ESTIMATING KILN SCHEDULES FOR TROPICAL AND TEMPERATE HARDWOODS USING SPECIFIC GRAVITY

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ABSTRACT

Dry-kiln schedules have been developed for many hardwood species, but many more, especially tropical species, do not have a recommended schedule. The study reported herein investigated the possibility of estimating kiln schedules using specific gravity (SG). Using known schedules and SG data of 268 hardwood species, a classification approach and linear regression analysis were applied and compared to establish the relationships between kiln schedule code numbers and SG. In general, schedule predictions matched reasonably well with recommended schedules, but for some species, the differences were large. The classification approach was slightly superior to regression analysis in predictive ability.

There are many tree species in the world, especially in the tropics, and the large number presents two problems in drying lumber cut from them. Some of these species have been used for timber products for many years, and dry kiln schedules for them have been recommended based on experience and/for research. However, there are many more less-utilized species for which there does not appear to be any published record of a recommended kiln schedule. Therefore, the first problem is the lack of recommended kiln schedules for many species.

The second problem stems from the sheer number of tropical species and their heterogeneous occurrence in the forest. One consequence of this is that sometimes it is not practical to dedicate and fill a dry kiln with a single species. Therefore, the second problem is the lack of a method to group species, based on similar drying characteristics, so that they can be mixed and dried in the same kiln.

The purpose of this paper is to present a solution to the first problem by providing a method for estimating kiln schedules.

BACKGROUND

RELATED RESEARCH

Studies have been conducted to relate known schedules of Southeast Asian (4,5) and African (2) species to physical properties, such as specific gravity (SG), tangential shrinkage, radial shrinkage, their ratio, and mechanical properties perpendicular to the grain. Multiple linear regressions were developed between several schedule parameters as the dependent variables, and physical properties as the independent variables. In general, good agreement was found between the recommended and estimated schedules; however, the estimated schedule for some species deviated considerably from the recommended schedule.

In a previous report (7), a method for both schedule estimation and species grouping was developed from 268 hardwood species for which both SG and a recommended schedule were known. Using least squares analysis, the initial dry-bulb temperature and initial wet-bulb depression were related to basic SG (green volume and ovendry weight). The result was a quantitative relationship that describes what we have known qualitatively for many years, i.e., that as SG increases, kiln schedules generally must be milder (lower dry-bulb temperature and wet-bulb depression) to minimize drying defects, such as surface checks, honeycomb, and collapse. A method was then developed to determine subsequent schedule steps. The result was nine kiln schedules, each applied to species that fall within certain SG intervals. Furthermore, species within the SG ranges are expected to dry within similar times (8,9), so they can be grouped together in terms of similar sensitivity to drying defects as well as similar drying times. The report also includes estimated schedules for more than 3,200 hardwood species with known specific gravities.

Although this system provides a convenient way to simultaneously estimate schedules and group for drying, the nine schedules do not belong to the standard group of hardwood schedules as given in the “Dry Kiln Operator’s Manual” (10). These standard schedules and their nomenclature may be more familiar to some people, who prefer to use them even though they do not lend themselves as readily to grouping species.

CURRENT RECOMMENDED SCHEDULES

The hardwood schedules developed

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in the United States and given in the "Dry Kiln Operator's Manual" have three components. The first component is the temperature schedule (14 possible schedules coded T1 to T14), which consists of temperatures applied at various levels of moisture content (MC) throughout drying. The second component is the MC class (6 possible, coded A to F) for various green MC levels. The third component is the wet-bulb depression schedule (8 possible, coded 1 to 8) applied at various levels of MC throughout drying. A typical schedule might be coded T6-D4 or, by substituting numbers for letters, 6-4-4. The greater the code number, the more severe the schedule component. The initial temperatures of the schedules range from 38°C for T1 to 82°C for T14. The MC class ranges from delaying the first wet-bulb depression increase until the lumber is at 30 percent MC (code A) to making that change as soon as the lumber is at 70 percent MC (code F). The initial wet-bulb depression ranges from a low of 1.7°C for code 1 to 14°C for code 8. The approach in this analysis was to relate the schedule code numbers to SG using appropriate statistical procedures.

Complete schedules can be assembled from these code numbers, as in the following example, for schedule T8-C3 by using **Table 1** to fill in columns 1 through 4 of **Table 2.**

1. In column 1 of **Table 2,** enter the MC values corresponding to MC code C.

2. In column 2, enter the dry-bulb temperatures corresponding to temperature code T8, noting that the first temperature listed, 54.4°C, is maintained until the MC reaches 30 percent.

3. In column 3, enter the wet-bulb depressions corresponding to wet-bulb depression code 3.

4. In column 4, enter the wet-bulb temperature as the wet-bulb depression subtracted from the dry-bulb temperature.

Recommended schedules for tropical and temperate hardwoods have been developed by numerous people in research institutions and industry throughout the world for many years (1,3,6,10). These schedules are recommended as conservative starting points, i.e., a safe reference to be adjusted upward in severity with experience.

The remainder of this article contains two parts. The first is a description of the statistical methods used to establish the relationship between kiln schedule and SG, using data from 268 species whose schedules and specific gravities are known. Two methods were developed: a classification method and a regression method. The second part of this article is the application of the results to estimate schedules for species where they are not known, with examples given. Readers interested only in the application can proceed directly to the section labeled "Application to other species" under the major section "Results."

METHODS

The kiln schedule code numbers for the 268 hardwood species are listed in **Table 3.** Under the "Dry Kiln Operators Manual" kiln schedule coding system, 672 hardwood schedules are possible, which is far more than experience or research has ever explored for verification. There are 40 schedules for the 268 species. The 40 schedules in **Table 3** are subdivided into 10 groups by degree of severity, based largely on initial temperature. In this paper, two approaches are

TABLE 1. — Schedules and code numbers for hardwoods.

Dry-bulb temperature step no.	MC at start of step	Dry-bulb temperatures for various temperature schedules													
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
	(%)	(°C (°F))													
1	> 30	37.8 (100)	37.8 (100)	43.3 (110)	48.9 (110)	48.9 (120)	48.9 (120)	54.4 (130)	54.4 (130)	60.0 (140)	60.0 (140)	65.6 (150)	71.1 (160)	76.7 (170)	82.2 (180)
2	30	40.6 (105)	43.3 (110)	48.9 (120)	43.3 (120)	54.4 (130)	54.4 (130)	60.0 (140)	60.0 (140)	65.5 (150)	65.6 (150)	71.1 (160)	76.7 (170)	82.2 (180)	87.8 (190)
3	25	40.6 (105)	48.9 (120)	54.4 (130)	54.4 (130)	60.0 (140)	60.0 (140)	65.6 (150)	65.6 (150)	71.1 (160)	71.1 (160)	71.1 (160)	76.7 (170)	82.2 (180)	87.8 (190)
4	20	46.1 (115)	54.4 (130)	60.0 (140)	60.0 (140)	65.6 (150)	65.6 (150)	71.1 (160)	71.1 (160)	71.1 (160)	76.7 (170)	76.7 (170)	82.2 (180)	87.8 (190)	93.3 (200)
5	15	48.9 (120)	65.6 (150)	71.1 (160)	82.2 (180)	71.1 (160)	82.2 (180)	71.1 (160)	82.2 (180)	71.1 (160)	82.2 (180)	82.2 (180)	82.2 (180)	87.8 (190)	93.3 (200)
Wet-bulb depression step no.		MC at start of step for various moisture content classes						Wet-bulb depressions for various wet-bulb depression schedules							
		A	B	C	D	E	F	1	2	3	4	5	6	7	8
		(%)						(°C (°F))							
1		> 30	> 35	> 40	> 50	> 60	> 70	1.7 (3)	2.2 (4)	2.8 (5)	3.9 (7)	5.6 (10)	8.3 (15)	11.1 (20)	13.9 (25)
2		30	35	40	50	60	70	2.2 (4)	2.8 (5)	3.9 (7)	5.6 (10)	7.8 (14)	11.1 (20)	16.7 (30)	19.4 (35)
3		25	30	35	40	50	60	3.3 (6)	4.4 (8)	6.1 (11)	8.3 (15)	11.1 (20)	16.7 (30)	22.2 (40)	27.8 (50)
4		20	25	30	35	40	50	5.6 (10)	7.8 (14)	10.6 (19)	13.9 (25)	19.4 (35)	27.8 (50)	27.8 (50)	27.8 (50)
5		15	20	25	30	35	40	13.9 (25)	16.7 (30)	19.4 (35)	22.2 (40)	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)
6 and 7		10	15	≤ 20	≤ 25	≤ 30	≤ 35	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)	27.8 (50)

used and compared: classification and regression analysis.

CLASSIFICATION

The classification approach considers the prior probability of a schedule being recommended. For example, 63 of the 268 schedules were T6-D2 (6-4-2), but only 1 of the 268 was T5-B2 (5-2-2). Classification also considers the distance in normalized basic SG units of a species to be classified from the mean basic SG

TABLE 2. — Assembled kiln schedule T8-C3.

Column 1	Column 2	Column 3	Column 4
MC at start of step	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
(%)	(°C (°F))		
> 40	54.4 (130)	2.8 (5)	51.7 (125)
40	54.4 (130)	3.9 (7)	50.6 (123)
35	54.4 (130)	6.1 (11)	48.3 (119)
30	60.0 (140)	10.6 (19)	49.4 (121)
25	65.6 (150)	19.4 (35)	46.1 (115)
20	71.1 (160)	27.8 (50)	43.3 (110)
15	82.2 (180)	27.8 (50)	54.4 (130)

TABLE 3. — Recommended kiln schedules for 268 hardwood species, with subclassification into severity groups.

Severity	Schedule no.	Initial temperature	Schedule code number: Temperature	MC	Depression	Mean SG (G_b)	SD[a] of SG	No. of occurrences
		(%)						
	1	38	1	2	1	0.915	0.0827	2
	2	38	2	2	2	0.659	0.0692*[b]	1
1	3	38	2	3	2	0.754	0.1056	25
	4	38	2	4	2	0.532	0.0692*	1
	5	38	2	4	4	0.675	0.1746	19
	6	43	3	3	1	0.863	0.0672	2
	7	43	3	4	1	0.620	0.0700	2
2	8	43	3	3	2	0.648	0.1164	40
	9	43	3	4	2	0.681	0.0711	9
	10	43	4	2	2	0.580	0.0692*	1
	11	49	5	2	2	0.740	0.0692*	1
	12	49	5	4	2	0.530	0.0692*	1
	13	49	5	3	3	0.410	0.0692*	1
	14	49	6	4	2	0.575	0.1074	63
3	15	49	6	1	3	0.660	0.0692*	1
	16	49	6	2	3	0.400	0.0692*	1
	17	49	6	3	3	0.625	0.0212	2
	18	49	6	6	3	0.400	0.0692*	1
	19	49	6	1	4	0.510	0.0692*	1
	20	49	6	4	4	0.509	0.1003	18
	21	54	7	2	3	0.750	0.0424	2
	22	54	7	2	6	0.360	0.0692*	1
	23	54	8	3	2	0.560	0.0692*	1
4	24	54	8	2	3	0.610	0.1400	3
	25	54	8	4	3	0.600	0.0692*	1
	26	54	8	2	4	0.510	0.0566	2
	27	54	8	3	4	0.493	0.0551	3
	28	54	8	4	4	0.470	0.0678	4
	29	60	10	3	4	0.480	0.0692*	1
	30	60	10	4	4	0.449	0.1149	20
5	31	60	10	5	4	0.398	0.0370	3
	32	60	10	6	4	0.345	0.0212	2
	33	60	10	4	5	0.448	0.0876	16
	34	60	10	6	5	0.340	0.0424	2
6	35	66	11	4	4	0.400	0.0692*	1
7	36	71	12	4	5	0.226	0.0692*	1
	37	71	12	5	5	0.40	0.0692*	1
8	38	71	12	5	7	0.335	0.0212	2
9	39	77	13	3	4	0.350	0.1364	9
10	40	82	14	3	6	0.334	0.0692*	1

[a] SD = standard deviation.
[b] * = pooled estimate based on groups for which the number of occurrences was 2, 3, or 4.

TABLE 4. — Matches between predicted and recommended kiln schedules for classification and regression analysis approaches.

Approach	Exact matches	Quasi-exact matches	Severity matches
Classification	81	- -	120
Regression analysis	13	45	88

TABLE 5. — Average and maximum absolute differences between predicted and recommended schedule code numbers.

Approach	Temperature	MC	Wet-bulb depression	Severity
Average				
Classification	1.80	0.422	0.784	0.985
Regression analysis	1.81	0.425	0.828	0.993
Maximum				
Classification	7	3	3	6
Regression analysis	6	3	3	6

for a particular schedule. For example, the 63 species for which the recommended schedule was T6-D2 had a mean SG of 0.575 and associated standard deviation of 0.107. The 20 species for which the recommended schedule was T10-D4 (10-4-4) had a mean SG of 0.449 and associated standard deviation of 0.115. Thus, if a new species had an SG x, its distance in normalized basic SG units from the T6-D2 group would be $(x - 0.575)/0.107$, and its distance from the T10-D4 group would be $(x - 0.449)/0.115$). The prior probability and distance measurements were combined to yield a posterior probability that a species belonged to a particular schedule. Details of this combination are given in the Appendix. The predicted schedule was taken to be the one with the highest posterior probability.

Regression analysis

Regression analysis is usually applied in cases where the dependent variable is continuous. In applying regression analysis to schedule code numbers, which are integers and not continuous, it is necessary to round predicted results to the nearest integer. The regression approach was used for three regressions: temperature code number on basic SG, MC class code number on basic SG, and depression code number on basic SG. Given the basic SG associated with a species, the regression equations were used to predict appropriate temperature, MC class, and wet-bulb depression code numbers. After the predicted code numhers were rounded to the nearest integers, the resulting schedules were again rounded to the nearest of the 40 schedules actually observed **(Table 3).**

Results

Actual compared with predicted

The number of matches achieved by the two approaches are compared in **Table 4.** A match was "exact" in the classification approach if the predicted schedule (based on the classification algorithm) was the same as the recommended schedule. The match was "exact" in the regression approach if the predicted schedule obtained after the initial rounding to the nearest integer was the same as the recommended schedule. In the regression approach, a match was considered "quasi-exact" if the predicted schedule obtained after both the initial rounding to the nearest integer and the subsequent rounding to the nearest of the 40 schedules was the same as the recommended schedule. For the classification approach, there was a "severity match" if the predicted schedule and the recommended schedule lay in the same severity class. For example, if schedule T5-D2 was recommended for a species and the classification approach predicted schedule T6-D4, there would be a severity match. For the regression approach, there was a severity match if the predicted schedule obtained after both the initial rounding to the nearest integer and the subsequent rounding to the nearest of the 40 schedules lay in the same severity class as the recommended schedule.

Table 5 contains the average and maximum absolute differences between the predicted and recommended schedules. In the regression case, the predicted schedule was the schedule obtained after the first rounding. The average differences do not seem excessive, given the inexact nature of kiln schedule recommendations, but some of the larger differences are large enough to be of serious concern. They could cause drying defects when the error is toward more severe schedules. One positive factor is that the known schedules on which the predictions are based are conservative, which moderates the danger of drying defects. Thus, although these methods for predicting schedules are imperfect, they can offer useful input for estimating a schedule when no other information is available.

TABLE 6. — Output from World Wide Web program for the classification method of estimating the drying schedule for a hardwood species of specific gravity 0.81.

temp	mc	depr	harsh	rel likeli
2	3	2	1	1.000
3	3	2	2	0.632
2	4	4	1	0.391
6	4	2	3	0.257
3	4	2	2	0.119
3	3	1	2	0.107
7	2	3	4	0.084
1	2	1	1	0.053
5	2	2	3	0.042
8	2	3	4	0.038
6	4	4	3	0.010
6	1	3	3	0.007
2	2	2	1	0.006
10	4	4	5	0.006
3	4	1	2	0.003
13	3	4	9	0.001
8	4	3	4	0.001
4	2	2	2	0.000

Table 4 suggests that the classification approach provides better schedule prediction than does the regression approach because of the greater number of matches. Also, for 179 of the 268 species, after the first rounding, the schedule predicted by the regression approach was not one of the 40 recommended schedules. Little difference between the two approaches was detected, as shown in **Table 5.**

Application to other species

Basic SG is a wood property that is known, at least approximately, for many species, including species for which we have no recommended kiln schedule. In most cases, the available SG is an average value known to be variable within a species. A Forest Products Laboratory (FPL) report (7) contains specific gravities for more than 3,200 species from Africa, Asia, and Latin America. Drying schedules can be predicted from these data. Both the classification and regression methods have been implemented in a Fortran computer program. This program can be run over the World Wide Web (see http://wwwl.fpl.fs.fed.us/drying.html), either by entering basic SG, G_b, or one of the more than 3,200 species names listed in the FPL report (7). Alternatively, a personal computer version is available (see http://www1.fpl.fs.fed.us/papers.html). Questions about these programs can be addressed to Steve Verrill at steve@ws13.fpl.fs.fed.us.

Following are several examples of estimating a kiln schedule.

Example 1 — Direct calculation. This method allows direct calculation of the estimated schedule from three regression equations. If the basic SG, G_b, is 0.620, the calculations are:

Temperature code number = $13.7 - 13.6G_b = 13.7 - 13.6 \times 0.620 = 5.2$

MC code number = $4.51 - 1.56G_b = 4.51 - 1.56 \times 0.620 = 3.5$

Wet-bulb depression code number = $5.20 - 3.95G_b = 5.20 - 3.95 \times 0.620 = 2.8$

These code numbers are rounded up or down to the closest whole number. The estimated kiln schedule is therefore 5-4-3, or T5-D3.

Example 2 — Regression method via the World Wide Web. If basic SG is 0.45, the resulting code numbers from the Web program are 8-4-3, which is schedule T8-D3.

Example 3 — Classification method via the World Wide Web: If basic SG is 0.81, the code numbers from the Web program are 2-3-2, or T2-C2. Note that with the Web program, the first results given are those of the regression method. Following that result, a table (partially reproduced as **Table 6** in this article) appears with the classification results. The first entry, labeled "1.000" under the column "rellikeli" (relative likelihood) is the correct choice. Note also that the regression result for SG 0.81 is T3-C2, which is slightly different than the classification results (final schedule dry-bulb temperature in T2-C2 is 66°C; in T3-C-2 it is 71°C). As noted, there is little statistical difference between the results of the two methods. To make a final decision, you could examine both schedules and choose the milder of the two. This is recommended procedure, especially in situations where close control of kiln conditions is not attainable or the reliability or variability of the SG information is in question.

Example 4 — Another way to use the Web program is by species name from the 3,237 species in the data bank. If an estimated schedule is needed for *Myristica irya,* choose the "species name" option and enter the species name. The result is 4-3-3, or T4-C3.

Conclusions

Classification and regression analyses offer reasonable first estimates of hardwood dry-kiln schedules using basic SG data. Although the estimates may be poor enough in some cases to cause concern, the bias is toward less severe schedules, which moderates the danger of the poor estimates. These estimation methods offer useful guidance when no other drying information is available for a species.

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Appendix

Classification algorithm:

$$P(group_j|sg = x) = P(group_j \text{ and } sg = x)/P(sg = x)$$

$$= P(sg = x|group_j)P(group_j)/\sum_{m=1} P(sg = x|group_i)P(group_i).$$

The item is placed in the $group_j$ that maximizes $P(group_j|sg = x)$ which is the $group_j$ that maximizes $P(sg = x|group_j)P(group_j)$.

We have:

$$P(sg = x|group_j) = (1/\sqrt{2\Pi})(1/s_j)\exp(-(x-u_j)^2/(2s_j^2))$$

and

$$P(group_j) = n_j/268$$

where n_j is the number of species in the data set for which the *j* th schedule is the recommended schedule. Taking logs, we see that we can maximize the posterior probability by maximizing

$$-\ln(s_j) - (x - u_j)^2 / (2s_j^2) + \ln(n_j/268).$$