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ARTICULOS

INDUSTRIAL EVALUATION OF RE-DRY STRATEGY FOR SOFTWOOD LUMBER

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ABSTRACT

This paper presents an experimental evaluation of the first commercial scale dry-sort-redry (DSRD) strategy for drying of 2x4 Pacific coast hemlock (PCH) lumber. The DSRD strategy is a methodology designed to reduce final moisture content variability in kiln dried lumber by complementing conventional drying with radio frequency vacuum (RFV) drying technology. The strategy's objective is to avoid producing over-dried lumber in conventional drying by setting the target moisture content to a value much higher than those usually used in industry. Then, RFV drying technology is implemented to quickly and efficiently re-dry the lumber that remains wet (under-dried) after the first conventional pass. Six experimental tests were performed in an industrial sawmill with the intention of studying the effect of target moisture content on the properties and quality of the dried lumber. In all cases, the first drying pass was performed in a 260m^3 industrial heat-and-vent conventional kiln, and the re-drying of wets was performed in a 75m^3 RFV kiln. Additionally, a mathematical model developed for prediction of data dispersion in lumber drying was calibrated with experimental data, and used to simulate the DSRD strategy under other hypothetical conditions. The results of the study demonstrate that the DSRD strategy reduces drying time, shrinkage and kiln drying degrade in comparison with a single conventional pass.

Keywords: lumber, drying, re-drying, radio-frequency, modeling

INTRODUCTION

In freshly cut softwood lumber there is always considerable variation in green moisture content (M_g) among pieces of lumber of the same charge, mainly due to the moisture differences between sapwood and heartwood. Once the lumber is in the kiln, random differences in M_g and wood properties induce individual boards of the same charge to dry at a different rates. As a result, lumber moisture content (M) after drying fluctuates within a wide range of values. In industrial drying, this problem is further aggravated by non-uniform kiln drying conditions due mainly to hardware calibration and malfunction issues. Typical sources of non-uniformity in an industrial kiln involve poor lumber package arrangement; unbalanced hot air distribution from the heaters; unbalanced fresh air distribution from the vents; incorrect air flow distribution from the kiln fans; excessive temperature drop across the load and excessive cold air leakage, among others (Esping 1982).

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M variability is a serious production problem because it produces pieces of lumber with *M* outside the minimum and maximum limits recommended for commercial proposes. Pre-sorting and re-drying strategies constitute opportunities to reduce *M* variability (Aune 2000; Avramidis 2001). Pre-sorting based on either M_g or species is a way to reduce the natural variability occurring in a kiln charge. The re-drying strategy consists in avoiding over-dry lumber by setting a final average moisture content (M_f) target higher than those normally used by industry, and then employing a subsequent re-drying pass to dry the larger amount of produced wets (Avramidis 2001).

Since the last modern development of the RFV technology (Avramidis & Zwick 1992), considerable research has been carried out in order to apply this technology to industrial drying of wood of various cross-sectional shapes and sizes (Avramidis *et al.* 1994, Avramidis & Lui 1994, Zwick 1995, Avramidis *et al.* 1996, Avramidis & Zwick 1996). More recently, the RFV technology has been proposed as a fast and efficient technology for re-drying of wets after conventional heat-and-vent drying. This method has been named "dry-sort-redry" (DSRD), and it consists of three steps:

1) Lumber is dried in a conventional kiln to an *M* target well above standard commercial levels.
2) Boards having final *M* higher than the maximum acceptable value (wets) are sorted-out from the rest to the dried charge.
3) Wets lumber is re-dried using RFV technology.

The DSRD strategy has been already modeled using stochastic simulation techniques (Elustondo *et al.* 2003, Elustondo & Avramidis 2003a-b), and simulated for different drying scenarios (Elustondo & Avramidis 2002-2003c). Currently, the DSRD is successfully implemented by a major US lumber producer, and the outcome of this study demonstrated that this strategy is an effective method to reduce drying time and increase the quality of the dried timber. This paper discusses the main advantages of the method, and it provides experimental and simulated data that support the claimed benefits.

MATERIALS AND METHODS

The DSRD strategy for drying PCH lumber (a mix of western hemlock and amabilis fir that grow, harvested and processed together) was tested at an industrial level with a major US lumber producer that operates with eight 260m^3 conventional kilns and a 75m^3-300kW RFV kiln (Figure 1). The RFV kiln is powered by two water-cooled 150 kW RF amplifiers. The heavy-duty, anti-corrosion drying chamber is designed to withstand the low pressures (30 mmHg to 60 mmHg) typically experienced during RFV drying. A cart-less material handling system allows for completely automated loading and unloading of the wood packages. Once the packages of wood have been loaded into the chamber, an aluminum electrode is lowered onto the package. A hydraulic compression system applies the equivalent of a 110,000 kg kiln weight on the load to reduce bowing, twisting and cupping. Electrode position is adjustable for different load heights and compensates for load shrinkage during drying. The Class B 50-ohm amplifiers use ceramic-metal vacuum tube tetrodes providing the energy efficient and rugged performance required for demanding industrial applications. The RF amplifier and matching network provide the shaped electrode with the optimal RF energy required to effectively deliver maximum power with uniform heating distribution. While a vacuum pump reduces the air pressure inside the chamber, the vacuum condenser cools water vapor extracted from the chamber preventing by-product steam from escaping untreated into the atmosphere. An end-point detection system automatically stops the process when the drying is complete.

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Figure 1: The 75.300 E-field RFV kiln used in this study.

For the sorting-out of wets part after the first conventional pass, the mill utilizes an automatic drop-out mechanism that uses an in-line (IL) transverse capacitance moisture meter to determine *M* at three points along the lumber length. Those that have at least one point with *M* above the accepted maximum limit are dropped-out by the action of a mechanical device, while the rest continues moving towards the planer, and thereafter, through a highly efficient production line where they are graded and sorted-out into packs containing only one of the possible grades of quality. In a secondary line, the dropped-out wets are automatically packed in non-sticker 13x23 piece bundles ready for the RFV re-drying pass. A diagram showing the main components of the DSRD strategy is shown in figure 2.

Six experimental runs for drying of 50mm by 100mm by 2.44m PCH lumber were performed in order to study the effect of the conventional pass target in lumber shrinkage, drying degrade and percentage of produced wets. The six experiments were labeled A, B, C, D1, D2 and E. Each of the A, B, C and E, runs was comprised of 390 pieces dried in two separated 13x32-piece packs at two different locations inside the conventional kiln. For experiments D1 and D2, only one 196-piece pack was dried in each run. The average dry-bulb and wet-bulb temperature were 82ºC and 65ºC, respectively, and average M_f between 16% and 29% were obtained by drying the lumber for different periods of time.

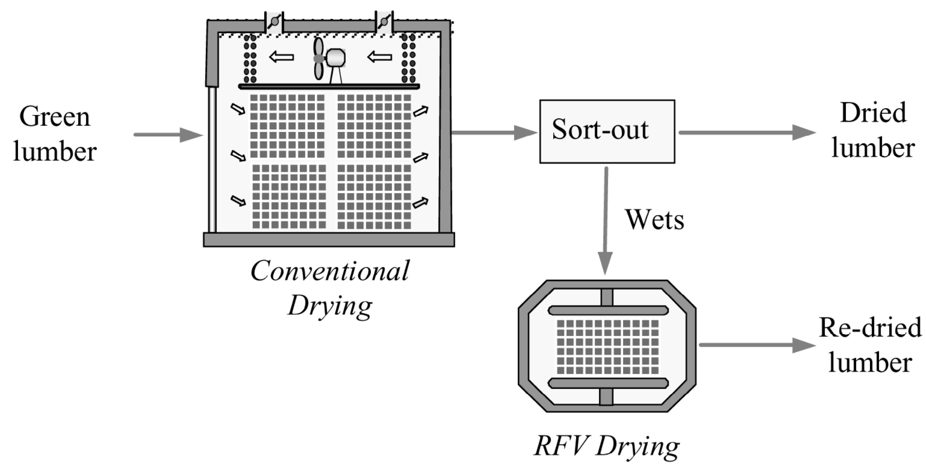

Figure 2: General diagram of the dry-sort-redry strategy.

The experimental measurements included lumber dimensions, weights, grades of quality, M_g, and M_f. Lumber thickness and width were measured with electronic calipers at three different locations along each lumber. Weights before and after each drying pass were determined with an electronic balance. M_g was calculated on the basis of the oven-dried method by cutting 25.4mm thick slices from one end of each lumber and oven-drying them during 24 hr at 103°C. M_f was measured with the mill's in-line capacitance moisture meter. The quality of the dried lumber was determined after both conventional and RFV drying passes by a professional grader, according to five different grades, namely, Premium, Stud, Utility, Economy and Dunnage (where the commercial value reduces from Premium to Dunnage).

From the numerical simulation point of view of the DSRD strategy, each piece of lumber is considered as an independent entity with particular thermo-physical properties, M_g, and local boundary conditions. Therefore, in an industrial kiln with hundreds (or thousand) of pieces dried at the same time, the relationship between initial and final *M* distributions has the characteristics of a random process. The Monte Carlo (MC) method has been applied before to predict *M* distributions in lumber drying (Kayihan 1984). The MC method produces different random results every time a new run is performed for the same conditions, thus it can not be applied for iterative fitting of experimental data. In the case of this study, a new stochastic method was developed to simulate the most probable *M* distribution as if the data were averaged for an infinite number of runs. The theoretical foundation of the method is explained in Elustondo & Avramidis (2005), and the stochastic parameters used to simulate both RFV and conventional timber drying are explained in Elustondo & Avramidis (2003-a) and (2003-b), respectively.

Additionally, the stochastic model was also adapted to predict shrinkage and degrade distributions. This requires two successive steps:

1) the stochastic model is first used to predict M_f distribution using the experimental M_g distribution as input. For this step, the stochastic parameters of the model are associated to natural variations in the lumber dry-ability;
2) the stochastic model is applied again to predict shrinkage and degrade distribution using the simulated M_f distribution using as input. For this step, the stochastic parameters of the model are associated to functions that relate shrinkage and degrade with the reduction of *M* below the fiber saturation point.

The probability of having kiln drying degrade after drying was considered only a function of *M*, thus kiln degrade distribution was generated from a straightforward transformation of the simulated M_f distribution. Shrinkage was also assumed proportional to the reduction of lumber *M* below the fiber saturation point, but due to the natural variations of wood characteristics, the shrinkage associated to one particular value of *M* was also assumed as a distribution of values within a certain range of dispersion.

The economic analysis of the DSRD strategy was based on the difference of costs and revenues between the DSRD strategy and a single conventional pass to a target of 16%. As it is shown in figure 3, benefits of DSRD are related to the dried lumber due to increased production rate; partial or total elimination of wets; reduction of the lumber planed volume and eduction of drying degrade. Costs of the DSRD strategy are originated in the operation of the RFV kiln and additional handling of the material and are associated to labor-maintenance-energy required for the RFV kiln; labor required to sort-out wet lumber and additional labor in the conventional pass due to the increased production rate.

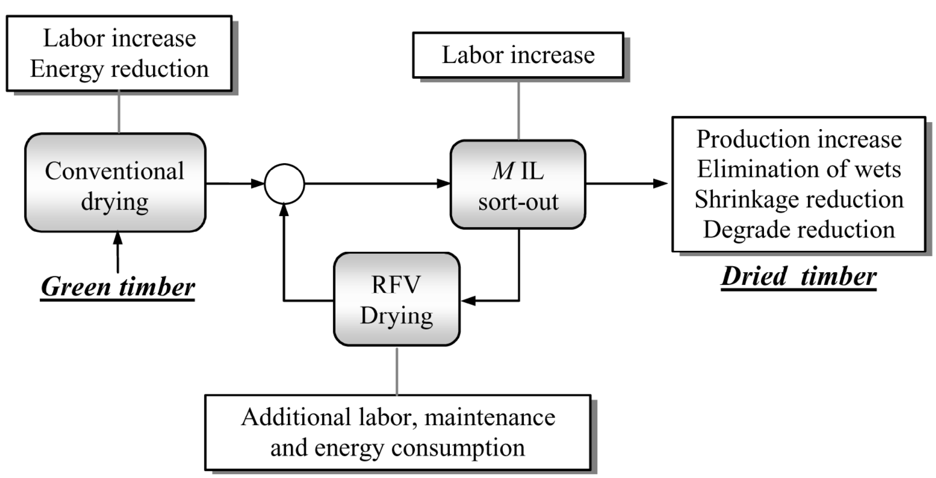

Figure 3: Components of the dry-sort-redry economic analysis.

There might also be a small reduction of energy consumption in the conventional pass (since the efficiency of the conventional kiln may increase when using higher targets), but this contribution is difficult to evaluate and it has been neglected. Maintenance costs and energy efficiency of the RFV kiln were provided by the manufacturer, and labor cost was calculated by assuming that the workers can be reassigned to different activities inside the mill so only the net number of hours spent on each drying stage is considered as a component of the total cost. For the case of this particular study, there is not labor increase in the *M* sort-out stage after the application of DSRD strategy, and this is because the production line operates continuously for 22 hours every day independently of the volume of sorted lumber.

RESULTS AND DISCUSSION

Table 1 lists the number of pieces measured on each conventional drying run, as well as the experimental drying time, average final M and its standard deviation, percentage of wets, kiln drying degrade, and shrinkage (where average shrinkage corresponds to only dried lumber after sorting-out the wets). The stochastic model was calibrated using the M_g distributions obtained by the oven-dry (OD) method and the final M distribution measured with the IL capacitance meter. Experimental data showed that there are discrepancies between the IL meter and OD method, thus an empirical OD vs. IL relationship was implemented in the stochastic model to simulate the "distortion" introduced by the measurement method. Simulations were performed with the six-test average M_g and model parameters, and the comparisons between the simulated and experimental average M and percentage of wets are shown in figures 4 and 5.

Table 1: Experimental average results after the first conventional pass.

First drying pass	A	B	C	D1	D2	E
Pieces (#)	378	392	393	196	196	392
Drying time (hrs)	68.0	71.0	67.8	73.5	60.8	60.0
Final average M (%)	16.3	17.9	18.5	19.1	23.9	28.9
Final SD (%)	3.9	4.4	4.4	7.2	5.5	6.7
Produced wets (%)	3.7	6.4	13.9	19.9	47.3	62.6
Drying degrade (%)	10.6	6.9	4.6	9.7	0.5	1.8
Width shrinkage (%)	2.3	2.3	2.2	1.7	2.1	0.7
Thickness shrinkage (%)	1.9	2.0	1.9	1.6	1.2	0.8

Relationships to predict shrinkage and kiln degrade as function of M were developed on the basis of the experimental data and calibrated inside the stochastic model by fitting experimental shrinkage distribution and probability of kiln drying degrade. Shrinkage is known to increase with the reduction of M below the fiber saturation point (M_{FSP}), and it was assumed that around each particular value of width (SH_W) and thickness (SH_T) shrinkage, there is normal distributed dispersion δ(SD) with SD standard deviation:

$$SH_W = 0.180\left(M_{FSP} - M\right) + \delta(0.74) \qquad M < M_{FSP} \qquad (1)$$

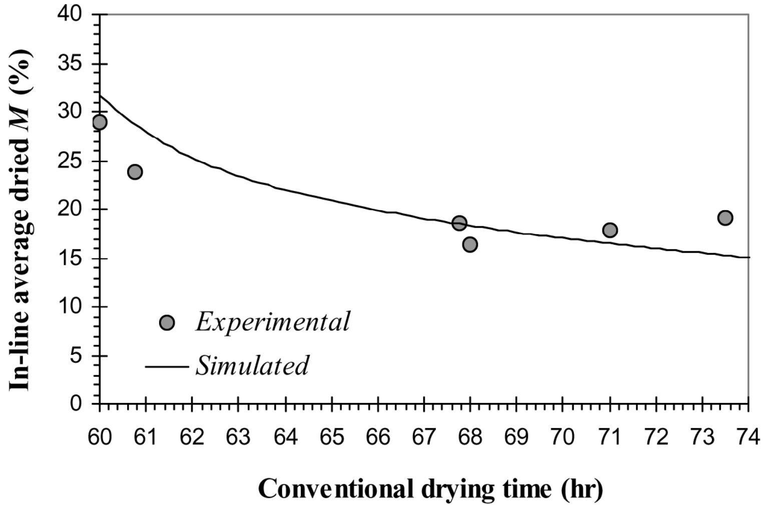

Figure 4: Simulated and experimental M as function of the conventional drying time.

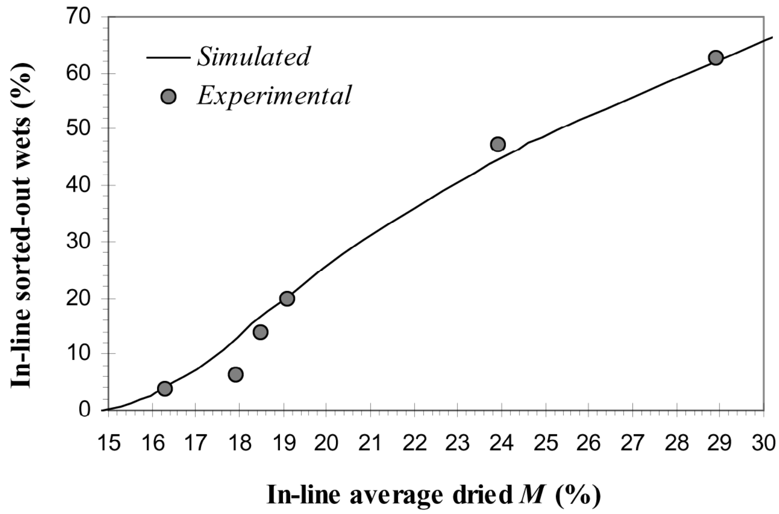

Figure 5: Simulated and experimental percentages of wets as function of the average M.

$$SH_T = 0.155\,(M_{FSP} - M) + \delta(0.68) \qquad M < M_{FSP} \qquad (2)$$

Figure 6 shows the comparison between experimental and simulated thickness shrinkage after the first conventional pass (corresponding to dried pieces after sorting-out the wets). Target of the RFV re-drying pass was always set to *M*=16%, thus, width and thickness shrinkage after the RFV re-drying pass was approximately independent of the conventional pass target. For the RFV re-drying pass, the six-test average width and thickness shrinkage were 2.3% and 1.9%, respectively. Wood losses due to shrinkage were estimated on the basis of transversal area reduction. The average lumber area reduction (ΔA) with respect to the green area was calculated with equation 3, where SH_W and SH_T correspond to the maximum between the conventional and the RFV passes.

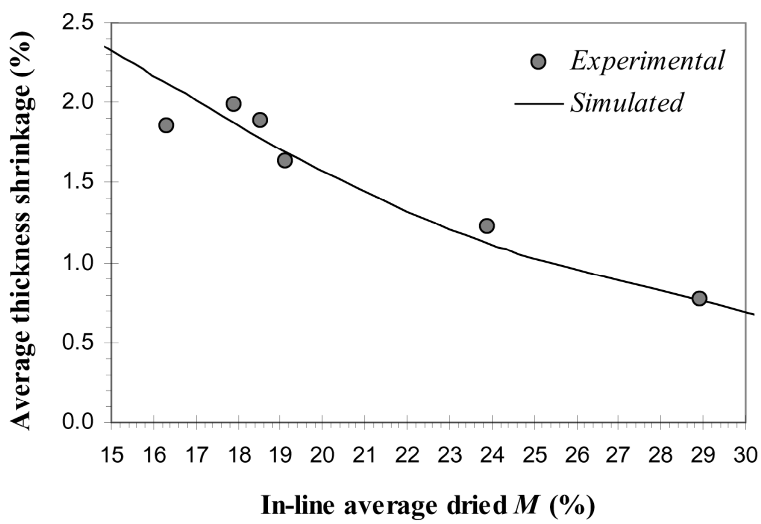

Figure 6: Simulated and experimental thickness shrinkage as function of the average *M*.

$$\Delta A = SH_W + SH_T - \frac{SH_W \cdot SH_T}{100} \qquad (3)$$

According to the experimental data, the probability to have kiln drying degrade (*KD*) increases proportionally to the reduction of*M* below a critical value of *M*=13% (equation 4). This relationship was implemented in the stochastic model and calibrated with experimental percentage of kiln drying degrade. The comparison between the simulated and experimental percentage of kiln drying degrade is shown in figure 7 as function of the conventional pass target.

$$KD = 30\,(13 - M) \qquad M < 13\% \qquad (4)$$

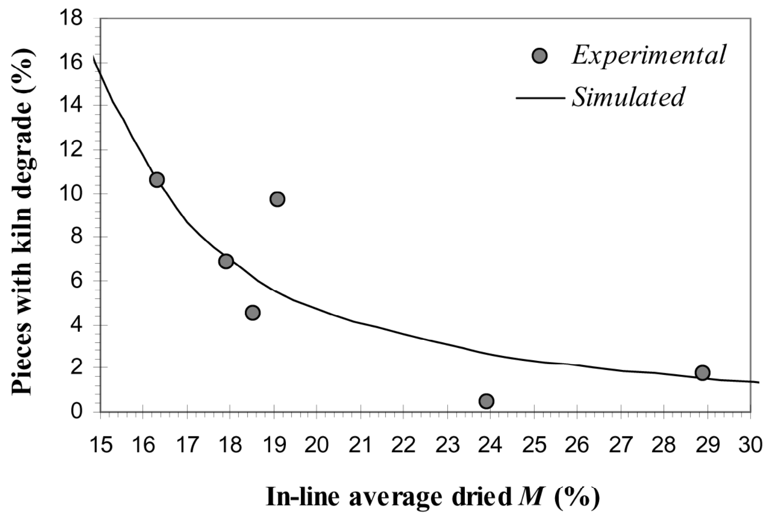

Figure 7: Simulated and experimental kiln degrade as function of the average *M*.

In order to determine the price of the lumber after the DSRD strategy, dried lumber was divided into three independent sub-groups:

1) Dried lumber with kiln drying degrade.
2) Dried lumber without kiln drying degrade.
3) Wets re-dried in RFV kiln.

Lumber with and without kiln drying degrade was determined by a professional grader, while wets were sorted out by the in-line *M* meter. Figure 8 shows the contribution of the different grades of quality to the average commercial price of the three sub-groups of dried lumber.

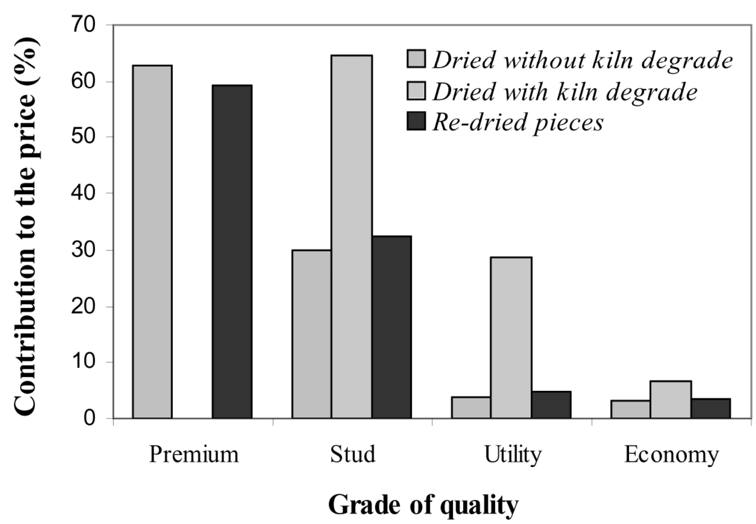

Figure 8: Grade comparison between the three independent timber sub-groups.

Dunnage grade was not included because its contribution is too small to be distinguished in the graph.

As it can be observed, the quality of lumber without kiln degrade is similar to the quality of re-dried lumber. Between these two groups, re-dried pieces have only 3.5% less contribution of premiums, and 2.4% and 0.9% more contribution of stud and utility. Alternatively, pieces with kiln drying degrade are characterized by not having any premium grade. In pieces with kiln drying degrade, all premiums were degraded into stud and utility. The average commercial prices of each of the lumber sub-groups, as well as wet lumber, are shown in table 2. As it can be observed, the price of re-dried lumber and lumber with kiln drying degrade is respectively US$2/m^3 and US$40/m^3 lower that the price of pieces without kiln drying degrade.

Table 2: Average lumber price corresponding to different timber sub-groups.

Average lumber price (US$/m^3)	
Dried without drying degrade	157
RFV re-dried	155
Dried with drying degrade	117
Sold as "wets"	112

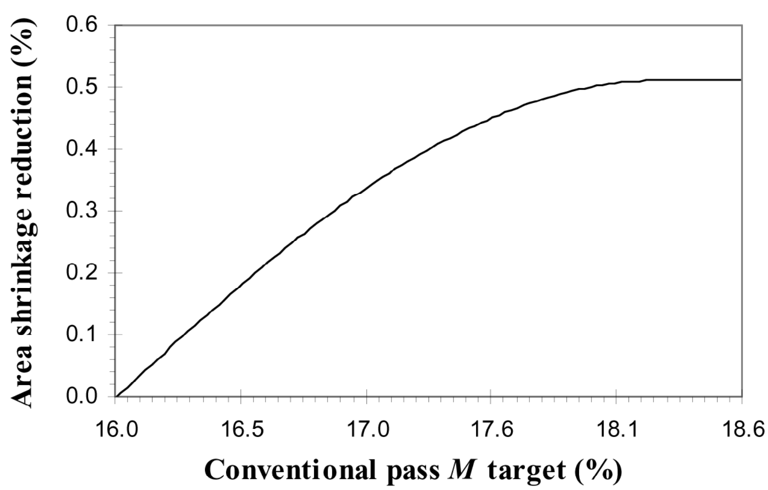

Figure 9: Reduction in area shrinkage with respect to the green timber.

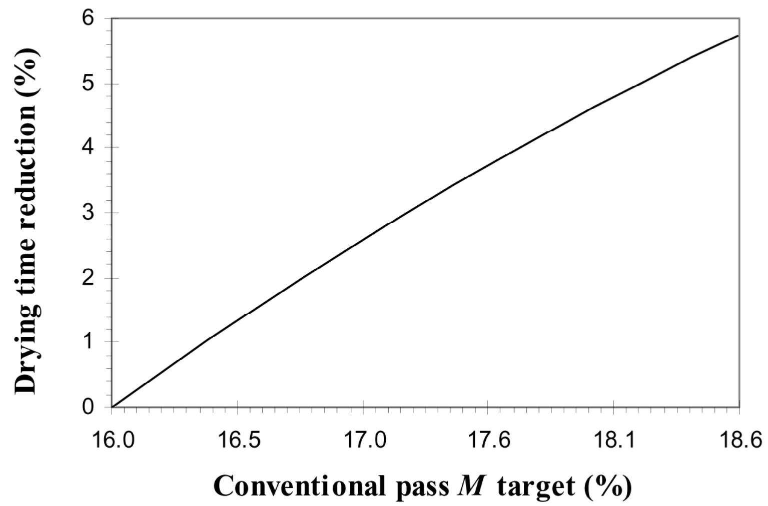

Figure 10: Reduction in drying time with respect to the base case.

The increase in revenues after the implementation of the DSRD strategy is consequence of a reduction in lumber shrinkage, a reduction in drying time, and an increase of the quality of the dried lumber. Figures 9, 10 and 11 show the results of the simulations for shrinkage reduction, drying time reduction and lumber value increase. Figure 9 shows that area shrinkage reduces with the increase of the conventional pass target, but only until a value of approximately M=18%.

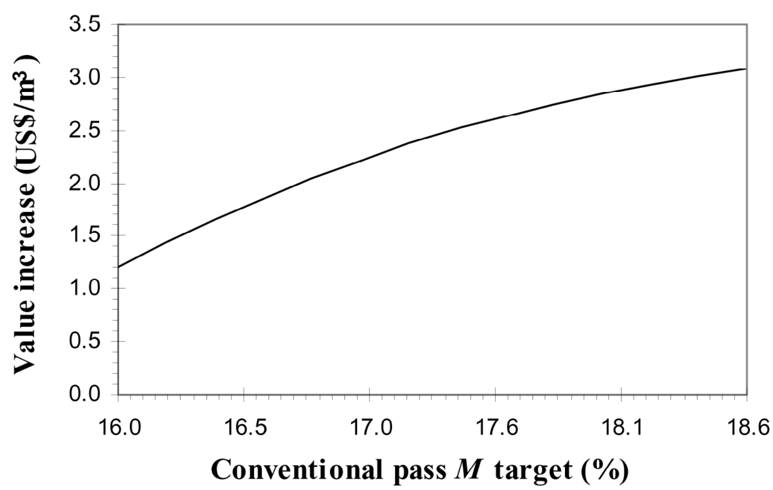

Figure 11: Increase in timber value with respect of the base case.

Beyond this value, shrinkage of the conventional pass is smaller than shrinkage of the RFV pass, so final lumber dimensions are determined by the re-drying pass. Figures 10 and 11 show that drying time reduces and lumber value increases with the increase of the conventional pass target. As it can be observed, the commercial price of the dried lumber after the application of the DSRD strategy increases even for an *M* target of 16%, and this is due to the recovery of wets that already existed before the application of the DSRD strategy.

Some of the values concerning the re-drying costs are shown in table 3. The 75m^3 RFV kiln requires 1 hour to be loaded and unloaded, and approximately 4 hours are required to transport the lumber to the RFV kiln and return it to the storage place. Labor cost is assumed at US$24/hr, and maintenance was estimated US$27,000/year by the manufacturer. Energy costs depend on electricity, approximately US$0.05/kWh. The energy consumption in the RFV kiln is 1.68 kWh/kg of total energy per kilogram of evaporated water, which includes the energy consumed for water evaporation, the kiln energy losses, and the energy consumed by the vacuum and cooling pump systems. The capital cost for the 75m^3 RFV kiln is approximately US$2.86M and is comprised of the RFV kiln purchase, site preparation, kiln foundation, mechanical and electrical service, and implementation of the automatic drop-out system. For the first conventional pass, the labor increase due to the higher production rate was determined by assuming 5 hours of labor to load and unload each conventional kiln.

Table 3: RFV re-drying labor and costs.

RFV re-drying costs	75m^3 kiln
Kiln installation	US$2,860,000
Load and unload	1 hrs/run
Timber movement	4 hrs/run
Labor cost	US$24/hr
Maintenance	US$27,000/year
Energy consumption	1.68 kW-h/kg
Energy cost	US$0.05/kW-hr

The result of the economic analysis showed that the viability of the DSRD strongly depends on the relation between the re-dried volume and RFV kiln capacity. If the volume of wets exceeds the capacity of the RFV kiln, then a further increase in the conventional pass target generates wets that exceeds the DSRD process, and if the volume of wets is lower than the RFV kiln capacity, then unnecessary costs are incurred that may make the strategy unviable. In the case of this study, the optimum target for the first conventional pass was 18.59% target, and it resulted in a payback time of 13.9 months.

CONCLUSIONS

The results of the industrial-scale evaluation showed that the SDRD strategy reduces drying time, increases lumber grade of quality, and reduces the planed lumber area. At a conventional pass target of 18% (that is approximately the target used by the company immediately after the installation of the RFV kiln), drying time reduction was 4.6%, lumber price increase was US\$2.8/m^3, and area shrinkage reduction was 0.51% with respect to the single conventional pass to a target of 16%. The increase in the average commercial price of the produced lumber is mainly product of the recovery of the wets, and a recovery of approximately 4.7% of lumber that showed kiln drying degrade before the application of the DSRD strategy. Lumber shrinkage after the first conventional pass always reduces with the increase of the moisture content target, but since the target of the RFV re-drying pass is always 16%, shrinkage reduction of the overall DSRD strategy showed a maximum of 0.51% of the green area.

The economic analysis demonstrated that in order to obtain an optimum payback time, the capacity of the RFV kiln must be similar to the volume of re-dried wets. In the case of this study, an optimum moisture content target of 18.6% for the 75m^3 RFV kiln produces payback time of approximately 13.9 months.

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