

# Equilibrium moisture content during storage, manufacturing, and shipping of Bolivian wood products

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## Abstract

After lumber is kiln-dried it is important to keep its moisture content (MC) as close as possible to its target value during all stages of production to assure final product quality. Knowledge of climate conditions at all stages of the manufacturing process is essential to provide a good control of lumber MC. This study is the first step to provide Bolivian companies and institutions with information, currently not available, about the potential for moisture change during postdrying activities. The potential for MC gain/loss during processing and shipping was evaluated by monitoring temperature and relative humidity during lumber storage, manufacturing, and containerized transport. These values were then used to estimate the equilibrium moisture content (EMC). Readings were taken between August 2005 and March 2006 in three Bolivian manufacturing plants, located in regions representative of the different climate conditions in the country. Measurements were also taken in three containerized ocean shipments of wood products to the United States. Results show maximum/minimum differences throughout the months of the study of 3.8, 6.4, and 7.6 percent EMC for Cochabamba, Santa Cruz, and La Paz, respectively. Average differences between storage and plant conditions ranged from 0 to 3.5 percent EMC in the plants where measurements were taken and were strongly influenced by the type of construction used. Average EMC values inside cargo containers reached 3 to 4 percent above the lumber MC for the routes investigated; packaging methods were found to influence conditions inside unit loads. The differences in EMC of the materials can lead to moisture-related problems during the manufacturing process and service.

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Many quality problems with solid wood products are caused by changes in moisture content (MC) of wood. MC changes lead to dimensional changes and can also cause problems in gluing, machining, finishing, and even biological attack. Dimensional changes are particularly detrimental in products assembled from numerous pieces since shrinking causes splits in panels, end checks, cracks in the finishing coats, and open joints (Eckelman 1998).

Even small changes in MC can cause quality problems, especially in assembled products (entry doors, cabinet doors, furniture, and frames) and solid flooring. As an example, for dense North American hardwoods, such as red or white oak, a 2 percent difference in MC can lead to significant splits and cracks in the end-grain (Wengert 1988).

Once lumber is dried to its target MC, it undergoes several conversion stages before reaching the final customer, and very often each of these steps takes place in environments with different climate conditions. The time wood spends in each step varies with product, production scheduling, demand conditions, and distance to the final market. It is common to

attribute moisture-related problems to poor drying, but in order to address these problems it is essential to know where the problems occur.

In Bolivia, kiln-dried lumber is usually stored in open sheds, without environment control. During the rainy season, December to March, lumber acquisition becomes very problematic, and companies usually stock large quantities to assure production continuity. Outdoor EMC during these months can be as high as 16 percent in the eastern region and then decrease to 11 percent during the dry season. In the west-

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ern side of the country, EMCs as low as 5 percent may exist during winter months (National Service of Meteorology and Hydrology of Bolivia 2006). Heated storage is not practiced, and lumber is commonly placed in open sheds, where it may be exposed to high winds and rain. Manufacturing activities are usually carried out in poorly controlled environments, usually open sheds without humidification or good air-circulation systems. Export of Bolivian wood products is usually done in containers, where temperature and relative humidity conditions can reach extreme values or change rapidly. However, it was observed during visits to Bolivian companies that most kiln operators and managers do not take prevailing climate into consideration when making decisions about target MC, dry-lumber storage, or packaging of final products (Espinoza 2006).

The objective of this study was to evaluate the potential MC change during lumber storage, manufacturing, and shipping of Bolivian wood products by collecting environmental data during various steps of the manufacturing process. This information can be used by the industry to identify potential causes of moisture-related problems, determine target MC, and design of packaging, storage, and manufacturing facilities.

### Methodology

To evaluate the MC change during postdrying stages, relative humidity and temperature were measured and recorded in manufacturing plants at different locations in Bolivia and in containerized shipments of Bolivian wood products to the United States. Temperature and relative humidity were continuously measured and recorded using Nomad® dataloggers. The sensors used had accuracy values of  $\pm 1.27$  °F (at 70 °F) for temperature and of  $\pm 5$  percent (41 to 122 °F) for relative humidity (OMEGA Engineering 2005). These data were then used to estimate the equilibrium MC (EMC), which is the MC wood attains when it reaches equilibrium with the surrounding air (Siau 1995). EMC can be estimated by means of the following equation (Forest Prod.Lab. 1999):

$$EMC = \frac{1,800}{W} \left[ \frac{Kh}{1 - Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2} \right]$$

where:

$$W = 330 + 0.452 T + 0.00415 T^2 \quad [1]$$

$$K = 0.791 + 0.000463 T - 0.000000844 T^2$$

$$K_1 = 6.34 + 0.000775 T - 0.0000935 T^2$$

$$K_2 = 1.09 + 0.0284 T - 0.0000904 T^2$$

where  $h$  is relative humidity in percent,  $T$  is temperature in °F, and  $K$ ,  $K_1$ , and  $K_2$  are diffusion coefficients developed by Hailwood and Horrobin (1946). Since the studies implied thousands of readings of temperature and relative humidity,

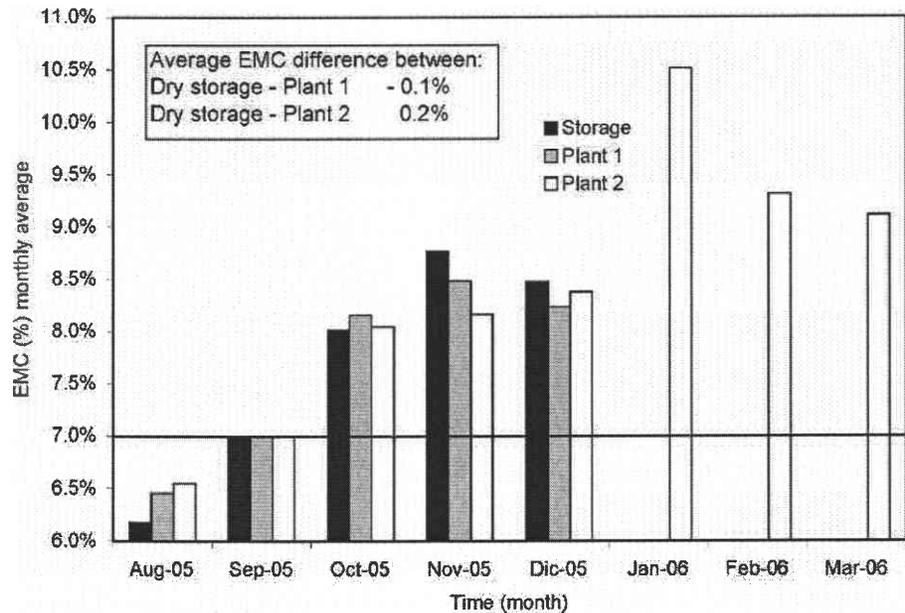


Figure 1. — Monthly average EMC values for plant in Cochabamba-Bolivia. August 2005 to March 2006. Horizontal line represents lumber MC after drying.

Equation [1] was programmed as a custom function in an Excel® spreadsheet.

*MC gain during storage and manufacturing* — The potential for MC change during processing and storage was investigated by monitoring temperature and relative humidity in three facilities located in the three main cities of Bolivia (Santa Cruz, Cochabamba and La Paz), which represent the different climate conditions that can be found in the country.

Three sensors were installed at each company, one in the dry lumber storage area and two inside the manufacturing plant, to identify differences between storage and manufacturing areas. Readings were taken during 5 months in Santa Cruz and La Paz (November 2005 to March 2006), and 8 months in Cochabamba (August 2005 to March 2006). Twenty measurements of temperature and relative humidity were made each day.

Results obtained apply only to the plants where the measurements were taken; thus, in order to provide the industry with a general reference, historical weather data from the National Service of Meteorology and Hydrology of Bolivia were used in combination with Equation [1] to generate an EMC table for the 12 months of the year and 11 Bolivian cities. Results are shown in Table 1. These values are required to control moisture change during dry-lumber storage.

*MC gain during shipping*. — The potential MC change during ocean shipping was studied by installing data loggers inside three cargo containers with Bolivian wood products sent to the United States. The first and third shipment consisted of solid-wood exterior doors from Cochabamba to Miami, Florida; and the second was of solid-wood furniture parts and flooring from La Paz to Norfolk, Virginia. Two sensors were installed in each shipment, inside and outside the packages, to investigate if packaging methods had an influence on climate conditions inside the unit loads. The frequency of measurements was 48 readings per day. Packaging materials and methods were similar in all three cases: The product bundle was wrapped in stretch-plastic, then covered with corrugated

cardboard and lastly, tied together with plastic or metal straps. The packages in the first shipment, however, did not have the top and bottom wrapped with plastic.

## Results and discussion

### Storage and manufacturing

*Storage and plant study in Cochabamba.* — Monthly averages of EMC values for manufacturing and storage areas for the plant in Cochabamba are shown in **Figure 1**. The chart also shows average differences between plant and storage. Conditions in the three locations are, from a practical standpoint, equivalent (average differences of only  $-0.1$  and  $0.2$  percent EMC for the two plant locations). This is not surprising considering that both dry-lumber storage and processing areas have a three-walled open-shade configuration in this company and the EMC profile follows that of the outside environment. It is also evident in **Figure 1** that EMC increases steadily with time during the first 6 months of the study and starts to decline from February (approximately 4.0 percent EMC increase from August to January).

This company manufactures solid wood doors and millwork and dries its lumber to 7 percent MC. Thus, during the months of the study, there is a potential gain on the order of 1.0 to 3.5 percent MC, represented by a difference between the initial MC of lumber (shown in the graph as a horizontal line) and the average EMC. The exact amount and distribution of the MC will depend mainly on time spent in storage and manufacturing, species, thickness, stacking method and MC distribution after drying.

*Storage and plant study in La Paz.* — Temperature and relative humidity were measured from November 2005 to March 2006 in a plant that manufactures flooring and furniture parts located in La Paz. Monthly averages of equilibrium MC were calculated from these readings and are shown in **Figure 2**. The embedded table shows a summary of the differences between the storage area and the two plant locations.

A marked difference between the storage and the manufacturing area is evident in **Figure 2**, with average differences between storage and processing plant of about 3.5 percent EMC. The construction types used can explain this difference. Dry-lumber storage in this company consists of a covered shed opened at its four sides, whereas the manufacturing area is a closed shed heated during winter months (heating was not working when the measurements were taken). An increase in

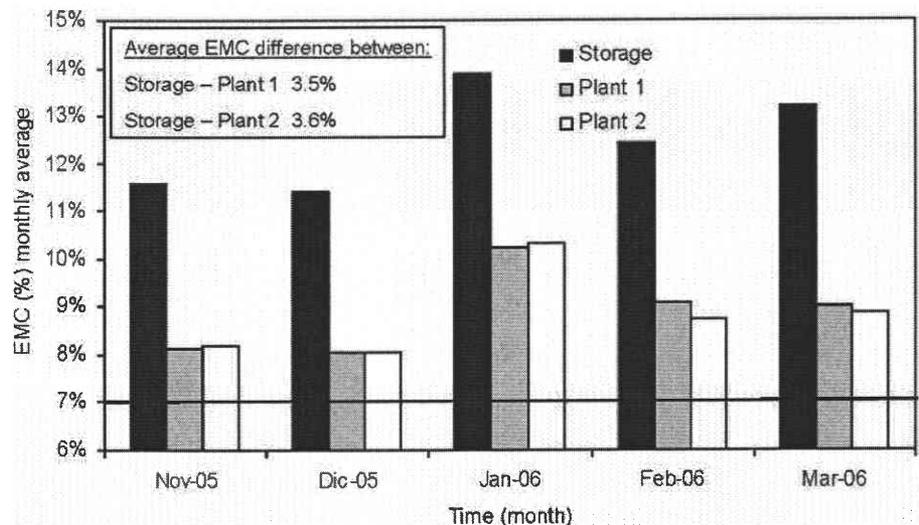


Figure 2. — Monthly average EMC values for plant in La Paz-Bolivia. November 2005 to March 2006. Horizontal line represents lumber MC after drying.

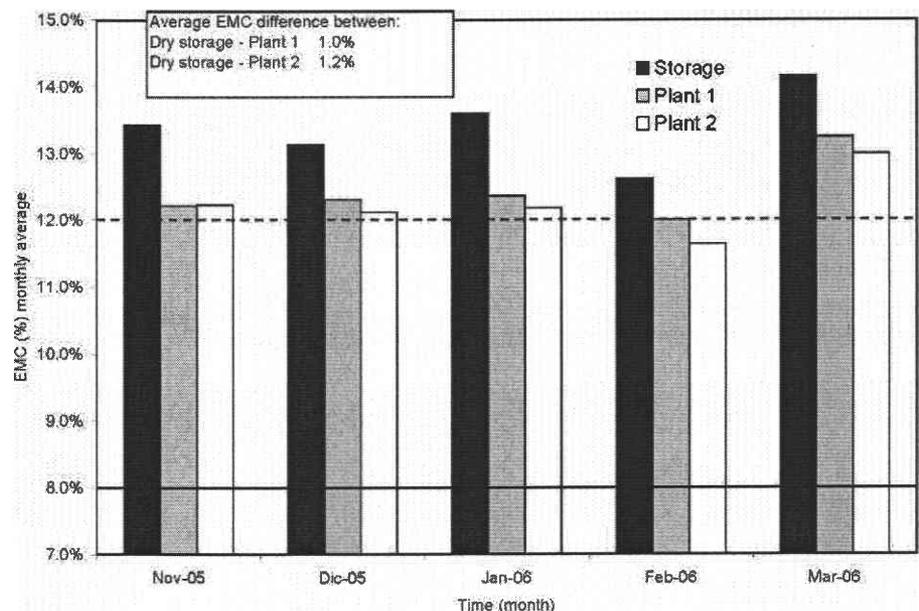


Figure 3. — Monthly average EMC values for plant in Santa Cruz-Bolivia. November 2005 to March 2006. Continuous and dashed horizontal lines represent respectively, lumber MC after drying for millwork (8%) and garden furniture (12%).

EMC is also apparent during the months of the study. This company dries lumber for furniture parts to 7 percent MC, as observed during visits to its facilities. Thus, lumber is exposed to a difference between its MC and an eventual EMC of about 4.5 percent (December) to 7 percent (January) in storage and from 1 to 3 percent for the same months inside the manufacturing plant. Furniture parts are usually of relatively small thicknesses, which increases the risk of dimensional changes and gluing problems.

*Storage and plant study in Santa Cruz.* — Temperature and relative humidity were measured from November 2005 to March 2006 in a millwork and garden furniture manufacturing plant in Santa Cruz. Monthly averages of the calculated EMC are shown in **Figure 3**. The table shows a summary of the differences between the storage and the two plant locations.

The average difference between storage and the two plant locations for this company was of approximately 1 percent EMC. Both storage and manufacturing areas use a three-walled shed configuration, but because of the presence of machinery and personnel, temperature is slightly higher (1.5 °F higher in average, according to the results of the study) inside the plant, which can explain the lower EMC. There is a sharp increase in EMC in March because of high rain precipitation

during this month (110.6 mm in February compared to 226.5 mm in March, according to the National Service of Meteorology and Hydrology of Bolivia 2006).

This company dries lumber to 8 percent and 10 percent MC for millwork and garden furniture, respectively. Therefore, during the months of the study, there was a difference between EMC and the lumber's initial MC (represented in Figure 3 as a horizontal line) of approximately 3 percent to 6 percent.

Thus, a moisture uptake could be expected in the lumber during the time of the study.

Table 1. — EMC in 11 Bolivian cities, calculated based on monthly averages data from the Bolivian National Service of Meteorology and Hydrology (SENAMHI).

City	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	-----(%)------											
Cobija	14.7	17.3	16.1	15.6	15.1	13.9	12.3	10.8	11.2	14.1	15.7	16.7
Guayaramerin	15.4	16.7	15.8	15.1	14.8	13.1	11.6	10.4	11.2	12.6	14.7	16.1
Trinidad	13.8	14.4	13.9	13.2	14.2	13.7	11.7	10.5	10.0	12.9	14.2	15.4
Tarija	11.0	12.5	12.2	12.5	9.5	9.7	9.9	8.9	8.9	9.1	10.4	11.7
La Paz	12.2	13.9	10.1	9.6	10.6	6.9	8.2	6.1	9.8	7.2	7.7	9.1
El Alto	13.0	14.0	11.3	10.9	7.0	6.6	7.0	6.3	8.9	10.5	10.3	10.7
Oruro	10.5	10.7	9.1	9.1	7.1	7.3	6.8	6.6	8.4	8.0	8.3	8.5
Potosi	13.0	16.1	11.8	11.3	8.2	7.8	7.6	7.6	8.5	9.2	10.5	12.3
Santa Cruz	12.4	12.2	12.4	13.3	15.1	16.0	10.4	10.2	9.6	12.7	13.4	14.2
Cochabamba	10.7	12.3	9.1	9.5	8.7	8.8	9.2	8.4	9.3	10.0	10.1	10.8
Sucre	12.6	15.0	12.4	12.8	8.4	8.2	9.6	8.6	11.4	13.1	11.9	12.4

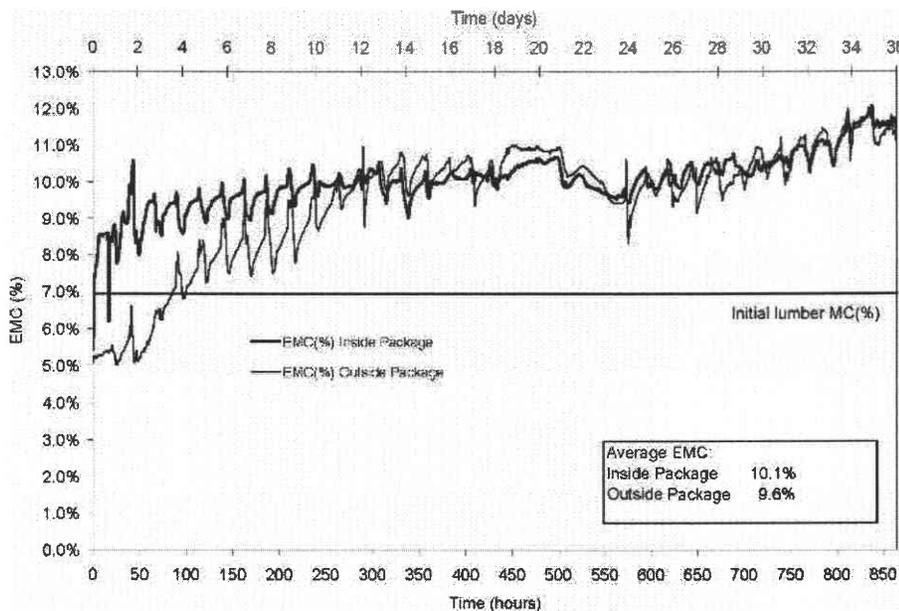


Figure 4. — Hourly EMC values during first shipment of wood products from Cochabamba to Miami, Florida. The horizontal line represents lumber MC after drying.

### Shipping studies

*Shipping from Cochabamba to Miami, Florida.* — Two sensors were installed in a shipment of solid wood doors from Cochabamba to Miami, Florida. The species used for the products was Mara Macho (*Cedrelinga catenaeformis*). The shipment was containerized and transported by truck to Arica port in Chile on July 31, 2005 and arrived at Miami on September 5, 2005. The frequency of relative humidity and temperature measurements was 48 per day. The maximum, minimum and average values for temperature, relative humidity, and calculated equilibrium MC are shown in Table 2.

The maximum temperatures occurred when the vessel was passing the equator. The lowest ones occurred when the truck passed the frontier between Bolivia and Chile, located in the Andean mountains at more than 15,300 feet above sea level, where freezing temperatures are common. The resulting equilibrium MC for the entire trip is plotted in Figure 4. Until the 12th day, there was a marked difference between EMC conditions inside and outside the packages. From that point, conditions level out (a maximum difference of 5.1 percent EMC in the 43rd hour; and from the 12th day the difference becomes lower than 1.0 percent EMC). This initial difference can be explained by the effect of the packaging materials used, especially the stretch-plastic wrap,

Table 2. — Conditions inside shipping containers of wood products from Bolivia to U.S.

Origin and destination	Temperature						Relative humidity						EMC					
	Inside package			Outside package			Inside Package			Outside package			Inside package			Outside package		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
	----- (°F) ----- (% ) -----																	
Cochabamba to Miami	43.9	97.0	72.5	33.3	97.8	72.7	25.8	73.6	55.6	23.4	67.8	52.3	5.4	14.0	10.1	5.0	12.4	9.6
Cochabamba to Miami	64.9	81.5	76.1	47.5	84.4	75.4	45.2	66.4	60.7	46.7	46.7	64.2	8.5	12.1	11.0	8.7	13.1	11.7
La Paz to Norfolk, VA	47.5	80.8	71.4	--	--	--	45.3	67.7	59.9	--	--	--	8.6	12.3	10.9	--	--	--

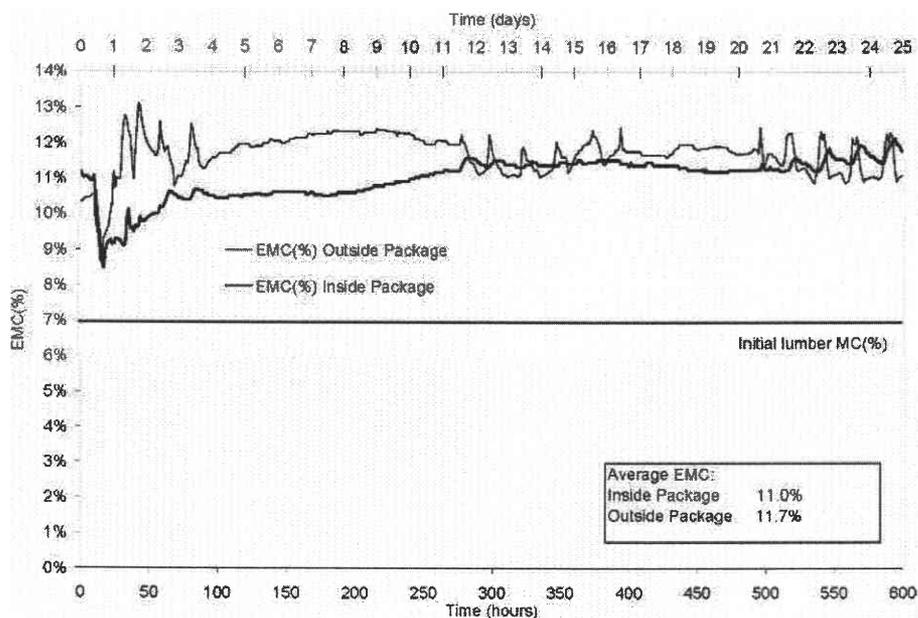


Figure 5. — Hourly EMC values during second shipment of wood products from Cochabamba to Miami, Florida. The horizontal line represents lumber MC after drying.

which provides a barrier against ambient moisture for some time, after which moisture inside the packs equalizes with the container environment. Another probable reason is the residual surface moisture in wood products.

Variations in EMC during the same day are less marked inside the package, with the curve showing less sharp changes. Apparently, the packaging materials provide a “shield” effect against extremes of temperature and humidity that can also help to avoid condensation (Knobout 1972).

If wood is shipped with initial MC of 7 percent (represented in Figure 4 as a horizontal line), it will be exposed to a high EMC for a relatively long period of time—a mean of about 10 percent, increasing to 12 percent when the shipment approaches its destination. These values, according to research (Forest Products Laboratories Division 1952, USDA Forest Service 1978, Zhang 2005) can lead to significant moisture gains in wood products, especially in pieces located in the exterior faces of the packages.

*Second shipment from Cochabamba to Miami, Florida.* — A second shipment of doors and mouldings from Cochabamba to Miami was monitored during January–February of 2006. Table 2 shows the main statistics for temperature, relative humidity, and EMC. Figure 5 shows the plotted EMC and the average values inside (11.0%) and outside (11.7%) the packages.

Average values for EMC were higher than those of the previous shipment, probably due to the more humid season. Initial conditions during the first shipment, that took place during dry season (July–August) were as low as 5 percent EMC (Fig. 4), compared with those in Figure 5, where initial EMC values were higher than 9 percent.

Overall, conditions outside and inside the packages changed less than in the first shipping study; a probable reason for this is that in this shipment the package was placed farther from the container walls and that the products in this shipment were completely wrapped with stretch-plastic, including the

top and bottom, which may have contributed to a smoother EMC curve. As in the first shipping study, conditions inside and outside the packs start to even out after the 12th day.

*Shipping study from La Paz to Norfolk, Virginia.* — This shipment consisted of furniture parts and panels. Departure from Arica was on December eighth, and the container arrived in Norfolk, Virginia on January third, after notice it was forwarded to Michigan (ground shipping). The packaging materials used in this case were similar to those in the previous studies. Although two data loggers were installed, the sensor outside the packages stopped working before departure owing to damage during loading. Thus, only readings from inside the packs were taken. Table 2 lists the main statistics for temperature, relative humidity, and calculated EMC. Figure 6

shows the curve with EMC values. The container arrived in Norfolk, Virginia, on the 28th day.

Changes in EMC were more gradual, as in the second study. Again, this is because the packages were wrapped in stretch-plastic, which attenuates sharp drops and peaks of temperature and relative humidity.

The exporting company dries lumber to 7 percent MC; thus the average EMC during shipping was 3.9 percent above initial MC and almost 5 percent above initial MC during days 18 through 28, with the potential moisture gain.

#### EMC during production stages

The data recorded in the study can be used to estimate how EMC may change during the stages of production and the potential MC change in wood. Figure 7 shows a hypothetical situation, using the data from the study, with different EMC conditions during various stages of production for the company in La Paz. For simplicity, all steps were assumed to take place in consecutive months starting with kiln-drying in December, and only average EMC is taken into account.

In the example, the company dries its lumber to 7 percent MC and then stores it in an open shed, where, in January, the average EMC is 13.9 percent. Next, lumber is processed in the manufacturing plant, where climate conditions during February result in an average of 9.1 percent EMC. Once products are ready, they are prepared and shipped in a container to Norfolk, Virginia. The container takes about a month to reach its destination port; the average is 10.9 percent EMC. An intermediate storage in the brokers’ warehouse is not considered in the example, but assuming the product reaches the final client directly, it will be exposed to indoor conditions of about 6 to 8 percent EMC for most of the United States (Forest Prod. Lab. 1973).

These changes in EMC can lead to changes in MC in lumber or wood products, which in turn may cause dimensional changes. Assembled products, like doors and furniture can experience open joints, cracked panels, gluing and finishing

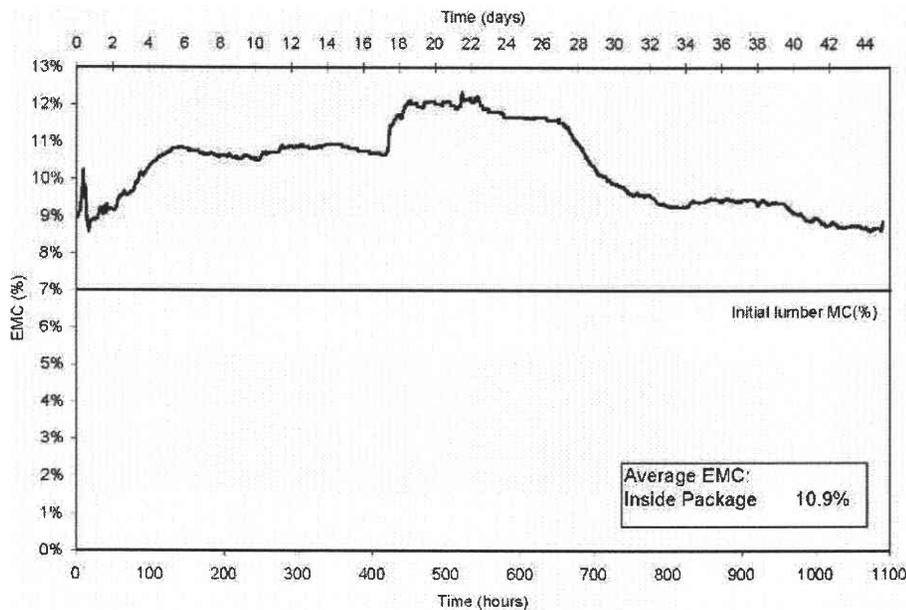


Figure 6. — Hourly EMC values during shipment of wood products from La Paz to Norfolk, Virginia. The horizontal line represents lumber MC after drying.

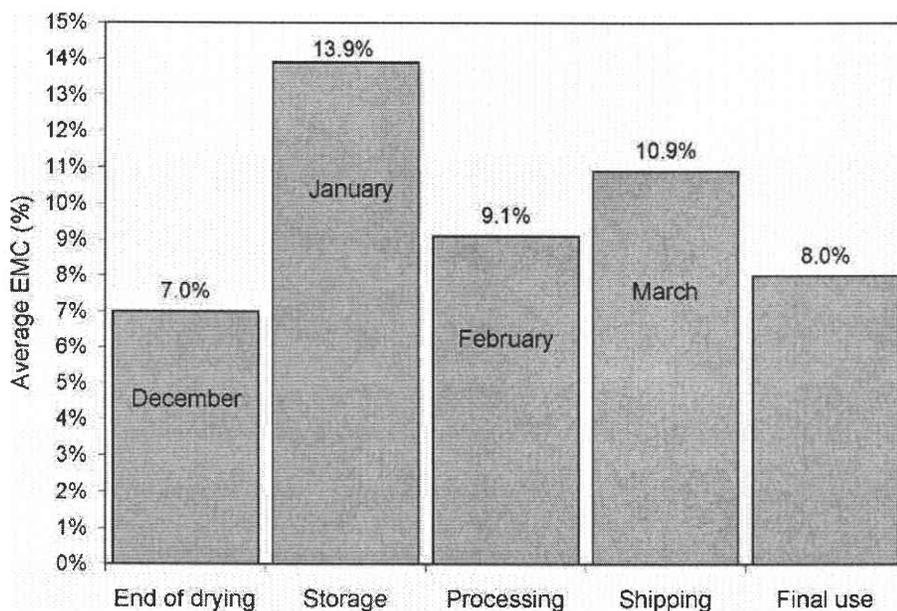


Figure 7. — Example of EMC through production stages for company in La Paz. Values represent average EMC conditions.

problems and warp (Eckelman 1998). In products like furniture parts and flooring, these MC changes can lead to problems like cup and gaps during flooring installation, or gluing and finishing problems when assembling parts into final products at destination. Decorative panels, balustrades and mantels, which usually have carved and turned surfaces, can develop checks due to shrinking and swelling. Other products that are usually dried to relatively high MC or not dried at all, like decking, posts and construction lumber may check and warp.

### Summary

Temperature and relative humidity were recorded during several months in three Bolivian wood manufacturing plants

and in three containerized ocean shipments of wood products to United States. Readings were used to estimate the EMC values.

Results of the studies showed that significant differences exist between EMC conditions in storage, manufacturing, and shipping of wood products in the companies where measurements were taken, and suggest a potential MC change in lumber and end products.

Results from storage and plant studies showed important differences between EMC and lumber MC during postdrying stages. Depending on the geographical region and month of the study, difference between lumber MC and monthly average EMC were found to be from -1 to 7 percent, with the biggest differences found in La Paz and Santa Cruz. Difference between storage and processing EMC for individual plants ranged from no difference to more than 3.6 percent, depending mainly on facilities design and region.

Results from storage and plant studies suggest the need to have a better control of dry-lumber storage and manufacturing facilities. If heating is not feasible, storage areas should at least be changed to a closed-shed facility with a design that facilitates the interior reaching temperatures above those outside in order to reach an EMC within  $\pm 2$  percent of the MC of the lumber.

Regarding shipping studies, differences between lumber MC and average EMC during ocean-transport ranged from 3 to 4 percent. The packaging of products had an influence in moderating sharp changes of temperature and relative humidity inside the container, thereby reducing the risk of condensation. However, packaging materials did not

prevent the interior of the unit loads to eventually reach the same average climate conditions as the container environment (at least after the 12th day). Better results were attained when plastic-wrap totally enclosed the bundles of products. Conditions inside the packs also depended on location in the container.

Results from the shipping studies suggest that it is a good practice to wrap wood products with stretch-wrap, as a vapor barrier, to avoid extreme conditions and condensation inside the packages. Also, whenever possible, packages should be placed away from the container walls.

In all cases, average EMC values during storage, manufacturing and shipping were different from the MC of lumber

after kiln-drying. The highest EMCs were recorded in open shed configurations and during shipping when the vessel was close to the equator.

Results of this study can be used by the Bolivian wood products industry to make more informed decisions regarding (1) design of their industrial facilities, (2) target MC of lumber, and (3) design of packaging methods and materials. Methods and recommendations presented here apply in most cases; however, differences in EMC will have different impact in other firms and locations. Companies may conduct similar studies for their particular operations, shipping routes and packaging methods.

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