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A NOVEL METHOD FOR ASSEMBLING A WOOD DRYING SCHEDULE BASED ON DESIGN OF EXPERIMENTS

Bogdan BEDELEAN
Transilvania University of Brasov, Faculty of Wood Engineering
Str. Universitatii nr. 1, 500068 Brasov, Romania
Tel: 0040 268 419581, Fax: 0040 268 419581, E-mail: bedelean@unitbv.ro

Daniela ȘOVA
Transilvania University of Brasov, Faculty of Mechanical Engineering
B-dul Eroilor nr. 29, 500036, Brasov, Romania
E-mail: sova.d@unitbv.ro

Abstract:

The aim of this study was to find the optimal values of air parameters during each step of a drying schedule for wood using the response surface methodology, which has been widely applied to drying optimization of food and drugs. The moisture content based schedule consisted in five steps, namely, 60 to 30% (step 1), 30-25% (step 2), 25 – 20% (step 3), 20 – 15% (step 4) and 15-10% (step 5). It was assembled for spruce boards of 38 mm thickness. The drying process was simulated in a drying kiln using TORKSIM software, which was validated experimentally in a laboratory kiln. The optimal combination of air parameters (temperature, relative humidity and velocity) was found using the desirability function approach, one of the most widely used methods in industry for the optimization of multiple response processes. The optimization criteria were short time, low drying cost and high quality of end products. The results showed that for each step of the schedule the optimum combination of air parameters is different. The results obtained using the proposed method were compared with those obtained using ten various methods (six from literature and four from industry) applied to develop wood drying schedules. The proposed method has both advantages (high quality) and disadvantages (long time and high cost) compared with various options that currently are used to assembly a drying schedule for spruce. However, further research is needed in order to adjust and implement the proposed method at industrial level.

Key words: *wood drying; spruce; drying schedule; optimisation; simulation.*

INTRODUCTION

The drying process control is accomplished according to a drying schedule. A wood drying schedule can be developed through various methods (Bedelean 2018). Each method has its own algorithm. Since there are differences in the temperature and relative humidity in each step of the drying schedule, there are differences in the kiln performance (time, quality, energy consumption and cost), if different drying schedules are applied.

Currently, the Response Surface Methodology (RSM) has been widely applied to drying optimization (Sova et al. 2016). RSM is a collection of statistical and mathematical techniques useful for developing, improving and optimizing processes. RSM implies the use of Box-Wilson Central Composite Design (CCD) (Georgescu et al. 2019). In this design, the two-level factorial design points estimate the first-order and two-factor interactions. These points take into account all possible combinations of the low (-1) and high (+1) levels of analyzed factors. In this study, there were three factors, namely, air temperature, air relative humidity and air velocity, and each was analyzed at two levels (-1, +1). The center points are needed in the experimental design to estimate the experimental error, meaning that each factor has to be analyzed at the center value (0). The axial points (- α, +α) allow the estimation of the pure quadratic effects. Two factors are analyzed at the center value (0) and the third one has the value of alpha.

Based on the applied experimental design, the following regression equation is figured out (Eq.1)

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 \qquad (1)$$

where:
Y represents the response (output);
X_i are the main effects (inputs);
X_iX_j are variables interactions;
X^2 are quadratic effects;
b are coefficients.

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The magnitude of coefficient values shows their importance; high values indicate great importance and low values, little importance. Also, a positive coefficient denotes that the response increases with increasing variable and a negative coefficient denotes that the response increases with decreasing variable.

The regression analysis and the analysis of variance (ANOVA) are performed for coefficients' assessment and for the determination of the significance of model parameters regarding each variable.The effects that are not significant can be excluded from the models in order to obtain a better fit of the model.

The optimization of the process that was analyzed is performed by using the desirability function approach, one of the most widely used methods in industry for the optimization of multiple response processes (NIST/SEMATECH 2013). This optimization method finds operation conditions X that provide the most desirable response values (Y). For each response $Y_i(X)$, a desirability function $d_i(Y_i)$ assigns numbers between 0 and 1, zero representing a completely undesirable value and one representing a completely desirable or ideal response value.

OBJECTIVE

The main objective of the present research was to assess if response surface methodology can be used to find the optimal combination of air parameters during each step of a wood drying schedule. Moreover, the research aimed to compare the RSM with other methods used to develop drying schedules. The simulation of the drying process was performed with Torksim software (SPTratek, Sweden), which it is industrially used for drying schedule optimization and process improvement.

MATERIAL, METHOD, EQUIPMENT

Ten moisture content based drying schedules for spruce *(Picea abies*) were assembled or collected from manufacturers of drying kilns. The initial data needed to develop a drying schedule were board thickness (38 mm), green moisture content (60%) and target moisture content (10%). The drying schedules were simulated with Torksim software in order to figure out the time needed to reach the target moisture content (10%), the energy consumption, the quality of the dried material (relative surface stress, moisture content gradient and slicing test gap) and the drying cost.

The eleventh drying schedule (Table 1) was developed using the Response Surface Methodology. The independent variables were the temperature of air (range: 55-90°C), the relative humidity of air (range: 45-85%) and the air velocity (range: 1.3-3m/s). The responses (dependent variables) were the drying time, the energy consumption per cubic meter of wood (kWh/m^3), the relative surface stress, the casehardening degree (slicing test) and drying the cost.

Table 1

The structure of the RSM drying schedule

Drying phase	MC (%)	T (°C)	RH (%)	v (m/s)	Desirability coefficient
Heating	60	77	90	3	-
Drying (RSM optimization)	60-30	77	85	3	0.86
	30-25	90	78	1.33	0.90
	25-20	71	78	1.80	0.57
	20-15	90	78	2.1	0.86
	15-10	90	70	3	0.74
Conditioning	10	80	78	3	-
Cooling	10	30	-	-	-

The Box-Wilson Central Composite Experimental Design was generated using Design-Expert V9 (Stat-Ease, Inc.) software. The experimental plan included 20 runs (combinations of air parameters) for each step of the drying schedule. These combinations were used in Torksim simulations in order to obtain the responses (outputs).

The equations that were used to find the optimum value of air temperature, relative humidity and air velocity are presented in Tables 2 –7.

Table 2

Equations in coded forms that were used to find the optimal values of input variables

MC	Drying time, hours
>30	$Y=16.35 - 6.20*X_1+13.70*X_2-6.10*X_3-3.62*X_1X_2+1.63*X_1X_3\ 4.12*X_2X_3+0.86*X_1^2+7.36*X_2^2+1.36*X_3^2$
30 - 25	$Y =4.76-2.30*X1_1+1.30*X_2-0.60*X_3-0.62*X_1X_2+0.38*X_1X_3-0.37*X_2X_3+0.59*X_1^2+0.59*X_2^2+0.091*X_3^2$
25 - 20	$Y =10.78-6.60*X_1+3.80*X_2-0.90*X_3-2.25*X_1X_2+0.25*X_1X_3-0.50*X_2X_3+1.55*X_1^2+1.55*X_2^2+0.045*X_3^2$
20 - 15	$Y=14.24-17.71*X_1+16.80*X_2-1.40*X_3-13.25*X_1X_2+0.75*X_1X_3-0.75*X_2X_3+5.41*X_1^2+8.91*X_2^2+1.91*X_3^2$
15 - 10	$Y=25.25-7.90*X_1+14.70*X_2-1.50*X_3$

Table 3

Equations in coded forms that were used to find the optimal values of input variables

MC	Energy consumption, kWh/m^3
>30	$Y=370.89-17.60*X_1-13.40*X_2-4.80*X_3+3.38*X_1X_2+0.88*X_1X_3-4.12*X_2X_3+1.27*X_1^2+12.27*X_2^2+4.27*X_3^2$
30 - 25	$Y=61.31-10.61*X_1-15.90*X_2+0.70*X_3+4.50*X_1X_2+4.75*X_1X_3-3.00*X_2X_3+2.73*X_1^2+2.23*X_2^2+8.23*X_3^2$
25 - 20	$Y=70.49-4.30*X_1-12.00*X_2-9.80*X_3+15.25*X_1X_2-8.75-X_1X_3-6.00*X_2X_3+1.77*X_1^2+16.27*X_2^2+4.27*X_3^2$
20 - 15	$Y=79.62-12.90*X_1-10.70*X_2-2.40*X_3-2.25*X_1X_2-0.25*X_1X_3+3.126E-014*X_2X_3+2.95*X_1^2+14.95*X_2^2+2.45*X_3^2$
15 - 10	$Y=95.80-2.10*X_1-16.90*X_2-1.60*X_3+23.38*X_1X_2-0.37*X_1X_3-0.62*X_2X_3$

Table 4

Equations in coded forms that were used to find the optimal values of input variables

MC	Moisture content gradient, %
>30	$Y=2.43+0.28*X_1-0.94*X_2+0.30*X_3-0.13*X_1X_2+0.055*X_1X_3+0.023*X_2X_3+0.11*X_1^2-0.36*X_2^2-0.058*X_3^2$
30 - 25	$Y=2.57+0.14*X_1-0.71*X_2+0.19*X_3-0.059*X_1X_2+0.074*X_1X_3-0.054*X_2X_3+0.18*X_1^2-0.070*X_2^2-0.080*X_3^2$
25 - 20	$Y=5.86+1.00*X_1-2.99*X_2+0.27*X_3-0.35*X_1X_2+0.023*X_1X_3-0.10*X_2X_3$
20 - 15	$Y=5.86+1.11*X_1-3.43*X_2+0.17*X_3+0.053*X_1X_2+0.050*X_1X_3-0.057*X_2X_3+0.16*X_1^2-0.54*X_2^2-0.059*X_3^2$
15 - 10	$Y=2.42+0.48*X_1-2.42*X_2+0.081*X_3-0.44*X_1X_2+0.019*X_1X_3-0.059*X_2X_3+0.087*X_1^2+0.41*X_2^2-0.098*X_3^2$

Table 5

Equations in coded forms that were used to find the optimal values of input variables

MC	Relative stress
>30	$Y=0.18-0.034*X_1-0.17*X_2+0.041*X_3$
30 - 25	$Y=0.31-0.055*X_1-0.065*X_2+9.200E-003*X_3+7.750E-003*X_1X_2-3.750E-003*X_1X_3+2.500E-003*X_2X_3$
25 - 20	$Y=0.30-0.051*X_1-0.068*X_2+0.010*X_3+0.011*X_1X_2-4.625E-003*X_1X_3+1.125E-003*X_2X_3$
20 - 15	$Y=0.27*0.038*X_1-0.070*X_2+8.000E-003*X_3+9.250E-003*X_1X_2-1.500E-003*X_1X_3-2.500E-004*X_2X_3$
15 - 10	$Y=0.21-0.029*X_1-0.074*X_2+6.200E-003*X_3+0.019*X_1X_2-1.750E-003*X_1X_3+7.375E-017*X_2X_3$

Table 6

Equations in coded forms that were used to find the optimal values of input variables

MC	Slicing test, mm
>30	$Y=0.057-6.000E-003*X_1-0.21*X_2+0.11*X_3-1.250E-003*X_1X_2-0.014*X_1X_3-0.12*X_2X_3-0.046*X_1^2+0.20*X_2^2-0.016*X_3$
30 - 25	$Y=1.92-0.037*X_1-1.29*X_2+0.24*X_3$
25 - 20	$Y=4.02+0.11*X_1-1.69*X_2+0.13*X_3+0.10*X_1X_2-0.035*X_1X_3-7.500E-003*X_2X_3-0.22*X_1^2-0.22*X_2^2-0.052*X_3^2$
20 - 15	$Y=3.57+0.45*X_1-1.71*X_2+0.11*X_3+0.14*X_1X_2+0.019*X_1X_3-0.016*X_2X_3+0.055*X_1^2-0.38*X_2^2-0.030*X_3^2$
15 - 10	$Y=1.80+0.23*X_1-1.41*X_2+0.056*X_3$

Table 7

Equations in coded forms that were used to find the optimal values of input variables

MC	Drying cost, EUR / % of evaporated water
>30	$Y=0.20-0.088*X_1+0.14*X_2-0.060*X_3-0.041*X_1X_2+0.016*X_1X_3-0.059*X_2X_3+0.014*X_1^2+0.094*X_2^2+0.014*X_3^2$
30 - 25	$Y=0.28-0.18*X_1+0.12*X_2-0.023*X_3-0.061*X_1X_2+0.014*X_1X_3-0.011*X_2X_3+0.049*X_1^2+0.034*X_2^2+8.636E-003*X_3^2$
25 - 20	$Y=0.62-0.58*X_1+0.50*X_2-0.040*X_3-0.33*X_1X_2+0.015*X_1X_3-0.030*X_2X_3+0.15*X_1^2+0.23*X_2^2+0.022*X_3^2$
20 - 15	$Y=0.83-2.50X_1+2.67*X_2-0.076*X_3-2.48*X_1X_2+0.053*X_1X_3-0.063*X_2X_3+0.79*X_1^2+1.55*X_2^2+0.48*X_3^2$
15 - 10	$Y=2.63-3.56*X_1+7.38*X_2-0.25*X_3-3.21*X1_1X_2+0.073*X_1X_3-0.27*X_2X_3-0.84*X_1^2+7.96*X_2^2-1.84*X_3^2$

The comparison among methods was firstly performed based on a single criterion, namely:

- drying rate;
- drying cost;
- moisture content gradient;
- slicing test gap;
- energy consumption;

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- maximum relative stress.

Secondly, the comparison among methods was performed based on a multiple-criteria analysis:
- short time (high drying rate);
- low drying cost;
- high quality (low moisture content gradient, low casehardening degree and low relative stress);

The minimum difference detected by the design during the analysis is presented in Table 8.

Table 8

Criterion and minimum difference to be detected by the Design Expert software

Criterion	Difference to detect
Drying rate, %/h	0.1
Drying cost, EUR / m^3	1
Casehardening degree, mm	0.5
Moisture content gradient, %	0.5

RESULTS AND DISCUSSION

The relative humidity of air that was revealed by RSM is higher than for all other classical methods when the moisture content of wood (MC) is below 35% (Fig. 1). Also, one can observe that RSM proposes the use of a high relative humidity of air for wood with green moisture content.

Regarding the temperature of air (Fig. 2), one can observe that the temperature of air indicated by RSM is in the same range with the temperature recommended by other methods when MC is below 50% and higher than the temperature proposed by other methods when the moisture content of wood is above 50%.

The moisture content evolution in the case of the drying schedule developed by means of RSM is in range with the other methods when MC is higher than 25% and is outside the range when the MC is lower than 25% (Fig.3). Therefore, a longer drying time is obtained compared to other methods.

The cost of drying process is in range with that obtained from other methods when MC is higher than 30% (Fig.4) and higher than that obtained from other methods when the MC is below 30%.

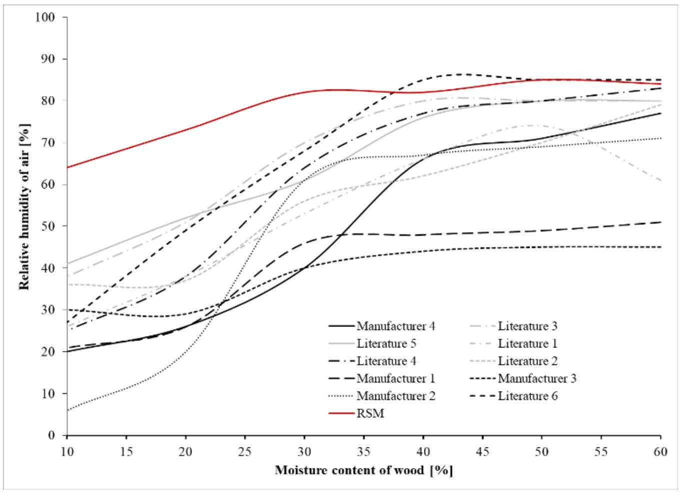

Fig. 1.
Evolution of air relative humidity according to various methods used to develop a drying schedule.

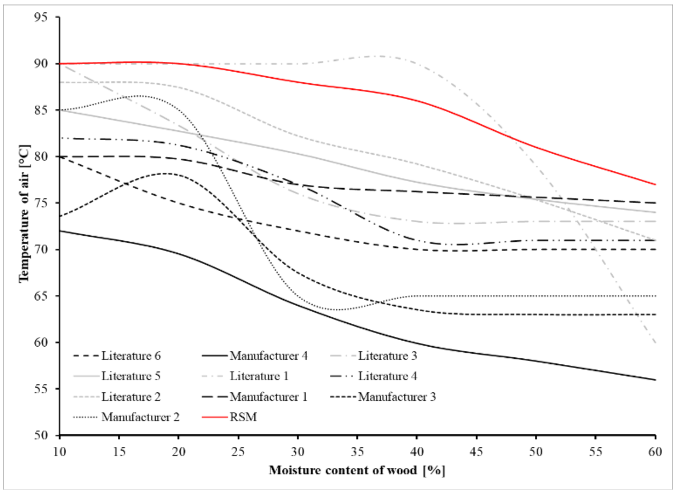

Fig. 2.
Evolution of air temperature according to various methods used to develop a drying schedule.

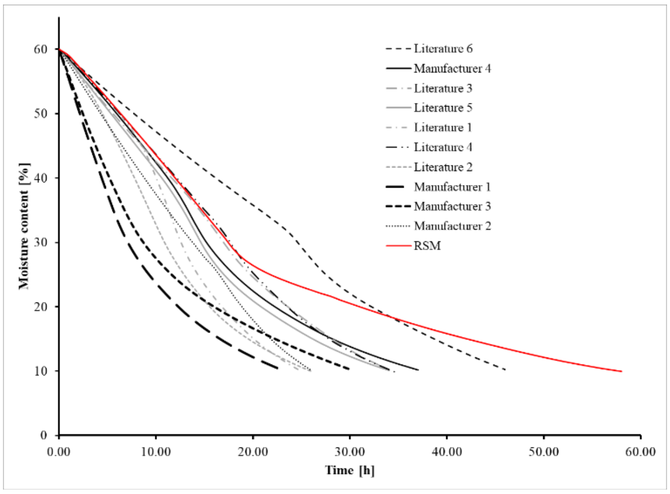

Fig. 3.
Evolution of moisture content of wood according to various approaches used to develop a drying schedule.

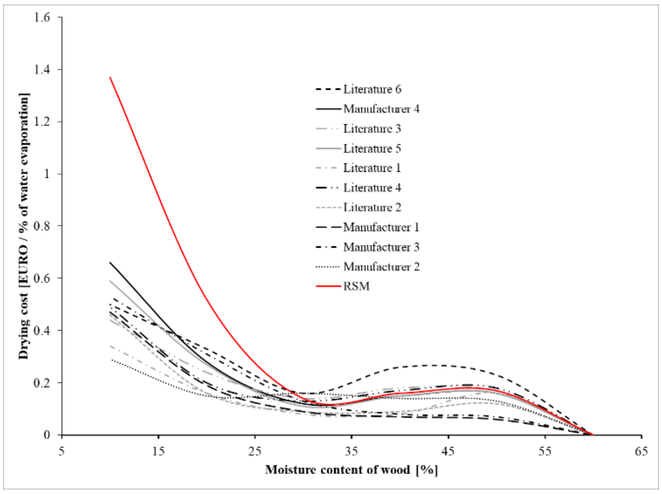

Fig. 4.
Evolution of drying cost of wood according to various approaches used to develop a drying schedule.

According to the single criterion comparison method, the drying schedule developed by means of RSM has the lowest drying rate (the longest drying time), as shown in Fig.5. Regarding the energy consumption it can be observed that the drying schedule developed by means of RSM led to an energy consumption that is in the range with that obtained from other methods (Fig. 6).

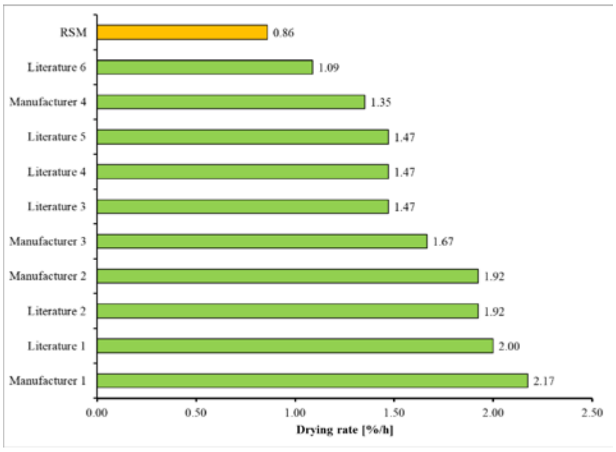

Fig. 5.
Drying rate of wood according to various approaches used to develop a drying schedule.

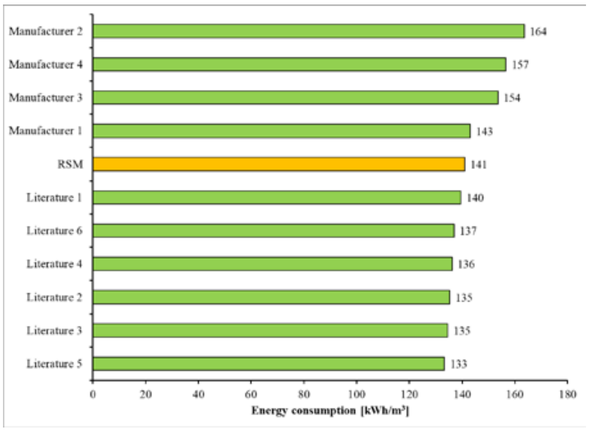

Fig. 6.
Energy consumption according to various approaches used to develop a drying schedule.

Also, a lower MC gradient could be obtained at the end of the drying process when the drying schedule is developed by means of RSM (Fig. 7). However, in practice it is almost improbably to achieve it. Moreover, one can observe that the RSM assures a relative stress that is in the range with that given by other methods (Fig. 8). Therefore, drying based on a schedule developed by RSM will not cause surface checks due to the fact that the relative stress is below 0.33, which is a threshold value in Torksim. In addition, the RSM allowed the obtaining a lower casehardening degree, comparative to other methods (Fig. 9).

Drying according to a RSM drying schedule is the most expensive comparative to other methods. This is in agreement with the high drying time and high quality we obtained. However, this is not desirable in practice.

According to the multiple-criteria analysis, RSM could not simultaneously fulfill all the criteria that were imposed (Fig.11). The desirability coefficient has in this case the lowest value. However, none of the analyzed methods had the maximum desirability coefficient (D=1). Therefore, more research is required in order to optimize the drying process according to industrial needs.

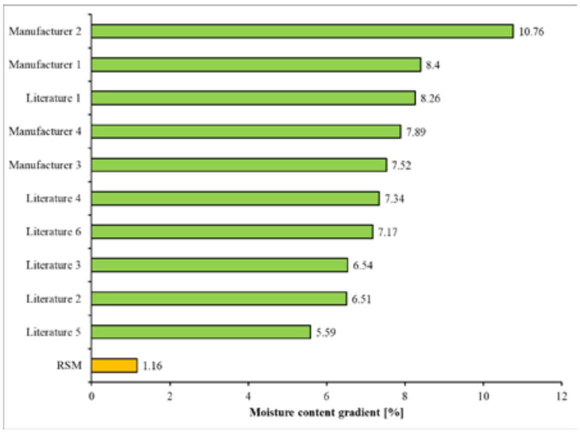

Fig. 7.
Moisture content gradient according to various approaches used to develop a drying schedule.

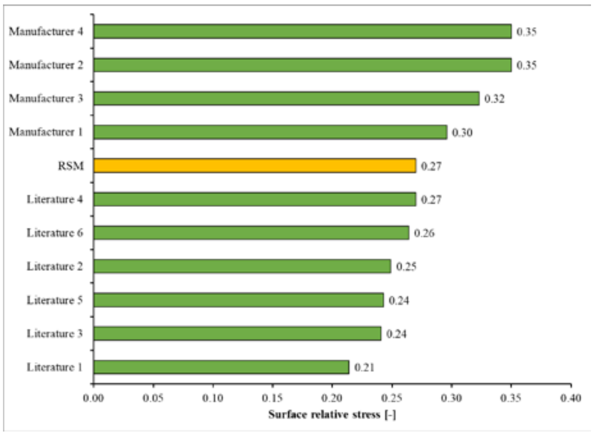

Fig. 8.
Relative stress according to various approaches used to develop a drying schedule.

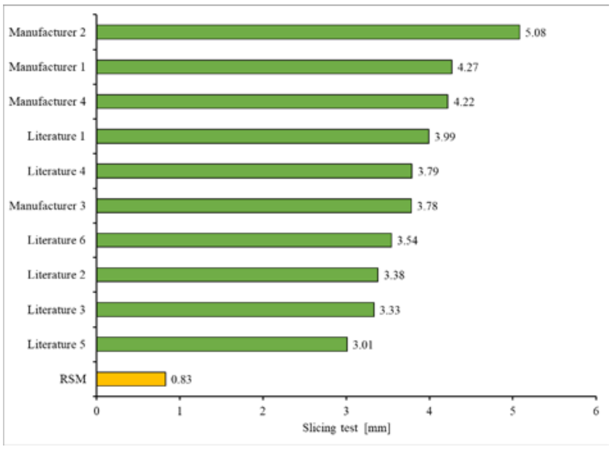

Fig. 9.
Slicing test values according to various approaches used to develop a drying schedule.

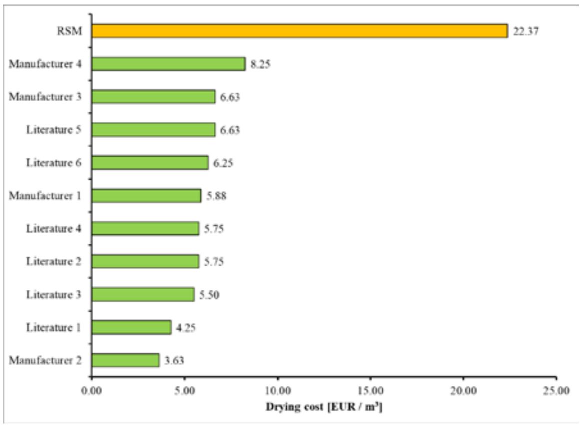

Fig. 10.
Drying cost according to various approaches used to develop a drying schedule.

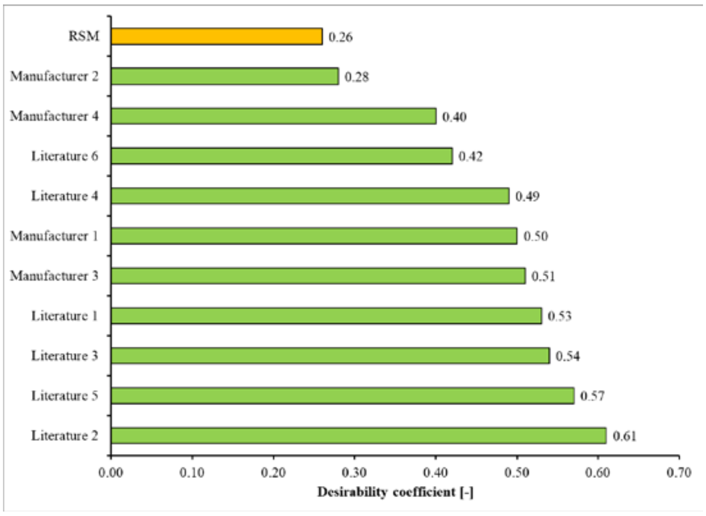

Fig. 11.
The desirability coefficient according to various approaches used to develop a drying schedule.

CONCLUSIONS

The results obtained within the present research demonstrated that

- drying with RSM is not economically viable;
- assembling a drying schedule with RSM is time consuming;
- RSM ensures high quality of dried wood;

Future research is needed to find a method that fulfils all optimization criteria. Narrower ranges of air parameters and wood moisture contents can be considered in developing future drying schedules.

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