USE OF RESPONSE SURFACE METHODOLOGY TO MAXIMIZE PAPER BIRCH UTILIZATION IN A THREE-LAYER, TWO-SPECIES ORIENTED STRANDBOARD[1]

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ABSTRACT

Response surface methodology (RSM) was used to maximize the use of paper birch in a laboratory three-layer aspen oriented strandboard (OSB) at a minimum core resin spread. The minimum possible resin spread for the core and maximization of paper birch usage were achieved by simultaneously varying the core strand thickness and reducing the face-to-core weight ratio. Sequential experimentation and model fitting procedures of RSM enabled the prediction of the response and the location of the optimum operating conditions. Simultaneous optimization of the ten board properties indicated that at a density of 39 pcf, a laboratory aspen OSB made with a core resin spread of 1.50 lb/1,000 ft^2 and 45 percent by weight of 0.025-inch-thick paper birch core strands would satisfy the minimum requirements of the performance standard. Overall, paper birch was a good supplemental furnish for the core of a three-layer aspen OSB.

Keywords: Oriented strandboard, response surface methodology, sequential experimentation, fractional factorial, simultaneous optimization and central composite design.

The significant characteristic of a two-species three-layer particleboard design proposed by Suchsland (1960) is that by changing the proper species, a differential in relative compressibility can be developed between the face and core materials. Aspen (*Populus tremuloides* Michx.) is ideal furnish for the face layers because of its low density and ease of compressibility. Paper birch (*Betula papyrifera* Marsh.), an underutilized medium density hardwood with higher compression properties, is ideal for the core. Subsequent work at the University of Minnesota (Chen et al. 1992) showed that paper birch was in fact an excel-

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TABLE 1. *Performance standards for aspen oriented strandboards (OSB).*

Board property	Limit	Units	Requirement
Modulus of elasticity[a] (MOE)	Min	psi	800,000
Modulus of rupture[a] (MOR)	Min	psi	4,200
Internal bond[a] (IB)	Min	psi	50
Wet MOE[b] (WMOE)	Min	psi	400,000
Wet MOR[a] (WMOR)	Min	psi	2,100
Linear expansion[b] (LE)	Max	%	0.10
Water absorption[b] (WA)	Max	%	135
Thickness swelling[b] (TS)	Max	%	30
Irreversible thickness swelling[b] (ITS)	Max	%	20
Cross linear expansion[b] (CLE)	Max	%	0.20

[a] Minimum requirement for type O-2 boards of the Canadian Standards Association (1985a) CAN3-O437.0-M85 parallel to the direction of face alignment.
[b] Not covered by a commercial standard; limit was set by the authors based on previous studies and a working knowledge of OSB requirements.

lent core material for aspen oriented strandboard (OSB) and waferboard, particularly if the wafers or strands were relatively thin.

This study was initiated to determine the optimum operating conditions for achieving minimum board property requirements while maximizing the use of paper birch for the core of three-layer aspen OSBs. Response surface methodology (RSM) was chosen as the method to achieve these objectives. RSM is a group of mathematical and statistical techniques introduced by Box and Wilson (1951) that reduces overall experimentation and hence expedites solution at reduced experimental costs. Recently, it has received considerable attention in industrial applications, as well as in areas such as chemistry, biology, food science, and nutrition. Very little has been published on the use of RSM in forest products research. However, Warren and Hailey (1980) and Hailey et al. (1980) have applied this methodology where they optimized the effect of lathe parameters (compression, gap ratio, and knife angle) on veneer yield and quality of Douglas-fir. In this study, board density, core resin spread, core strand thickness and core strand content were varied, and through RSM we determined the maximum thickness of the core strands, minimum acceptable core resin spread, minimum face-to-core weight ratio, and minimum board density that could be employed to meet minimum property requirements.

Achieving specific property requirements in particleboard is a very complex process because of the many processing variables and their interactions. Mat moisture distribution and press closing time, for example, have very important influences on board properties (Suchsland 1960), but these, like many other variables, were held constant to keep the study reasonable in terms of size and duration. Also, the primary intent of the study was to demonstrate the application of RSM to the design of a two-species, three-layer OSB and not to develop an understanding of the complex relationships between processing variables and resultant board properties.

PROCEDURE

The design strategy for this study involved the simultaneous optimization of ten responses that depended on board density, resin spread, core strand thickness, and core strand content. Incorporated in the design strategy was the innate ability to manipulate the above processing parameters to meet the required performance standards (Table 1) of the final product.

The experimental investigation of a response surface can be divided into two phases: a design phase and an analysis phase. In the design phase, the selected experimental variables are set at certain levels for a particular set of experiments. In the analysis phase, the information from the set of experiments is used to answer questions regarding the operating conditions.

Paper birch strands 3 inches long and 0.7

inch wide were manufactured in the laboratory. The target strand thicknesses were achieved by adjusting the two knives on a laboratory disk waferizer. Commercial aspen strands were used for all faces. The laboratory core strands and commercial face strands were prepared and screened for board manufacture using procedures identical to those described by Chen et al. (1992). All aspen faces contained 5% liquid phenol formaldehyde (PF) resin solids and 1% wax emulsion solids.

Since the combinations of experimental variables for each board were unique, only the face and core strands at 3% moisture content required for one board were blended at one time. Strands were aligned into three-layer mats 18 inches by 21 inches using a laboratory mechanical orienter set at 1.35-inch plate spacing and 1.5-inch free-fall distance. The mats were hot pressed at 400 F to 0.5-inch stops using a 1-minute closing time, 6-minute press time at stops and 0.5-minute decompression.

Four static bending samples, 13 inches long by 3 inches wide, two strips 13 inches long by 2 inches wide for cross linear expansion (CLE), and six 2-inch square internal bond (IB) samples were cut from each panel. Two static bending samples from each panel were subjected to the Canadian Standards Association (1985b) CAN3-0437.1-M85 2-hour boil (bond durability) test. These test samples were designated as aged samples, with the remaining two samples as non-aged samples. All the test samples then were equilibrated at 65% relative humidity (RH) and 72 F. Moduli of rupture (MOR) and elasticity (MOE) were obtained from the non-aged static bending samples. Aged static bending and CLE samples were subjected to the 2-hour boil bond durability test. Linear expansion (LE), thickness swelling (TS), and water absorption (WA) were determined from the aged bending samples. Wet MORs and MOEs (WMORs and WMOEs) were obtained from the aged samples, which were tested wet in static bending. Irreversible thickness swellings (ITS) were determined from the aged samples after being reconditioned at 65% RH and 72 F. All tests were conducted in accordance with ASTM D1037-87 (ASTM 1987).

RESULTS AND DISCUSSION

Board density, core resin spread, core strand thickness, and core strand content would be tested initially using a 2^{4-1}fractional factorial design, augmented with a replicated center point taken at the design center (Table 2). The notation, 2^{4-1}, indicates that the design had four variables, each at two levels, but only $2^{4-1} = 8$ runs were employed. Therefore, a 2^{4-1}fractional factorial design contains only one-half the number of experimental runs of a 2^4 factorial design. The four experimental variables were expressed as coded variables via the following standard factorial coding:

x_1 = (Board density − 40)/3,

x_2 = (Core resin spread − 1.675)/0.335,

x_3 = (Core strand thickness − 0.025)/0.005

and

x_4 = (Core strand content − 40)/3.

The intention of using a 2^{4-1}design along with two center points is to seek a more detailed knowledge of the relation between a response and the experimental variables. This relation can be approximated by a planar surface with a first order polynomial model as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + \epsilon \quad (1)$$

where y represents the response variable, bs are the regression coefficients usually estimated using the method of least squares, xs represent the experimental variables and ϵ the error. The errors are assumed to be normal and independent and have zero mean and a common variance.

Actual board densities were used to fit the first order polynomial models due to an unequal distribution of strands during the formation of a mat. So, variation in density exists between the run conditions and also within the run conditions at the same level of board density.

Two center points taken at the origin of the design for which $(x_1, x_2, x_3, x_4) = (0, 0, 0, 0)$ in coded units, were used to provide a signif-

TABLE 2. *Experimental design partitioned into blocks, design types, center points and axial points.*

Block number	Type	x_1	x_2	x_3	x_4
1	2^{4-1} design	−1	−1	−1	−1
		1	−1	−1	1
		−1	1	−1	1
		1	1	−1	−1
		−1	−1	1	1
		1	−1	1	−1
		−1	1	1	−1
		1	1	1	1
		0	0	0	0
	Center points	0	0	0	0
2	2^{4-1} design	−1	−1	−1	1
		1	−1	−1	−1
		−1	1	−1	−1
		1	1	−1	1
		−1	−1	1	−1
		1	−1	1	1
		−1	1	1	1
		1	1	1	−1
	Axial points	−1.50	0	0	0
		1.50	0	0	0
		0	−1.50	0	0
		0	1.50	0	0
		0	0	−1.50	0
		0	0	1.50	0
		0	0	0	−1.50
		0	0	0	1.50
	Center points	0	0	0	0
		0	0	0	0
		0	0	0	0
		0	0	0	0
3	2^{4-1} design	−1.67	−2.02	−0.80	−0.50
		−0.33	−2.02	−0.80	0.50
		−1.67	−0.09	−0.80	0.50
		−0.33	−0.09	−0.80	−0.50
		−1.67	−2.02	0.40	0.50
		−0.33	−2.02	0.40	−0.50
		−1.67	−0.09	0.40	−0.50
		−0.33	−0.09	0.40	0.50
	Center points	−1	−1.42	−0.20	0
		−1	−1.42	−0.20	0

icance test for the existence of curvature in the response surface through a single degree of freedom. Interaction between the variables would be measured by the coefficient b_{ij} of the corespondent term x_ix_j as follows:

$$y = b_0 + \sum_{i=1}^{k} b_ix_i + \sum_{i=1}^{k-1} \sum_{\substack{j=2 \\ i<j}}^{k} b_{ij}x_ix_j + \epsilon \quad (2)$$

where $k = 4$.

Tables 3 to 6 summarize the physical and mechanical properties for the ten boards. The information available was used to adjust the levels of the experimental variables for the next block of experiments. The other half of the 2^4 factorial design was augmented with a central composite design, which allowed an estimate of the coefficients in the second order model. Eight axial points and four center points along with 2^{4-1}runs contributed a total of 20 labo-

TABLE 3. *Modulus of elasticity (MOE) and modulus of rupture (MOR) and various combinations of coded variables* x_1, x_2, x_3 *and* x_4.

Blk no.	Run no.	Nominal x_1	Actual x_1	x_2	x_3	x_4	MOE (psi)	MOR (psi)
1	1	−1	1.44	−1	−1	−1	1,104,500	5,680
1	2	1	−0.62	−1	−1	1	1,016,100	6,540
1	3	−1	1.14	1	−1	1	720,300	3,260
1	4	1	−1.14	1	−1	−1	1,023,400	6,250
1	5	−1	−1.11	−1	1	1	667,200	3,030
1	6	1	0.72	−1	1	−1	924,700	5,440
1	7	−1	0.16	1	1	−1	1,000,900	4,760
1	8	1	0.79	1	1	1	869,400	4,910
1	9	0	0.04	0	0	0	1,071,300	5,830
1	10	0	0.12	0	0	0	1,029,500	5,710
2	11	−1	−0.93	−1	−1	1	853,200	5,490
2	12	1	−0.05	−1	−1	−1	1,121,100	5,900
2	13	−1	−1.31	1	−1	−1	850,100	5,190
2	14	1	0.49	1	−1	1	908,300	5,710
2	15	−1	−1.87	−1	1	−1	758,400	4,490
2	16	1	0.87	−1	1	1	809,600	4,660
2	17	−1	−1.56	1	1	1	724,600	4,090
2	18	1	0.37	1	1	−1	934,800	5,080
2	19	−1.50	−1.69	0	0	0	589,400	2,990
2	20	1.50	0.65	0	0	0	906,800	5,290
2	21	0	−0.61	−1.50	0	0	774,800	4,470
2	22	0	−0.58	1.50	0	0	1,029,500	6,220
2	23	0	−0.50	0	−1.50	0	963,800	5,430
2	24	0	−0.63	0	1.50	0	698,700	4,070
2	25	0	−0.74	0	0	−1.50	825,400	5,230
2	26	0	−0.14	0	0	1.50	810,200	4,540
2	27	0	−0.55	0	0	0	913,000	5,200
2	28	0	−1.00	0	0	0	842,200	4,790
2	29	0	−0.32	0	0	0	853,100	4,680
2	30	0	−0.51	0	0	0	993,900	4,930
3	31	−1.67	−1.39	−2.02	−0.80	−0.50	782,200	4,220
3	32	−0.33	−0.07	−2.02	−0.80	0.50	725,500	3,880
3	33	−1.67	−1.30	−0.09	−0.80	0.50	631,700	3,020
3	34	−0.33	−0.15	−0.09	−0.80	−0.50	761,700	4,710
3	35	−1.67	−1.71	−2.02	0.40	0.50	654,000	3,140
3	36	−0.33	−0.42	−2.02	0.40	−0.50	850,100	4,230
3	37	−1.67	−1.35	−0.09	0.40	−0.50	806,800	3,680
3	38	−0.33	−0.28	−0.09	0.40	0.50	781,500	4,570
3	39	−1	−1.18	−2.02	−0.20	0	735,700	3,770
3	40	−1	−0.86	−2.02	−0.20	0	826,900	4,870

ratory aspen OSBs for the second block of experiments.

Blocking is important in sequential experimentation. In this study, there was a time lapse between the first and the second block of experiments so there were opportunities for systematic differences to occur. Therefore, the accuracy of the experiment was increased by the removal of this extraneous source of variability, and thus the estimates of the linear, cross product, and quadratic coefficients were not influenced by block differences.

The data for both blocks of experiments were fitted with a linear model of the form

$$y = b_0 + \text{blk} + \sum_{i=1}^{k} b_i x_i + \epsilon \qquad (3)$$

where blk is the block effect, and k = 4. To

TABLE 4. *Internal bond (IB) strength and various combinations of coded variables x_1, x_2, x_3 and x_4.*

Blk no.	Run no.	Nominal x_1	Actual x_1	x_2	x_3	x_4	IB (psi)
1	1	−1	−0.90	−1	−1	−1	59
1	2	1	0.18	−1	−1	1	86
1	3	−1	−1.04	1	−1	1	75
1	4	1	0.26	1	−1	−1	91
1	5	−1	−1.92	−1	1	1	25
1	6	1	−0.49	−1	1	−1	54
1	7	−1	−0.50	1	1	−1	87
1	8	1	−0.33	1	1	1	97
1	9	0	−0.45	0	0	0	85
1	10	0	0.10	0	0	0	83
2	11	−1	−1.64	−1	−1	1	70
2	12	1	−0.18	−1	−1	−1	103
2	13	−1	−1.70	1	−1	−1	79
2	14	1	0.65	1	−1	1	106
2	15	−1	−1.74	−1	1	−1	72
2	16	1	0.45	−1	1	1	100
2	17	−1	−1.75	1	1	1	75
2	18	1	0.63	1	1	−1	108
2	19	−1.50	−2.27	0	0	0	60
2	20	1.50	0.14	0	0	0	105
2	21	0	−1.01	−1.50	0	0	93
2	22	0	−0.91	1.50	0	0	100
2	23	0	−0.87	0	−1.50	0	86
2	24	0	−1.09	0	1.50	0	93
2	25	0	−0.59	0	0	−1.50	109
2	26	0	−0.70	0	0	1.50	91
2	27	0	−0.80	0	0	0	92
2	28	0	−1.24	0	0	0	85
2	29	0	−1.09	0	0	0	81
2	30	0	−1.12	0	0	0	83
3	31	−1.67	−1.73	−2.02	−0.80	−0.50	102
3	32	−0.33	−0.45	−2.02	−0.80	0.50	121
3	33	−1.67	−2.12	−0.09	−0.80	0.50	94
3	34	−0.33	−0.42	−0.09	−0.80	−0.50	100
3	35	−1.67	−1.98	−2.02	0.40	0.50	75
3	36	−0.33	−0.73	−2.02	0.40	−0.50	89
3	37	−1.67	−1.49	−0.09	0.40	−0.50	99
3	38	−0.33	−0.19	−0.09	0.40	0.50	105
3	39	−1	−1.32	−1.42	−0.20	0	95
3	40	−1	−0.79	−1.42	−0.20	0	96

check if the first order model was adequate, a second order (quadratic) model then was fitted as follows:

$$y = b_0 + \text{blk} + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{\substack{j=2 \\ i<j}}^{k} b_{ij} x_i x_j + \epsilon \qquad (4)$$

where $k = 4$. An *F*-test was performed to check whether the linear model (null hypothesis) provided an adequate description of the experimental data as compared to that of the quadratic model (alternative hypothesis). Linear model for the respective board properties provided an adequate description for the experimental data.

However, physical and mechanical properties of aspen OSB panels still exceeded the required performance standards. Another

TABLE 5. *Wet modulus of elasticity (WMOE), wet modulus of rupture (WMOR), linear expansion (LE), water absorption (WA), thickness swelling (TS) and irreversible thickness (ITS) and various combinations of coded variables* x_1, x_2, x_3 *and* x_4.

Blk no.	Run no.	Nominal x_1	Actual x_1	x_2	x_3	x_4	WMOE (psi)	WMOR (psi)	LE (%)	WA (%)	TS (%)	ITS (%)
1	1	−1	−0.95	−1	−1	−1	514,900	2,290	−0.009	132	24	14
1	2	1	0.88	−1	−1	1	531,300	2,710	0.036	112	30	20
1	3	−1	0.44	1	−1	1	492,300	1,970	0.062	118	20	12
1	4	1	1.33	1	−1	−1	635,200	3,390	−0.009	105	27	18
1	5	−1	−1.35	−1	1	1	414,700	1,970	0.062	132	24	15
1	6	1	0.39	−1	1	−1	517,400	2,590	0.050	124	32	23
1	7	−1	−0.15	1	1	−1	588,100	2,840	0.007	119	24	16
1	8	1	0.53	1	1	1	566,700	2,750	0.040	115	27	18
1	9	0	−0.17	0	0	0	536,700	2,770	0.019	122	24	15
1	10	0	−0.10	0	0	0	605,800	2,970	0.015	124	30	19
2	11	−1	−0.90	−1	−1	1	453,700	2,140	0.003	126	19	10
2	12	1	−0.25	−1	−1	−1	501,100	2,440	−0.033	123	24	13
2	13	−1	−1.40	1	−1	−1	411,800	2,200	0.002	134	23	13
2	14	1	0.26	1	−1	1	461,100	2,750	−0.029	116	24	13
2	15	−1	−1.37	−1	1	−1	373,500	2,000	0.018	138	23	12
2	16	1	0.60	−1	1	1	432,700	2,320	0.038	120	30	18
2	17	−1	−1.51	1	1	1	404,700	2,140	0.058	131	21	19
2	18	1	1.83	1	1	−1	508,600	3,150	0.012	121	27	24
2	19	−1.50	−2.54	0	0	0	270,900	1,400	0.018	145	20	10
2	20	1.50	0.28	0	0	0	461,600	2,740	0.029	122	28	16
2	21	0	−0.35	−1.50	0	0	443,800	2,940	0.016	125	27	15
2	22	0	−0.72	1.50	0	0	505,300	2,420	0.010	126	21	11
2	23	0	−0.60	0	−1.50	0	535,300	2,960	0.002	124	20	11
2	24	0	−1.23	0	1.50	0	455,100	2,320	0.017	132	25	13
2	25	0	−0.56	0	0	−1.50	439,500	2,610	0.012	128	25	14
2	26	0	0.07	0	0	1.50	519,500	2,580	0.051	118	24	13
2	27	0	−0.39	0	0	0	447,000	2,290	0.062	126	23	14
2	28	0	−1.02	0	0	0	445,800	2,490	0.071	131	23	12
2	29	0	−0.27	0	0	0	494,600	2,800	0.033	125	25	14
2	30	0	−0.61	0	0	0	466,200	2,530	0.021	127	25	14
3	31	−1.67	−1.19	−2.02	−0.80	−0.50	411,200	2,150	0.010	138	22	15
3	32	−0.33	−0.35	−2.02	−0.80	0.50	418,200	2,460	−0.017	130	28	20
3	33	−1.67	−1.60	−0.09	−0.80	0.50	400,400	1,980	0.010	137	22	14
3	34	−0.33	−0.50	−0.09	−0.80	−0.50	395,700	2,170	0.022	128	26	17
3	35	−1.67	−1.74	−2.02	0.40	0.50	354,200	1,970	0.013	139	22	13
3	36	−0.33	−0.54	−2.02	0.40	−0.50	527,900	2,770	0.004	127	25	16
3	37	−1.67	−1.56	−0.09	0.40	−0.50	437,600	2,190	0.017	135	21	12
3	38	−0.33	−0.13	−0.09	0.40	0.50	420,100	2,500	−0.001	129	28	19
3	39	−1	−1.21	−1.42	−0.20	0	442,700	2,460	0.024	134	25	15
3	40	−1	−1	−1.42	−0.20	0	498,800	2,630	−0.018	131	22	13

2^{4-1} fractional factorial along with center points was run on the path of steepest descent. Observations from the third block of experiments indicated that with the exception of static bending properties, most of the aspen OSB panels exceeded the required performance standards. Further experimental runs on the path of steepest descent would only yield lower static bending properties and for that reason, a stopping rule was applied to the sequential experimentation. F-tests revealed that the linear model still provided a good fit for the re-

TABLE 6. *Cross linear expansion (CLE) and various combinations of coded variables x_1, x_2, x_3 and x_4.*

Blk no.	Run no.	Nominal x_1	Actual x_1	x_2	x_3	x_4	CLE (%)
1	1	−1	−0.42	−1	−1	−1	0.119
1	2	1	1.11	−1	−1	1	0.081
1	3	−1	−0.82	1	−1	1	0.091
1	4	1	0.67	1	−1	−1	0.124
1	5	−1	−1.16	−1	1	1	0.132
1	6	1	0.79	−1	1	−1	0.138
1	7	−1	−1.17	1	1	−1	0.164
1	8	1	1.18	1	1	1	0.105
1	9	0	−0.40	0	0	0	0.107
1	10	0	−0.17	0	0	0	0.064
2	11	−1	−0.89	−1	−1	1	0.100
2	12	1	1.44	−1	−1	−1	0.084
2	13	−1	−0.90	1	−1	−1	0.123
2	14	1	1.52	1	−1	1	0.066
2	15	−1	−0.31	−1	1	−1	0.119
2	16	1	1.35	−1	1	1	0.134
2	17	−1	−0.73	1	1	1	0.123
2	18	1	0.90	1	1	−1	0.132
2	19	−1.50	−0.78	0	0	0	0.063
2	20	1.50	1.67	0	0	0	0.107
2	21	0	0.39	−1.50	0	0	0.094
2	22	0	−0.40	1.50	0	0	0.148
2	23	0	−0.33	0	−1.50	0	0.070
2	24	0	−0.87	0	1.50	0	0.136
2	25	0	0.58	0	0	−1.50	0.125
2	26	0	1.17	0	0	1.50	0.087
2	27	0	0.10	0	0	0	0.063
2	28	0	−0.05	0	0	0	0.079
2	29	0	0.40	0	0	0	0.079
2	30	0	0.02	0	0	0	0.119
3	31	−1.67	−1.74	−2.02	−0.80	−0.50	0.070
3	32	−0.33	−0.34	−2.02	−0.80	0.50	0.040
3	33	−1.67	−0.69	−0.09	−0.80	0.50	0.025
3	34	−0.33	−0.49	−0.09	−0.80	−0.50	0.044
3	35	−1.67	−1.44	−2.02	0.40	0.50	0.012
3	36	−0.33	0.32	−2.02	0.40	−0.50	0.055
3	37	−1.67	−1.64	−0.09	0.40	−0.50	0.020
3	38	−0.33	0.12	−0.09	0.40	0.50	0.036
3	39	−1	0.01	−1.42	−0.20	0	0.039
3	40	−1	−0.04	−1.42	−0.20	0	−0.012

spective board properties. Diagnostic checking of the fitted model was performed by plotting the residuals, $y - \hat{y}$, against the predicted responses, $\hat{y}$. In all cases, there was no evidence that the linear model was inadequate or that assumptions concerning the errors were violated.

Given that the linear model provided a good fit for the ten responses, the use of linear programming (LP) as a tool to determine the optimal allocation of the four experimental variables among the competing responses was indicated. Based on the relative increase over the required performance standards, the objective function along with its constraints could be formulated in a LP model as follows:

TABLE 7. *Intercepts and regression coefficients of board density (x_1), core resin spread (x_2), core strand thickness (x_3) and core strand content (x_4) for physical and mechanical for the three blocks of experiments.*

Board properties	b_0	x_1	x_2	x_3	x_4
MOE	389,408.7	25,096.15	5,565.274	−8,918,031	−6,662.431
MOR	−361.5965	218.3313	12.29909	−72,157.4	−36.90851
IB	−109.1861	5.039095	15.10622	−423.121	−0.119567
WMOE	−62,765.63	15,043.52	33,978.16	−1,408,132	−1,310.484
WMOR	−2,059.827	132.1024	154.4473	−4,763.57	−14.48105
LE	−0.044399	−0.001346	0.000610	2.41778	0.001193
WA	231.2018	−2.552065	−3.768364	246.745	−0.147090
TS	−21.86962	1.212905	−2.821089	346.702	−0.093085
ITS	−23.65509	1.039534	−1.982702	241.071	−0.912596
CLE	0.094602	−0.001010	0.008073	2.75511	−0.001157

$$\text{Maximize } z = \frac{\text{MOE}}{800{,}000} + \frac{\text{MOR}}{4{,}200} + \frac{\text{IB}}{50} + \frac{\text{WMOR}}{2{,}100} + \frac{\text{WMOE}}{400{,}000} \quad (5)$$

subject to

(1) $\text{LE} < 0.10$

(2) $\text{WA} < 135$

(3) $\text{TS} < 30$

(4) $\text{ITS} < 20$

(5) $\text{CLE} < 0.20$

Using the linear equations for the respective responses in Table 7, the above LP model could be expressed in terms of x_1, x_2, x_3 and x_4 as follows:

$$\text{Maximize } z = 0.2846x_1 + 0.4705x_2 - 42.5790x_3 - 0.02968x_4 \quad (6)$$

subject to

(1) $-0.0014x_1 + 0.0006x_2 + 2.4178x_3 + 0.0012x_4 < 0.1444$

(2) $-2.5521x_1 + 3.7684x_2 + 246.745x_3 - 0.1471x_4 < -96.2018$

(3) $1.2129x_1 - 2.8211x_2 + 346.702x_3 - 0.0930x_4 < 51.8692$

(4) $1.0395x_1 - 1.9827x_2 + 241.071x_3 - 0.0913x_4 < 43.6551$

(5) $-0.0010x_1 + 0.0081x_2 + 2.7551x_3 - 0.0012x_4 < 0.1054$

(6) $36 < x_1 < 39$

(7) $1.1 < x_2 < 1.5$

(8) $0.025 < x_3 < 0.028$

(9) $45 < x_4 < 50$

With multiple responses, it was necessary to locate regions where the physical and mechanical properties simultaneously meet the performance standards. Constraints 6 through 9 represented the operating ranges of the experimental variables in the search for a "compromised" optimal solution.

Constraint 6 assured that the board density was within the commercial range of OSB presently manufactured. Constraint 7 limited a maximum core resin spread of 1.5 lb/1,000 ft^2, which was equivalent to 3.8% resin content. Constraint 8 assured that the advantage of particle geometry (strand thickness) was fully exploited in conjunction with the amount of resin used. Constraint 9 maximized the amount of paper birch in the core of a three-layer aspen OSB.

The LP model was solved using a software called LINDO (Schrage 1987) which is an interactive linear, quadratic, and integer programming system for microcomputers. Solution of the LP model was as follows:

Objective function (%)	9.407
Board density (pcf), x_1	39

TABLE 8. *Results of the confirmatatory test using the optimal settings for the four experimental variables.*

Board number	MOE (psi)	MOR (psi)	IB (psi)	WMOE (psi)	WMOR (psi)	LE (%)	WA (%)	TS (%)	ITS (%)	CLE (%)
1	813,500	4,270	106	532,200	2,590	0.05	111	24	19	0.10
2	805,000	4,380	96	446,700	2,130	0.07	113	22	20	0.14
3	851,000	4,170	84	475,800	2,650	0.03	110	24	20	0.14
4	818,500	4,740	97	558,800	2,870	0.02	110	25	20	0.11
5	808,700	4,620	75	441,300	2,430	0.05	113	22	19	0.11
6	833,500	4,250	91	439,500	2,890	0.06	113	22	19	0.15

Core resin spread (lb/1,000 ft^2), x_2	1.50
Core strand thickness (inch), x_3	0.025
Core strand content (%), x_4	45

The final solution yielded an objective function value (z) of 9.407. This number, which can be referred to as the relative increase index, is of no real significance but for the fact that it represents the maximum value of z attainable under the existing constraints.

A confirmatory test was performed to validate the experimental results of the RSM technique. Using the optimum settings for the four experimental variables, six laboratory aspen OSB panels were manufactured. Physical and mechanical properties of the six experimental boards for the confirmatory test are summarized in Table 8. With the exception of MOR for board 3, all requirements for the ten specified properties were met for the six experimental boards.

SUMMARY AND CONCLUSIONS

Response surface methodology (RSM) is a technique for solving optimization problems in a multiresponse experiment. In this study, RSM was applied successfully to optimizing the use of paper birch in a three-layer aspen oriented strandboard. Sequential experimentation and model fitting procedures of the RSM technique were used to evaluate the influence of process variables, within the established experimental constraints, on the properties of aspen OSB. Simultaneous optimization of the ten board properties indicated that at a density of 39 pcf, a laboratory OSB made with a core resin spread of 1.50 lb/1,000 ft^2 and 45% of 0.025 inch thick paper birch core strands by weight would satisfy the minimum requirements of the performance standard.

Overall, paper birch was a good supplemental furnish for the core of a three-layer aspen OSB. The use of this medium density species at an optimum strand thickness and reasonable core resin spread would result in reduced manufacturing costs and increased utilization of this underutilized resource.

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