\ interest\ rate\ (\%) * Quantity\ of\ wood\ dried\ annually\ (M\ bm))}$$

- *Maintenance and repair of yard*

7. $Total\ yard\ Maintenace\ \left(\frac{\$}{M\ bm}\right) =$

$$\frac{\left(Total\ drying\ yard\ investments\ \left(\frac{\$}{yr}\right) + Snow\ removal\ \left(\frac{\$}{yr}\right) + Yard\ cleaning\ \left(\frac{\$}{yr}\right) + Annual\ lightning\ expense\ \left(\frac{\$}{yr}\right)\right)}{Quantity\ of\ wood\ dried\ annually\ (M\ bm)}$$

Land area investments

- *Land area*

8. $Total\ Land\ costs(\$) =$

$Air\ drying\ area\ \ (\$) + Road\ area\ (\$) + Area\ for\ buildings, kiln, boiler\ (\$))$

- *Land area interest*

9. $Land\ area\ interest\ \left(\frac{\$}{M\ bm}\right) = \frac{\left(Total\ land\ costs\ (\$) * Land\ value\ \left(\frac{\$}{ft^2}\right) * annual\ interest\ rate\ (\%)\right)}{Quantity\ of\ wood\ dired\ annually\ (M\ bm)}$

- *Taxable values*

$$\begin{aligned} Taxable\ values\ (\$) &= \left[\left(Total\ land\ costs\ (\$) * Land\ value\ \left(\frac{\$}{ft^2}\right)\right) + Buildings\ costs\ (\$)\right. \\ &+ Kilns\ equipment\ (\$) + Fences\ (\$) + lightning\ (\$) + sprinklers\ (\$) \\ &\left. + drainage\ (\$)\right] \end{aligned}$$

11. $Taxes\ on\ kiln\ and\ air\ drying\ yard = \frac{Total\ taxable\ values\ (\$) * Tax\ rate}{Quantity\ of\ wood\ dried\ annually\ (M\ bm)}$

- *Insurable values*

10. $insurable\ values\ (\$) = Total\ direct\ investments\ (\$) + storage\ sheds\ (\$) + Fences\ (\$) +$

$\left(Average\ price\ of\ lumber\ \left(\frac{\$}{M\ bm}\right) *\right.$

$\left. Average\ daily\ volume\ of\ lumber\ on\ yard\ and\ in\ kilns\ on\ any\ given\ day\ (M\ bm)\right)$

11. $Total\ insurance\ \left(\frac{\$}{M\ bm}\right) = \frac{Insurable\ values\ (\$) * Insurance\ rate\ (\%)}{Quantity\ of\ wood\ dried\ annually\ (M\ bm)}$

Stacking cost

12. $stacking\ cost\ \left(\frac{\$\ M\ bm}{hr}\right) = stacking\ time\ \left(\frac{M\ bm}{hr}\right) * hourly\ stacking\ cost\ \left(\frac{\$}{hr}\right)$

Kiln maintenance

13. $Kiln\ maintenence\ \left(\frac{\$}{M\ bm}\right) = \frac{Maintenence\ of\ kiln\ and\ boiler\ (\$)}{Quantity\ of\ wood\ dried\ annually\ (M\ bm)}$

Stock interest cost

14. $Volume\ air\ dry\ yard\ stock\ (m3) = total\ capicity * \frac{air\ drying\ time * 7 * 24}{final\ drying\ time}$

15. $\text{cost of air dry stock interest } \left(\frac{\$}{\text{yr}}\right) = \text{volume air dry yard stock} * \text{wood value} * \frac{\text{interest rate}}{1000}$

16. $\text{Cost of air dry stock interest } \left(\frac{\$}{\text{m3}}\right) = \frac{\text{cost of air dry stock interest } (\frac{\$}{\text{yr}})}{\text{annual throughput}}$

Similarly, the following calculations are performed to determine the annual interest and interest per cubic meter on the kiln stock:

19. $cost\ of\ kiln\ stock\ interest\ \left(\frac{\$}{yr}\right) = total\ capacity * wood\ value * \frac{interest\ rate}{1000}$

20. $cost\ of\ kiln\ stock\ interest\ \left(\frac{\$}{m3}\right) = \frac{cost\ of\ kiln\ stock\ interest\ \left(\frac{\$}{yr}\right)}{annual\ throughput}$

The total Finance costs are calculated as follows:

21. $\text{total finance cost } \left(\frac{\$}{\text{yr}}\right) = \text{interest on direct investment} + \text{interest on air drying yard investments} + \text{maintenence and yard repair} + \text{land area interest} + \text{stacking cost} + \text{cost air dry stock interest} + \text{cost of kiln interest}$

22. $\text{total finance cost } \left(\frac{\$}{\text{m3}}\right) = \frac{total\ capital\ cost\ (\frac{\$}{yr})}{annual\ throughput}$

CAPACITY

Annual throughput

The annual throughput is defined as:

23. *total capacity (m3) = no.of kilns × kiln capacity*

24. *annual throughput (m3 /yr) = total capacity × kiln cycles per year*

Where,

25. $Kiln\ cycles\ per\ year = operational\ year * \frac{24}{run\ times}$

OPERATIONAL COSTS

Forklift Cost

26. $Forklift\ cost\ \left(\frac{\$\ M\ bm}{hr}\right) = forklift\ time\ \left(\frac{M\ bm}{hr}\right) * Hourly\ forklift\ cost\ \left(\frac{\$}{hr}\right)$

Kiln labor

27. $Kiln\ labor =$
$((Time\ spent\ each\ day\ observing\ and\ running\ kilns, boilers\ (hr) *$
$Hourly\ wage\ rate\ and\ fringe\ benefits\ for\ kiln\ operator\ and\ auxilary\ equipment\ (\$/hr) *$
$Average\ lenghth\ of\ kiln\ run))/(Total\ capacity\ of\ kilns\ )$

Office overhead

28. $Total\ office\ overhead\ \left(\frac{\$}{M\ bm}\right) = \frac{Annual\ office\ costs\ attribued\ to\ drying\ (\$)}{Quantity\ of\ wood\ dried\ annually\ \ (M\ bm)}$

Air Flow

The cost of running the kiln fans is calculated as:

29. $air\ flow\ cost\ \left(\frac{\$}{yr}\right) = kiln\ cycles\ per\ year * no.of\ fans * fan\ rating * number\ of\ kilns *$
$kiln\ drying\ time * electrictity\ cost.$

30. $\text{air flow cost}\ \left(\frac{\$}{\text{m3}}\right) = \frac{air\ flow\ cost\ (\frac{\$}{yr})}{annual\ throughput}$

Degrade

The cost of degrade is calculated as:

31. $Total\ degrade\ (\$) =$

$$Average\ price\ of\ lumber\ \left(\frac{\$}{M}bm\right) * Average\ drying\ degrade\ (percent\ as\ decimal)$$

Heat

The quantity of heat energy used per cubic meter for heating the wood, heating the water within the wood and vaporization of water during kiln drying are calculated as:

32. $energy\ to\ heat\ wood\ \left(\frac{MJ}{m3}\right) = wood\ basic\ density * \frac{specif\ heat\ of\ wood}{1000} * \ \Delta T$

Where the specific heat of hardwood is 1.2 kJ/(kg°C) and ΔT is the maximum – minimum drying temperature (°C). For the purpose of this study the minimum drying temperature is assumed ambient temperature at 25°C.

33. $energy\ to\ heat\ water\ \left(\frac{MJ}{m3}\right) = \frac{initial\ MC}{1000} * wood\ basic\ density * \frac{specific\ heat\ of\ water}{1000} * \ \Delta T$

Where the specific heat of water is 4.186 kJ/(kg°C).

The total amount of heat per cubic meter, taking into account the thermal loss is calculated using:

34. $energy\ to\ vaporise\ water\ \left(\frac{MJ}{m3}\right) = \frac{initial\ MC - Final\ MC}{100} * wood\ basic\ density * heat\ of\ vaporisation.$

The total amount of heat per cubic meter, taking into account the thermal loss is calculated using:

35. $total\ heat\ energy\ \left(\frac{MJ}{m3}\right) =$

$$(energy\ to\ heat\ wood + energy\ to\ heat\ water + energy\ to\ vaporise\ water) * \left(\frac{1 - thermal\ loss}{100}\right)$$

The total cost of heat energy is calculated as follows:

36. $heat\ cost\ \left(\frac{\$}{yr}\right) = (kiln\ cycles\ per\ year * total\ capacity * total\ heat\ energy) * cost\ of\ heat\ (\$) *$

$$(annual\ fuel\ consumption\ (gal) * Fuel\ cost\ \left(\frac{\$}{gal}\right)$$

37. $heat\ cost\ \left(\frac{\$}{m3}\right) = \frac{heat\ cost\ \left(\frac{\$}{yr}\right)}{annual\ throughput}$

Extra vacuum drying energy calculations

38. $vacuum\ pump\ energy\ (kJ) = vacuum\ pump\ rating * \frac{vacuum\ pump\ usage}{100} * drying\ time$

39. $condensor\ fan\ energy\ (kJ) = condensor\ fan\ rating * \frac{condensor\ fan\ usage}{100} * drying\ time$

The total extra energy is calculated using:

40. $total\ extra\ energy\ (kJ) = vacuum\ pump\ energy + condensor\ fan\ energy$

The total cost of extra vacuum drying energy is determined by:

41. $vacuum\ specific\ energy\ \left(\frac{\$}{yr}\right) = total\ extra\ energy * kiln\ cycles\ per\ year * no.of\ kilns * electricity\ cost$

42. $vacuum\ specific\ energy\ \left(\frac{\$}{m3}\right) = \frac{vacuum\ specific\ energy\ (\frac{\$}{yr})}{annual\ throughput}$

Operational costs – totals

The total operational cost per year for conventional drying is determined by:

43. $total\ operational\ cost\ \left(\frac{\$}{yr}\right) = Forklift\ cost + kiln\ labor + office\ overhead + \ air\ flow\ cost\ \left(\frac{\$}{yr}\right) + heat\ cost\ \left(\frac{\$}{yr}\right)$

The total operational cost per year for vacuum drying is determined by:

44. $Total\ operational\ cost\ \left(\frac{\$}{yr}\right) = Forklift\ cost + kiln\ labor + office\ overheadair\ flow\ cost\ \left(\frac{\$}{yr}\right) + heat\ cost\ \left(\frac{\$}{yr}\right) + vacuum\ specific\ energy\ \left(\frac{\$}{yr}\right)$

For both drying types, the total operational cost per cubic meter is calculated using:

45. $total\ operational\ cost\ \left(\frac{\$}{m3}\right) = \frac{total\ operational\ cost\ \left(\frac{\$}{yr}\right)}{annual\ throughput}$

Total costs

The total cost of drying is calculated using:

46. $total\ drying\ cost\ \left(\frac{\$}{yr}\right) = total\ finance\ \ cost\ \left(\frac{\$}{yr}\right) + total\ operational\ cost\ \left(\frac{\$}{yr}\right)$

47. $total\ drying\ cost\ \left(\frac{\$}{yr}\right) = \frac{total\ drying\ cost\left(\frac{\$}{yr}\right)}{annual\ throughput}$

APPENDIX C. VARIABLES USED TO DETERMINE CONVENTIONAL DRYING COSTS.

FINANCE VARIABLES	VALUES	INFORMATION SOURCE
Direct investments (total costs)		
Buildings, sheds, etc.	$675,000	Plant D
Kiln (including, auxiliary equipment, boiler, installation)	$2,225,000	Kiln company A
Stickers	$406,010	Plant D
Pile roofs	$116,750	Plant D
Pile bases, bolsters	$139,164	Plant D
Depreciation period for direct investments (years)		
Buildings, sheds, etc.	20	McMillen and Wenegert 1978
Kiln, auxiliary equipment (including boiler)	20	McMillen and Wenegert 1978
Stickers*	3	McMillen and Wenegert 1978
Pile roofs*	5	McMillen and Wenegert 1978
Pile bases, bolsters*	5	McMillen and Wenegert 1978
Drying yard investments (Total costs)		
Temporary road construction (includes drying alleys)	$120,000	Plant D
Fences	$9,191	ESTIMATED
Lighting systems	$1,377	ESTIMATED
Drainage systems	$4,090	ESTIMATED
Sprinkler systems	$2,160	ESTIMATED
Depreciation period for drying yard investments		
Fences	20	ESTIMATED
Lighting systems	20	ESTIMATED
Sprinkler systems	15	ESTIMATED
Storage sheds for stickers, dried lumber, etc.	20	ESTIMATED

Continue Appendix C.

OTHER FINANCE VARIABLES(If applicable)		
Maintenance of kilns and boiler ($).	$29,925	Fortin 2010
Maintenance and repair of yard ($)	$15,000	Fortin 2010
Snow removal ($/yr)	$4,500	On line estimator
Land area (ft2)		
Air drying area (include space between the piles) ($/Acre)	$100,000.00	Plant D
Road area ($/Acre)	$75,000.00	Plant D
Area for buildings, kiln, boiler, etc. ($/Acre)	$75,000.00	Plant D
Land value ($/Acre)	$25,000.00	Plant D
Annual interest rate (%)	9.00	ESTIMATED
Tax rate to be applied to the total of taxable values (%)	5.00	Plant D
Insurance rate applied to the total of insurable values (%)	1.71	Plant D
CAPACITY VARIABLES		
Average price of lumber ($/MBF)	$1,275.00	Hardwood Report Market
Average drying degrades based on lumber value (percent as decimal)	0.30	Plant C
Average daily volume of lumber on yard and in kilns on any given day (MBF)	4000.00	Plant C
Total capacity of kilns	480000.00	Plant D
Number of Kilns	6.00	Plant D
Operational year	365.00	Plant D
Annual throughput (MBF/yr)	12000.00	Plant D
Run times	24.00	Plant D
Kiln cycles per year	25.00	Plant D
Average length of kiln run (include loading and unloading time)	12.30	Plant D
Number of fans	35.00	Plant D
Fan rating (kW)	4.66	Plant D
Air drying time (weeks)	6.00	Plant D
Final Drying time (hrs)	295.20	Plant D
Volume air dry yard (MBF)	4125.00	Plant D
Maximum drying temperature (F)	180.00	Plant D
Minimum drying temperature (F)	105.00	Plant D

Continue Appendix C.

OPERATIONAL VARIABLES		
Forklift wage ($/yr)	$114,000	Plant D
Lumber graders ($/yr)	$160,000	Plant D
Wage for kiln operator and yard supervisor ($/yr)	$67,000	Plant D
ENERGY COSTS		
Fuel consumption (hog waste) (tons/day)	13.50	Plant D
Fuel cost ($/ton)	35	Plant D
Annual electrical usage attributed to drying (kWh/yr)	1845770.47	Plant D
Electrical cost ($/kWh)	0.10	Plant D
Initial MC (%)	20	Plant D
Final MC (%)	8	Plant D
Raw Material Cost ($/MBF)	$14,673,750	Hardwood Report Market

Previews Energy Calculations		
Thermal loss (%)	65	Redman 2011
Total Wood Volume	1132.82	
Wood basic density (Kg)	634381.20	
Specific heat of hardwood (KJ/(Kg*oC)	1.20	Redman (2011)
Specific heat of water (KJ/(Kg*oC)	4.19	Redman (2011)
Heat of Vaporization (MJ/kg)	2.25”	Redman (2011)
Specific gravity at FSP	0.56	ESTIMATED
Water density (kg/m3)	1000	ESTIMATED
1KJ	0.95	BTU's
1ton	16000000	BTU's
Maximun Temperature (oC)	82.22	
Minimum Temperature (oC)	40.56	
Energy to heat wood (KJ)	31719059.76	
Energy to heat water (KJ)	27661663.36	
Energy to vaporize Water (KJ)	242650807.14	
Total heat energy (KJ)	407742565.85	
Total BTUs/charge used for drying	386465335.53	
Total tons/charge used for drying	24.15	
Total Energy cost ($/yr)	21134.82	
Total Electrical cost ($/yr)	184577.05	

APPENDIX D. VARIABLES USED TO DETERMINE VACUUM (WITH AIR DRYING) DRYING COSTS

.FINANCE VARIABLES	VALUES	INFORMATION SOURCE
Direct investments (total costs)		
Buildings, sheds, etc.	$440,347	Plant D
Kiln (including boiler, vacuum pump, material handling, auxiliary equipment)	$3,333,85	Company A
Stickers	$1,397,126	Plant D
Pile roofs	$401,750	Plant D
Pile bases, bolsters	$224,980	Plant D
Depreciation period for direct investments (years)		
Buildings, sheds, etc.	20	McMillen and Wenegert 1978
Kiln, auxiliary equipment (including boiler)	10	McMillen and Wenegert 1978
*Stickers**	3	McMillen and Wenegert 1978
*Pile roofs**	5	McMillen and Wenegert 1978
*Pile bases, bolsters**	5	McMillen and Wenegert 1978
Drying yard investments (Total costs)		
Temporary road construction (includes drying alleys)	$120,000	Plant D
Fences	$9,191	ESTIMATED
Lighting systems	$1,377	ESTIMATED
Drainage systems	$4,090	ESTIMATED
Sprinkler systems	$4,680	ESTIMATED
Depreciation period for drying yard investments		
Fences	20	ESTIMATED
Lighting systems	20	ESTIMATED
Sprinkler systems	15	ESTIMATED
Storage sheds for stickers, dried lumber, etc.	10	ESTIMATED

Continue Appendix D.

OTHER FINANCE VARIABLES(If applicable)		
Maintenance of kilns and boiler ($).	$29,925	Fortin 2010
Maintenance and repair of yard ($)	$15,000	Fortin 2010
Snow removal ($/yr)	$4,500	On line estimator
Land area (ft2)		
Air drying area (include space between the piles) ($/Acre)	$100,000	Plant D
Road area ($/Acre)	$75,000	Plant D
Area for buildings, kiln, boiler, etc. ($/Acre)	$75,000	Plant D
Land value ($/Acre)	$25,000	ESTIMATED
Annual interest rate (%)	9	ESTIMATED
Tax rate to be applied to the total of taxable values (%)	4	ESTIMATED
Insurance rate applied to the total of insurable values (%)	1.71	ESTIMATED
CAPACITY VARIABLES		
Average price of lumber ($/MBF)	$1,275	Hardwood Report Market
Average drying degrades based on lumber value (percent as decimal)	0.3	Plant C
Average daily volume of lumber on yard and in kilns on any given day (MBF)	4000	Plant C
Total capacity of kilns	133485	Company A
Number of Kilns	11	ESTIMATED
Operational year	365	Plant D
Annual throughput (MBF/yr)	24000	Plant D
Run times (hr)	24	ESTIMATED
Kiln cycles per year	91	ESTIMATED
Average length of kiln run (include loading and unloading time) (days)	4	ESTIMATED
Air drying time (weeks)	16	Plant D
Final Drying time (hrs)	96	ESTIMATED
Volume air dry stock (MBF)	14197	Plant D
Maximum drying temperature (F)	180	Plant D
Minimum drying temperature (F)	105	Plant D

Continue Appendix D.

OPERATIONAL VARIABLES		
Forklift wage ($/yr)	$114,000	Plant D
Lumber graders ($/yr)	$160,000	Plant D
Wage for kiln operator and yard supervisor ($/yr)	$67,000	Plant D
Vacuum pump rating kw/1000bf)	1.5	Redman 2011
Vacuum pump usage	20	Redman 2011
Condenser fan rating	11	Redman 2011
Condenser fan usage	25	Redman 2011
ENERGY COSTS		
Fuel consumption (gal/day)	20	Company A
Fuel cost ($/gal)	$3.50	Company A
Annual electrical usage attributed to drying (kW/year)	1012984.5	Company A
Electrical cost ($/kWh)	0.1	Plant D
Initial MC (%)	43	ESTIMATED
Final MC (%)	8	ESTIMATED
Raw Material Cost	$43,634,986	Hardwood Report Market

Previews Energy Calculations		
Thermal loss (%)	30	Redman 2011
Total Wood Volume	315.0311526	
Wood basic density (Kg)	176417.4455	
Specific heat of hardwood (KJ/(Kg*oC)	1.2	Redman (2011)
Specific heat of water (KJ/(Kg*oC)	4.186	Redman (2011)
Heat of Vaporization (MJ/kg)	2.25”	Redman (2011)
Specific gravity at FSP	0.56	ESTIMATED
Water density (kg/m3)	1000	ESTIMATED
1KJ	0.947817	BTU's
1 oil gallon	134200	BTU's
Maximum Temperature (oC)	82.22	
Minimum Temperature (oC)	40.56	
Energy to heat wood (KJ)	8820872.27	
Energy to heat water (KJ)	7692535.70	
Energy to vaporize Water (KJ)	67479672.90	
Total heat energy (KJ)	142788237.47	
Total BTUs/charge used for drying	135337118.88	
Total gal/charge used for drying	1008.47	
Total heat cost ($/yr)	322081.16	
Total Electrical cost ($/yr)	101298.45	
Vacuum Pump Energy (KJ)	28.80	
Condenser fan energy (KJ)	264	
Total extra energy (KJ)	292.80	
Vacuum specific energy ($/yr)	29389.80	

APPENDIX E. VARIABLES USED TO OBTAIN VACUUM (WITHOUT AIR DRYING) DRYING COSTS.

FINANCE VARIABLES	VALUES	INFORMATION SOURCE
Direct investments (total costs)		
Buildings, sheds, etc.	$228,980.00	Plant D
Kiln (including boiler, vacuum pump, material handling, auxiliary equipment)	$6,659,700.00	Company A
Stickers	$1,100.00	Plant D
Depreciation period for direct investments (years)		
Buildings, sheds, etc.	20	McMillen and Wenegert 1978
Kiln, auxiliary equipment (including boiler)	10	McMillen and Wenegert 1978
*Stickers**	3	McMillen and Wenegert 1978
OTHER FINANCE VARIABLES(If applicable)		
Maintenance of kilns and boiler ($).	$29,925	Fortin 2010
Land area (ft2)		
Area for buildings, kiln, boiler, etc. ($/Acre)	$75,000	Plant D
Land value ($/Acre)	$25,000	ESTIMATED
Annual interest rate (%)	9	ESTIMATED
Tax rate to be applied to the total of taxable values (%)	4	ESTIMATED
Insurance rate applied to the total of insurable values (%)	1.71	ESTIMATED
CAPACITY VARIABLES		
Average price of lumber ($/MBF)	$1,275	Hardwood Report Market
Average drying degrades based on lumber value (percent as decimal)	0.3	Plant C
Average daily volume of lumber on yard and in kilns on any given day (MBF)	4000	Plant C
Total capacity of kilns	266970	Company A
Number of Kilns	22	ESTIMATED
Operational year	365	Plant D
Annual throughput (MBF/yr)	12000	Company A
Run times (hrs)	24	ESTIMATED
Kiln cycles per year	46	ESTIMATED
Average length of kiln run (include loading and unloading time) (days)	8	ESTIMATED
Final Drying time (hrs)	192	Company A
Volume air dry stock (MBF)	8250	Plant D
Maximum drying temperature (F)	180	Plant D
Minimum drying temperature (F)	105	Plant D

Continue Appendix E.

OPERATIONAL VARIABLES		
Forklift wage ($/yr)	$114,000	Plant D
Wage for kiln operator and yard supervisor ($/yr)	$67,000	Plant D
Vacuum pump rating kw/1000bf)	1.5	Redman 2011
Vacuum pump usage	20	Redman 2011
Condenser fan rating	11	Redman 2011
Condenser fan usage	25	Redman 2011
ENERGY COSTS		
Fuel consumption (gal/day)	20	Company A
Fuel cost ($/gal)	$3.50	Company A
Annual electrical usage attributed to drying (kW/year)	1021310.4	Company A
Electrical cost ($/kWh)	0.1	Plant D
Initial MC (%)	25	ESTIMATED
Final MC (%)	8	ESTIMATED
Raw Material Cost	$11,174,443	Hardwood Report Market
PreviewS Energy Claculations		
Thermal loss (%)	30	Redman 2011
Total Wood Volume	630.06	
Wood basic density (Kg)	352834.89	
Specific heat of hardwood (KJ/(Kg*oC)	1.20	Redman (2011)
Specific heat of water (KJ/(Kg*oC)	4.19	Redman (2011)
Heat of Vaporization (MJ/kg)	2.25”	Redman (2011)
Specific gravity at FSP	0.56	ESTIMATED
Water density (kg/m3)	1000	ESTIMATED
1KJ	0.95	BTU's
1 oil gallon	134200	BTU's
Maximun Temperature (oC)	82.22	
Minimum Temperature (oC)	40.56	
Energy to heat wood (KJ)	17641744.55	
Energy to heat water (KJ)	15385071.39	
Energy to vaporize Water (KJ)	134959345.79	
Total heat energy (KJ)	285576474.95	
Total BTUs/charge used for drying	270674237.76	
Total gal/charge used for drying	2016.95	
Total heat cost ($/yr)	324728.41	
Total Electrical cost ($/yr)	102131.04	
Vacuum Pump Energy (KJ)	57.60	
Condensor fan energy (KJ)	528	
Total extra energy (KJ)	585.60	
Vacuum specific energy ($/yr)	59262.72	