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

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Many wood product manufacturers are trying to increase competitiveness by implementing continuous improvement programs such as lean manufacturing. However, the lumber drying process can significantly affect manufacturing time and inventory size, thus limiting how "lean" the entire process can become. The goal of this research was to determine how vacuum drying technology could support lean manufacturing concepts relative to conventional drying technology in hardwood manufacturing. Two flooring manufacturers with drying operations were modeled, and simulations were used to determine differences in cycle time and work-in-process inventory. The total cycle time of vacuum drying was 78% and 90% less than conventional drying. Work-in-process inventory was reduced by 57% and 52%. The reduction of work-in-process inventory in the drying process represents a potential cost savings of $7.3 million and $13.6 million per year for each manufacturer, respectively. The reduction in inventory carrying costs, faster drying rates, and reduced cycle time demonstrate that vacuum drying could significantly improve the competitiveness of hardwood flooring manufacturers.

Keywords: Vacuum drying; Lean manufacturing; Simulation

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INTRODUCTION

The U.S. hardwood lumber industry has encountered many challenges during the past several years. Increasing global competition and energy prices and the decelerating housing market has led to decreasing lumber manufacturing in the U.S. (Gazo and Quesada 2005; Grushecky *et al.* 2006; Pepke 2010; Espinoza *et al.* 2011). A decrease in lumber manufacturing has led to the increase in wood product imports from China due to weaker regulations, their ability to build furniture, and an abundant supply of cheap labor (NCGE 2009).

The wood product industry needs to change their business model to remain competitive, and one way to increase competitiveness is by implementing continuous improvement programs (Pirraglia *et al.* 2009). Lead-time reduction has become a common goal for wood product supply chains. However, the conventional lumber drying process remains elusive to lead-time reduction efforts because it is a slow operation, where large amounts of inventory are required to feed the rest of the processes and meet customer demand.

Species such as red oak are normally air dried and then kiln-dried in large batches, which consumes a large percentage of the total manufacturing time. Air drying is often done to reduce drying costs and increase kiln throughput; however, the practice further increases wood inventory that must be stored and managed. Research is needed on alternatives to conventional drying technology that would allow manufacturers to reduce the cash tied up in inventory and to achieve a leaner production system.

Manufacturing lines are based on three parameters: work-in-process-inventory (WIP), cycle time (CT), and throughput (TH) (Hopp and Spearman 2001). WIP is defined by Hopp and Spearman (2001) as: “the inventory between the start and end points of a product routing. CT is defined by Hopp and Spearman (2001) as: “the 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).” TH is defined by Hopp and Spearman (2001) as: “the average output of a production process (machine, workstation, line plant) per unit time.”

Lean manufacturing philosophy helps to improve the product flow through the process (reduction of WIP), shortens the manufacturing lead times (cycle times, CT), reduces defects, and supports continuous improvement (Lean Enterprise Institute 2007). Also, improvements in time flexibility can lead to higher customer satisfaction, reduction of costs (less WIP in the system), and increased competitiveness (Quesada and Buehlmann 2011). Vacuum drying has the potential to achieve shorter drying times, the use of smaller drying loads, and maintaining the same drying quality as conventional drying, while allowing delivery of the product to the customer on time. In a very demanding market, a one-day difference in lead time (cycle time) can improve the competitiveness of an industry. These potential benefits can help improve the overall hardwood supply chain in the U.S., leading towards increased competitiveness.

The goal of this research was to evaluate how vacuum drying technology could support lean manufacturing concepts compared to conventional drying and ultimately increase the competitiveness of the hardwood industry by reducing WIP and CT, while sustaining a products TH meeting customer demand.

EXPERIMENTAL

Product Identification and Data Collection Instrument

Two examples of industrial wood flooring processing systems were observed and modeled to determine the impact of vacuum drying versus conventional drying on WIP, CT, and TH. Flooring manufacturing was chosen since it consists of a simple production line, while furniture or cabinet manufacture contains a more complex array of production and assembly lines. A flooring line tends to be linear from when lumber enters the system until the final product is delivered to the customer. Often, flooring companies will have a prefinished and unfinished flooring line. Only one flooring line from each facility was modeled to reduce complexity.

Value stream data were collected over a six month period of time to determine which flooring line would be modeled based on simplicity and to collect data about each process in the line. For manufacturer A, a 3.25” wide red oak prefinished flooring line was chosen, and for manufacturer B, a 3.25” wide red oak unfinished flooring line was chosen. These products use four quarter (4/4) red oak lumber, which has relatively long drying times and quality issues (compared to other species). Quantitative data about each process was collected using the value stream mapping methodology described by Rother and Shook (1999). Processing times were collected from production data provided by manufacturers A and B.

Vacuum and Conventional Drying Times and Costs

Data regarding drying times and costs for vacuum drying were collected from companies that sell vacuum drying equipment and from companies using the drying technology. Information from McMillen and Wengert (1978) and Fortin (1998) was also used to complete the project.

In the case of conventional drying, data about drying times and costs was gathered from the two flooring companies: manufacturer A and B. However, both companies were not able to provide all information needed for the drying costs, so drying cost data was also acquired from a conventional kiln manufacturer and literature. The data collection methods used to determine drying costs can be found in Brenes-Angulo (2014).

Simulation Model Development

Simio^{TM} software (USA) was used to develop the simulation model for each production line. The information from each process (batch size, process time, inventory, work shift) was obtained using a data collection instrument provided to the production manager of manufacturers A and B.

Simulation incorporates variability into the models. Characterizing variability such that it is representative of the observed manufacturing system is called input modeling. Variability in simulation is represented by random variables that can be continuous (*e.g.*, time) or discrete (*e.g.*, quantity). In Simio^{TM}, for example, an input model can be used to characterize the variable nature of processing times for each machine. This variability is derived from the distribution of the continuous or discrete values that comes from the observed data; in our case, it was from the record of processing times of the machines observed at the manufacturers.

According to Kelton *et al.* (2011), 30 is the minimum sample number to estimate a good initial value for the variation of a process to determine an appropriate sample size. For this study, thirty processing times were collected randomly from the shop floor of each manufacturer. The 30 processing times were used to provide an initial estimate of the sample variance to calculate the sample size needed for the input modeling of the simulation model for each manufacturer. The sample size was calculated by the following formula (Eq. 1) (Ott and Longnecker 2010),

$$n = \left[\frac{z\frac{\alpha}{2} * \sigma}{E} \right]^2 \tag{1}$$

where, n = is the required 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 at a confidence level; σ is the initial estimate of the sample standard deviation; and E is the tolerable error for the sample mean (in same units as the mean).

The simulation sample size for the input modeling was 70 processing times for each machine, with α equal to 0.05, and a standard deviation of 0.19. The 70 points were gathered randomly from the production rates provided by manufacturers A and B.

EasyFit software (MathWave Technologies, USA) was used to fit a distribution to the processing times of each process for both manufacturers A and B. EasyFit software is recommended by Simio^{TM}, and it fits a distribution to the observed process data. Using EasyFit, frequency histograms were analyzed, and tests of goodness of fit were applied to determine the best probability distributions that fitted the data. Input model results for Plants A and B are shown in Table 1 and 2, respectively. Parameter descriptions for the probability models are described in Joines and Roberts (2012). The obtained parameters of the distributions were then incorporated into the Simio^{TM} simulation coding.

Table 1. Probability Distributions for Each Process at Plant A

Process	Distribution
Grading/Stacking*	Random.Uniform(0.31,0.41)
Air drying**	Random.Uniform(36,48)
Kiln drying**	Random.Uniform(11.9,12.4)
Surface Planer*	Random.LogLogistic(1.18,1.07)
Ripsaw*	Random.Pert(1.70,1.73,1.90)
Moulder*	Random.LogLogistic(2.06,1.97)
Prefinishing*	Random.Weibull(1.3,0.21)

*seconds, **days

Table 2. Probability Distribution for Each Process at Plant B

Process	Distribution
Grading/Stacking*	Random.Uniform(0.33,0.39)
Air drying**	Random.Uniform(36,48)
Kiln drying**	Random.Uniform(11.9,12.2)
Ripsaw *	Random.Uniform(0.33,0.39)
Chop saw*	Random.Uniform(0.35,0.41)
Moulder*	Random.Uniform(0.42,0.48)
End matchers*	Random.Uniform(0.42,0.48)
Grading*	Random.Uniform(0.49,0.55)
Nesting/bundling*	Random.Uniform(0.49,0.55)

*seconds, **days

Two simulation models for each manufacturing plant (A and B) were created to determine the impact on TH, WIP, and CT of the production line—one model using conventional drying (air drying plus kiln drying) and the other one substituting conventional drying with vacuum drying. 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 of the kilns. Conventional drying times were provided by the flooring manufactures using the technology; while vacuum drying times were obtained by vacuum kiln manufacturers and from Fortin (1998). WIP values used were as observed and measured from manufacturing Plants A and B. The vacuum drying model used the same WIP levels as observed in conventional drying, except that the drying processing times changed.

Simulation models for Plant A and B were both run for a period of 13 weeks to simulate an approximation of the total lead time required to complete a production order for each company. Each scenario was run with 30 replications to build statistical confidence intervals given the random input models described earlier. Then, the WIP, cycle times, and throughput values obtained from the simulation were compared qualitatively to the actual scenarios of manufactures A and B to verify the models and establish model validity. Details of the simulation modeling and validation procedures are described in Brenes (2014).

Inventory Cost Reduction

An inventory cost reduction from the drying process was estimated for both manufacturers and drying methods. The inventory cost reduction was calculated with the purpose to determine the impact of vacuum drying in a flooring company. The methodology proposed by Keown *et al.* (2006) was used to estimate the inventory cost reduction of the drying operation. The cost of inventory used the following formula (Eq. 2),

Cost of Inventory = Beginning Inventory + Inventory Purchases - Ending Inventory (2)

where, the beginning inventory is the value of the inventory at the beginning of the time period; inventory purchases are the inventory cost for inventory added during the time period; and ending inventory is the inventory value at the end of the time period.

RESULTS AND DISCUSSION

Manufacturer A's product was 3.25" prefinished flooring, and the production line consisted of 7 processes: grading and stacking, air drying, kiln drying, surface planer, rip saw, moulder, and pre-finishing. Data used to model the production line are presented in Table 3. The second modeled production line was a 3.25" unfinished red oak flooring line located at a different manufacturing plant using 9 manufacturing processes, and the data are presented in Table 4.

As shown in Tables 3 and 4, for both manufacturers A and B, air drying contributed to the largest lead times, since that process takes approximately 42 days. The second operation with largest inventory was kiln drying, where approximately 12 days are needed to dry the lumber. The main reason for the high inventory in the drying operation is that 42 days are needed (for both companies) for air drying and then 12 days (for both companies) to dry a batch of lumber to the desired moisture content. 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 manufacturer A and B, 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 possible to reduce capital costs by reducing cash tied up in inventory.

Table 3. Parameters Observed and Reported by the Company for Each Workstation in the 3.25" Wide Red Oak Prefinished Line Production for Manufacturer A

Process parameters	Process						
	Grading and Stacking	Air Drying	Kiln Drying	Surface Planer	Rip Saw	Moulder	Pre-Finishing
Number of Machines	1	0	7	1	1	1	1
Batch size	Continuous	variable	75 MBF*	1.2 MBF*	1.1 MBF*	0.85 MBF*	0.85 MBF*
Process time	0.36 sec/ BF	42 days	12 days	0.74 sec/BF	1.7 sec/BF	2.07 sec/BF	1.2 sec/BF
Changeover time	0	not applicable	180 min	5 min	5 min	5 min	8 min
Inventory	11.4 MBF	1890 MBF*	717.7 MBF*	143.5 MBF*	470.6 MBF*	333.5 MBF*	245.3 MBF*
Quality	97%	85%	97.50%	97.50%	97.50 %	97.50%	97.50%
Yield	100%	100%	97%	100%	80%	63%	98.50%

*MBF=Thousand board feet of lumber; Overall System Performance: Daily Demand = 16.275 MBF/day; Total WIP = 3812 MBF/day; Throughput (TH) = 13.2 MBF/day; Total Lead Time (CT) = 288 days

Table 4. Parameters for Each Workstation in the 3.25" Un-Finished Line Production for Manufacturer B

Process parameters	Process								
	Grading	Air Drying	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	Continuous	variable	77.5 MBF*	90 MBF*	78 MBF*	65 MBF*	65 MBF*	57 MBF*	57 MBF*
Process time	0.36 sec/BF	42 days	12 days	0.36 sec/BF	0.38 sec/BF	0.45 sec/BF	0.45 sec/BF	0.52 sec/BF	0.52 sec/BF
Number of employees	6	1	2	4	12	4	12	10	16
Change-over time	1 min	0	3 h	5 min	5 min	2 min	2 min	2 min	2 min
Inventory	2 MBF*	3890 MBF*	465 MBF*	200 MBF*	33.5 MBF*	1 MBF*	0	0	0
Quality	95%	97%	95%	N/A	N/A	85%	95%	99%	95%
Yield	100%	97%	95%	87%	83%	98%	88%	N/A	N/A
Uptime machine	90%	0	98%	95%	90%	95%	95%	95%	99%

*MBF=Thousand board feet of lumber; Overall System Performance: Daily Demand = 50 MBF/day; Total WIP = 4392 MBF; Throughput (TH) = 47.7 MBF/day; Total Lead Time (CT) = 92 days; N/A = not applicable

The system performance summaries provided in Tables 3 and 4 represent the observed performance of the manufacturing systems when the lumber first arrives to when the finished products are delivered to the costumers. Inventory reduction can help to smooth production flow and minimize costs. Vacuum drying has the potential to dry lumber faster, which can significantly reduce the inventories needed in conventional drying. Simulation was used to determine the impact of vacuum drying technology on a flooring line manufacturer.

Simulation Analysis

Simulation was used to model one production line for both manufacturer A and B. The purpose of the simulation was to model the actual system, and with this, to derive one new model for each manufacturer, using the same processes but changing the conventional drying (air drying + kiln drying) operation to a vacuum drying operation. For both models, the starting WIP levels were the same as observed during the study, only the processing times and number of kilns for conventional and vacuum drying changed.

Simulations were run for a period of 13 weeks. Thirteen weeks were needed to reach a steady state in the production lines of both manufacturers. The lead time was obtained from the overall system performance as shown in Tables 3 and 4. Each simulation had 30 replications. According to Kelton *et al.* (2001), 30 replications is the minimum number to get statistically representative parameters (mean, confidence interval, and others). The simulation results for inventory and cycle time values for companies A and B with a 95% of confidence are summarized in Figs. 1, 2, and 3.

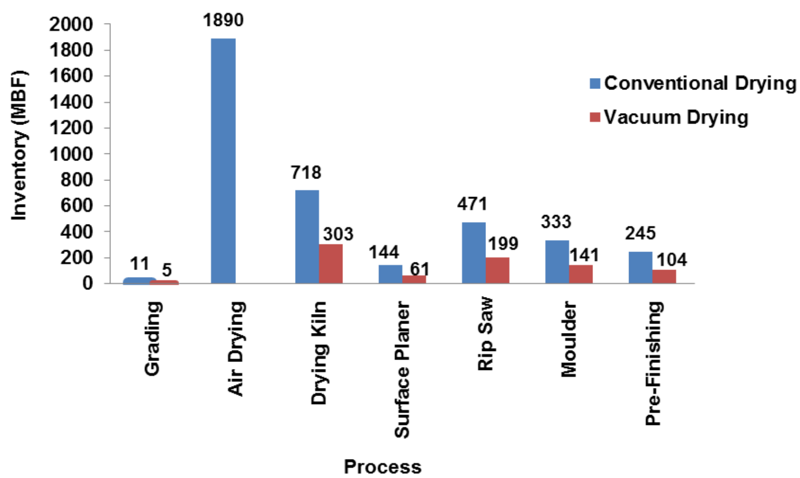

Fig. 1. Simulation results for work-in-process inventory (WIP) for manufacturer A

Figure 1 shows the 58% reduction in WIP levels between the conventional and vacuum drying models for manufacturer A. Conventional lumber drying required an inventory of 717.7 MBF, while vacuum drying required an inventory of only 303.26 MBF, which represented a 58% reduction. WIP reductions were also observed in the other manufacturing processes. For example, the grading, surface planer, rip saw, and moulder processes also resulted in a 58% reduction in their WIP levels (Fig. 1).

Figure 2 shows the inventory levels between conventional and vacuum drying for manufacturer B. A 52% reduction in WIP levels for each process of the production line was observed. Conventional lumber drying required an inventory of 465 MBF, while vacuum drying required an inventory of only 222.35 MBF, which represented a 52% reduction. Processes such as grading, rip saw, knot machine, and floor machine required an inventory of 20.62 MBF, 200 MBF, 3.5 MBF, and 1 MBF for conventional drying;

while, for vacuum drying, the processes required an inventory of 9.86 MBF, 95.63 MBF, 1.67 MBF, and 0.48 MBF, which showed a 52% reduction.

The values shown in Figs. 1 and 2, demonstrate how vacuum drying technology can impact a flooring manufacturing line, by reducing the WIP levels of the production, while TH remains constant. The WIP levels from company A and B were significantly reduced (by 52 to 58%) because the flooring production lines are meeting the daily demand as the costumer products are delivered on time.

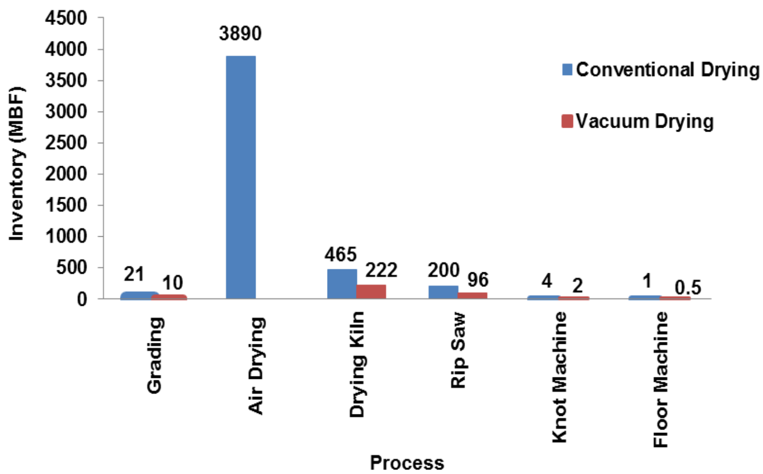

Fig. 2. Simulation results for work-in-process inventory (WIP) for manufacturer B

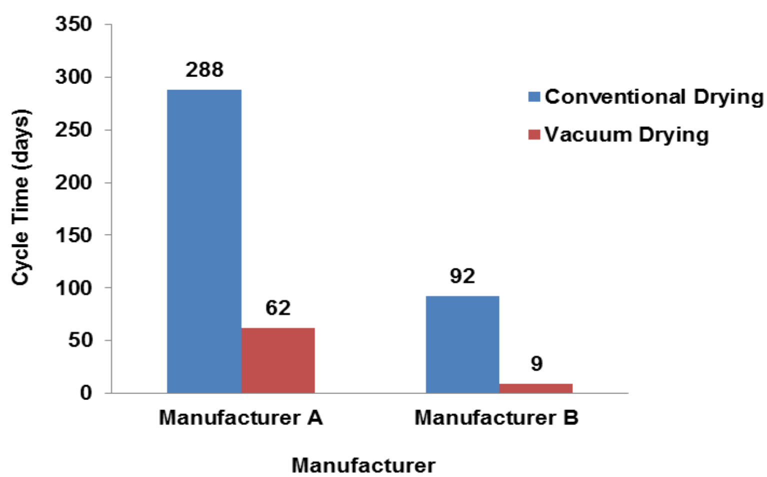

Fig. 3. Simulation results for cycle time (CT) for manufactures A and B

The use of vacuum drying also led to a reduction in the lead times (CT) for manufacturer A and B, as shown in Fig. 3. Company A's total lead time (CT) was reduced 78%, from 288 days to 62. Company B's total lead times were reduced 90%, from 92 days to 9 days. The simulation results reflect what Hopp (2001) and Spearman (2001) established, which is that a reduction in cycle time indicates a reduction in the WIP while the TH is constant.

The impact of using vacuum drying versus conventional drying can be further demonstrated by estimating the reduction in inventory cost between the two types of drying. Table 5 presents the inventory costs of the conventional and vacuum drying operations for company A and B. The inventory cost of lumber required for lumber drying was calculated for a period of 4 months to represent the total lead time of the actual inventory in the system. A projection for a year was then done to calculate the cost savings that each company would have for a year using vacuum drying.

The conventional and vacuum drying inventory cost for Company A was of $7,465,527 and $206,661, respectively. Company B obtained an inventory cost of $13,591,986 and $209,950 for conventional and vacuum drying, respectively. This means that manufacturer A could reduce their annual inventory holding cost by $7,258,866 per year in lumber costs, while manufacturer B could reduce it by $13,382,036 per year by implementing vacuum drying. These cost reductions free up enough cash to pay off the capital investment of the vacuum kiln equipment. Our results agree with Apel *et al.* (2007), who established that reducing drying times would allow the industry to dry lumber in a faster way and that the reduction in drying times would mean a reduction in manufacturing cost, an increase in earnings, and a competitive advantage for the industry.

Table 5. Comparison between Conventional and Vacuum Drying Inventory Cost for Case Study A and B for a Period of 4 Months

Parameter	Manufacturer A		Manufacturer B	
	Conventional Drying	Vacuum Drying	Conventional Drying	Vacuum Drying
Kiln equipment investment	$2,575,000	$6,659,700	$2,225,000	$7,566,750
Annual Inventory Cost	$7,465,527	$206,661	$13,591,986	$29,950

The results demonstrate how vacuum drying technology could support lean manufacturing concepts in comparison to conventional drying. In conventional drying, it takes a long time to cycle through one batch of the same product (thickness, species) and results in more inventory needing to be held in case other products demanded by customers. The total lead time associated to conventional drying increases the amount of inventory in the system, and therefore the annual inventory costs. For vacuum drying, technology total lead times are shorter, which means that there is no need of large amounts of inventory in the system because the business is capable of cycling through all of the product possibilities much faster. Shorter drying times reduce inventory, which leads to a reduction in the inventory costs. For example, orders placed for products that can be delivered with shorter lead times 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 reduced cycle times, lower inventory, and reduced lead times are ways that vacuum drying supports lean manufacturing concepts and thus sustains a more effective hardwood supply chain.

CONCLUSIONS

1. According to the lean manufacturing philosophy, improvements in time flexibility can lead to cost reduction and higher customer satisfaction (Quesada and Buehlman 2011). The use of vacuum drying reduced total lead times (CT) by 78% for manufacturer A and 90% for manufacturer B, compared to conventional drying. The reduction in lead times (CT) leads to a decrease in the WIP levels: 57% and 52% less than conventional drying for manufacturers A and B, respectively. The large reductions in CT and WIP demonstrate that vacuum drying is a potential technology to make flooring manufactures more competitive.
2. The costs involved in a flooring manufacturing line 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 longer lead times, late deliveries leading to lost sales, and higher finished goods inventory. The shorter drying times and the WIP levels reductions indicate a WIP saving costs of $725,866/year and $13,382,036/year for manufacturers A and B, respectively. The reduction in capital and inventory costs, and faster drying rates than conventional drying further demonstrates the ability of vacuum drying to support lean manufacturing concepts and improve the competitiveness of flooring manufacturers using 4/4 red oak lumber.

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