Application of Response Surface Methodology to Optimization of Wood Drying Conditions in a Pilot-Scale Kiln

DANIELA SOVA[1], BOGDAN BEDELEAN[2*] AND VENETIA SANDU[1]

[1]Department of Mechanical Engineering, TRANSILVANIA University of Brasov, 1 Politehnicii Str., 500024 Brasov, Romania.

[2] Department of Wood Processing and Wood Products Design, TRANSILVANIA University of Brasov, 1 Universitatii Str., 500068 Brasov, Romania.

** Corresponding author: bedelean@unitbv.ro, phone number: 004/0268415315*

Sova, D., Bedelean, B.* and Sandu, V. 2016. Application of Response Surface Methodology to Optimization of Wood Drying Conditions in a Pilot-Scale Kiln. *Baltic Forestry* 22(2): 348-356.

Abstract

The aim of this study was to investigate the effectiveness of the application of design tools such as Composite Central Design (CCD) and Response Surface Methodology (RSM) in modeling and optimization of spruce drying. The models were developed based on drying simulation in a pilot-scale kiln. Optimization assumed three criteria, namely, minimization of drying time, energy consumption and drying stress. In addition, the influence of air parameters (temperature, relative humidity and velocity) on time, energy consumption and drying stress was analyzed. Optimal process parameters were obtained (3 m/s velocity, 72 °C temperature, 44% relative humidity) using the desirability function approach. The temperature was the most important factor that affected all responses. The second important one was the relative humidity of air and the last important one was the air velocity. The interaction between temperature (T) and relative humidity (RH) on responses was stronger than the other interactions (T vs. V, RH vs. V).

Keywords: convective drying, spruce, drying simulation, composite central design, response surface methodology.

Introduction

Convective wood drying is one of the most important steps in wood products manufacturing because it enhances wood mechanical and technological properties. It also ensures the protection of wood against insect and fungal attack.

How fast the wood reaches the target moisture content is a function of the aggressiveness of the drying schedule and the kiln design. The former makes the difference when the kilns have the same design.

Choosing the right drying schedule is a difficult task. For example, an aggressive schedule could lead to short drying time, but the stress developed inside wood could be strong enough to produce defects like surface and end checks, honeycomb and deformation. On the other hand, a mild drying schedule might lead to a longer residence time than needed and therefore, to a lower drying stress. Consequently, there is a trade-off between residence time and quality of dried wood, when a drying schedule is going to be developed (Pérre and Olek 2007).

A drying schedule consists in three parameters, namely, temperature, relative humidity and velocity of air. The role of temperature is to stimulate the water evaporation from wood. Its value is chosen as function of species and moisture content of wood in order to avoid stress during drying. Relative humidity is another key parameter of the convective drying process. This is due to the fact that a too low relative humidity leads to a high degree of stress inside wood, which has as result a poor quality of the dried wood. On the other hand, a too high relative humidity leads to an extension of timber residence time. However, a too high relative humidity could support the growth of mould, and/or, discolourations, e.g. blue stain, as pointed out by Perré and Olek (2007). The role of the air velocity is the most important until the moisture content of wood decreases below the fiber saturation point (FSP), which is roughly 30% for most species.

Drying schedules are developed based on both trial-and-error approach and experimental tabulated data. One method is that proposed by Terazawa (1965) cited by Ofori and Brentuo (2010), which assumes to dry wood samples in oven at 100 °C. During this time, the samples are monitored in order to observe possible drying defects (end checks, cross-sectional deformations and honeycomb). Based on tabulated data, the critical drying condi-

tions are figured out. Another method is that developed at the Forest Products Laboratory and supposes to choose the values of air parameters from tabulated data that were experimentally obtained (Simpson 1991). Furthermore, Truebswetter's method can be used to assembly a drying schedule using some tabulated guidelines and taking into account the critical moisture content of each species (Truebswetter 2006). One can find a short description of other methods applied to develop a drying schedule within the chapter written by Pérre and Keey (2006).

Currently, the Response Surface Methodology (RSM), which is a class of designs of experiments, has been widely applied to drying optimization of food (Diamante and Yamaguchi 2012, Kumar et al. 2014, Dalvand et al. 2014) and drugs (Nekkanti et al. 2009, Miletić et al. 2014). RSM allows the reduction in the number of experiments, which would be necessary to estimate multiple parameters and their interactions. Thus, time and effort are greatly shortened.

The objective of the research reported below was to assess if RSM can be used to find the optimal combination of air parameters in a pilot-scale kiln based on the minimization criteria of drying time, energy consumption and relative stress. The first and third criteria have been usually prioritized before energy consumption reduction (Anderson 2012). However, wood convective drying efficiency must be estimated in all terms, such as drying time, energy consumption and product quality.

Materials and Methods

Drying simulation

Over the years, substantial effort has been devoted by researchers to develop mathematical models in order to better understanding and optimizing the drying process (Stanish 2008). One very practical model (TORKSIM) was developed by Salin (1999) at SP Technical Research Institute of Sweden. It can be used for drying schedule optimization and process improvement.

TORKSIM has been tested against 28 full scale measurements and the measured and simulated final moisture content resulted in a 1.4% standard deviation (Salin 1999, 2010). The program was also tested by Tamme et al. (2011). They validated the results of computer simulation with results from industrial and laboratory drying experiments.

The TORKSIM computer program is based on information regarding wood properties, drying schedule and kiln model and the results consist in drying time, energy consumption and drying costs calculation and quality aspects.

Within this research, convective drying was simulated in a pilot-scale kiln (Figure 1). The pilot-scale kiln is a controlled climate air duct of rectangular section (145×175 mm), comprising a rectangular test section (250×300×1500 mm).

The simulation input data were:

• wood species: spruce (*Picea abies*)

• board thickness: 20 mm

• wood initial moisture contents: 90 % / 60 % / 30 %

• wood target moisture content: 10 %

• drying schedule: the moisture content based drying schedules, constant in time, were used in the drying simulation

• the air velocities were chosen from a range of values commonly used in the industrial kiln for spruce drying (2–3 m/s)

• the air temperature ranged from 50 to 75 °C

• the air relative humidity ranged from 40 to 58 %

• kiln model: the simulation was carried out for a single board drying in the pilot-scale kiln, TORKSIM being based on the same approach.

The simulation output data were:

• drying time: the time for the spruce sample to dry from the initial moisture content (90 %, 60 % and 30 %, respectively) to the average target moisture content (about 10 %).

• energy consumption: it included the energy losses by transmission and with exhaust air, heat accumulated in

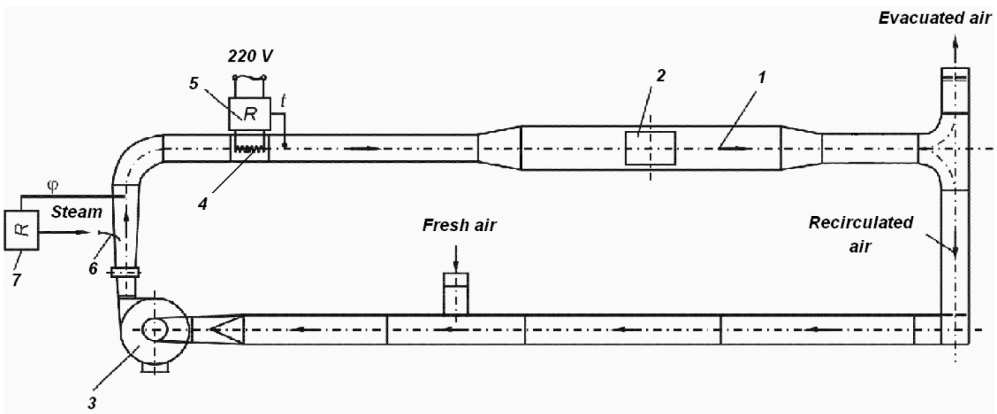

Figure 1. Pilot-scale drying kiln
1 – test section;
2 – door; 3 – centrifugal fan; 4 – electric heater;
5 – automatic temperature adjustment system;
6 – steam injector; 7 – automatic relative humidity adjustment system

different parts and the energy consumed to evaporate the wood moisture.

• relative stress: it indicates the risk of surface checking. The relative stress values calculated by TORKSIM express the stress related to wood tensile strength. Checks start to develop close to the relative stress value 0.33 and increase as the stress increases (Tratek 2008). The maximum relative stress occurred in the surface layer up to the end of the drying time was obtained from the program.

The drying schedule must be developed so that the drying stresses do not exceed the strength of the wood at any given temperature and moisture content (Bergman 2010).

Statistical analysis

The Response Surface Method (RSM) was used to estimate interaction and quadratic effects of input variables on responses. A quadratic fit is appropriate in most of the cases in industry. RSM designs are applied in order to find improved or optimal process settings (NIST/SEMATECH 2013). One can find more details about theoretical bases of modeling using RSM in Whitcomb and Anderson (2005). The three input variables were temperature, velocity and relative humidity of air and the responses were drying time, energy consumption and relative stress. The input variables were selected from the drying schedule range of parameters according to the requirements of the experimental design (Box-Wilson Central Composite Design, simply called CCD), which was used in this paper. This experimental design includes five levels of each factor: low axial (-α), low factorial (-1), center (0), high factorial (+1), and high axial (+α), as shown in Figure 2. The coded and actual values for each factor are presented in Table 1. The number of runs required by CCD for a number of 3 factors was 20 (Table 2).

This experimental design allows the estimation of a second-order polynomial equation:

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

where Y represents the response (output), X_i are the main effects (inputs), X_iX_j are variables interactions, X_i^2 are quadratic effects and b are coefficients. 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) were performed for coefficients assessment and in order to determine the significance of model parameters for each variable. ANOVA includes the F-value, which indicates the statistical significance at 1% and 5% levels. The model accuracy was checked by the coefficient of determination. Drying optimization (minimization of drying time, energy consumption and relative stress) was 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. For each response $Y_i(X)$, a desirability function $d_i(Y_i)$ assigns numbers between 0 and 1 to the possible values of Y_i, with $d_i(Y_i) = 0$ representing a completely undesirable value of Y_i and $d_i(Y_i) = 1$ representing a completely desirable or ideal response value. The individual desirabilities are then combined using the geometric mean, which gives the overall desirability, D.

$$D = (d_1(Y_1)d_2(Y_2)\ldots d_k(Y_k))^{1/k} \quad (2)$$

where k denotes the number of responses.

In this case, the goal was to determine the optimal process variables, for which all responses were minimized and the overall desirability maximized. A comparison between predicted and simulated responses was also performed.

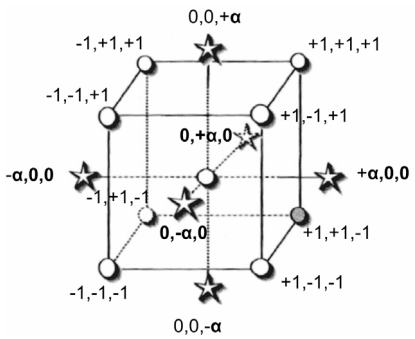

Figure 2. Face-centered central composite design (FCD) (Whitcomb and Anderson 2005)

Table 1. Factors and levels used in the factorial design

	Levels				
Factors	(α = -1.68)	(-1)	0	(+1)	(α = + 1.68)
T, °C	41.47	50	62.5	75	83.52
RH, %	33.86	40	49	58	64.13
V, m/s	1.65	2	2.5	3	3.34

Table 2. Independent process variables in the central composite design and responses

Run no.	T (°C)	RH (%)	V (m/s)	R_1: Drying time (hours)			R_2: Energy consumption (kWh/m^3)			R_3: Stress value (-)		
				30%	60%	90%	30%	60%	90%	30%	60%	90%
1	75	40	2	14	17	20	79	171.7	267.2	0.32	0.31	0.31
2	62.5	64.1	2.5	64	69	71	105	197.3	287.3	0.32	0.31	0.31
3	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
4	50	40	2	41	47	50	99	215.7	330.7	0.43	0.43	0.42
5	50	58	2	88	95	97	109.8	211.4	310.5	0.38	0.37	0.37
6	75	58	3	20	24	26	77.9	166.6	252.8	0.29	0.29	0.28
7	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
8	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
9	62.5	49	1.65	30	36	40	87.5	185.7	282.7	0.34	0.34	0.33
10	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
11	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
12	75	58	2	21	26	30	78	167.6	256.3	0.28	0.28	0.27
13	62.5	49	2.5	28	32	35	86	182.6	279.4	0.36	0.35	0.35
14	41.47	49	2.5	84	90	92	106.6	222.2	336.5	0.47	0.46	0.45
15	83.52	49	2.5	11	14	16	71.7	159	245.0	0.27	0.27	0.27
16	75	40	3	13	16	18	78	172.6	263.6	0.32	0.32	0.32
17	62.5	33.8	2.5	22	25	27	87.7	196.6	303.8	0.39	0.39	0.38
18	62.5	49	3.34	27	30	32	85.3	181.3	277.1	0.36	0.36	0.36
19	50	40	3	39	48	45	98.4	213.7	328.4	0.45	0.44	0.44
20	50	58	3	84	88	89	108	208.1	306.9	0.40	0.40	0.39

The statistical package Design-Expert Software Version 9 (Stat-Ease Inc.) was used for design of experiments and RSM applications, regression analysis, statistical evaluation of the models, process optimization and graphical representation of the response surface.

Results

Simulation results and Response Surface Modeling

RSM models were developed from simulated data according to CCD (Table 2) for each response. All models were significant at 1 % level. Each factor was analyzed regarding its significance with respect to calculated *p* values. According to ANOVA (Table 3), all main factors were statistically significant at 5 % level excepting velocity in the model developed for energy consumption, when the initial moisture content was equal to 30 % and 60 %, respectively. It might be explained by the fact that at 90 % initial moisture content the drying time is longer and the velocity becomes significant in the model developed for energy consumption.

Regarding interactions between factors, the following remarks can be outlined:

• the interaction between temperature and relative humidity was statistically significant in what concern the models developed for time and relative stress for each initial moisture content (90 %, 60 % and 30 %, respectively). This shows that the temperature and relative humidity do not independently act upon the drying process, but there is an interaction between them. Therefore, there can be different combinations that can negatively or positively influence the drying time and/or the drying stress that develop in wood. Anyway, the effect of this interaction is less strong than the individual effects of both parameters (Table 3). The interaction between temperature and relative humidity was statistically significant for the model developed for energy consumption only when the green moisture content was 90 %. In any case, the combined action of both parameters on the energy consumption has lesser effect at this initial moisture content than the individual action of each parameter. As regards the other initial moisture contents (30 % and 60 %), the interaction between temperature and relative humidity has no influence on energy consumption, the individual influence being dominant (Table 3).

• the interaction between temperature and velocity was significant for the model developed for drying time when the green moisture content was 90 %. This effect shows that for a certain combination of temperature and velocity a reduction in the drying time can be acquired

if the initial moisture content is 90 %. The effect of this interaction is lesser than the effect of each parameter and than the effect of the interaction between temperature and relative humidity (Table 3 and Figure 3). Also, this interaction was significant for the model developed for relative stress regardless of the initial moisture content. Again, some combinations of temperature and velocity can positively or negatively influence the drying stress that develop during drying for all three initial moisture contents that were analyzed. The effect of this combination is lesser as compared to the effect of each parameter and to the interaction between temperature and relative humidity in the drying stress model.

• the interaction between relative humidity and velocity was significant only for the model developed for drying time, when the initial moisture content was 60 % and 90 %, respectively. This means that a certain combination between relative humidity and velocity can reduce the drying time, when the initial moisture is 60 % and 90 %, respectively. Anyway the effect of this combination is lesser than that of the interaction between temperature and relative humidity (Table 3). Also, the individual effect of both parameters is more important. At 60 % initial moisture content, the interaction between relative humidity and velocity is stronger than the interaction between temperature and velocity.

The quadratic effects of temperature and relative humidity were statistically significant at 5 % level in the drying time, energy and relative stress models. An exception was the energy model, whose quadratic effect of temperature was not significant for the initial moisture content of 30 %. The quadratic effect of velocity was statistically significant only for the relative stress model, when the initial moisture content was equal to 60 % and 90 %, respectively. This effect is less strong than the quadratic effects of temperature and relative humidity (Table 3).

The regression coefficients of the second-order polynomial equations for the process variables and the coefficients of determination are indicated in Table 4.

The coefficients of determination are high, very close to 1, showing that a high percent of the data is close to the regression of best fit.

The effects of the process variables on responses are illustrated in Figures 3, 4 and 5. They show the three-dimensional response surfaces and the effects of different two factors on responses.

Drying time was mostly influenced by temperature, which had a quadratic effect, considerably decreasing with temperature increase, but slightly increasing with increasing initial moisture content (Figure 3 and Table 4). The relative humidity was the second factor that influenced the drying time. The increase of relative humidity had a negative effect on drying time raising with the growth in initial moisture content. High relative humidity slows down the moisture evaporation process, increasing the drying time. The influence of velocity was less important. The results of

Table 3. ANOVA results of different models (in terms of coded factors)

Variables / factors	*F* - value								
	R_1: Drying time			R_2: Energy consumption			R_3: Relative stress		
	30%	60%	90%	30%	60%	90%	30%	60%	90%
Model	1430 ***	700 ***	3964 ***	58 ***	145 ***	282 ***	2389 ***	1508 ***	2227 ***
A: temperature	8115 **	4108 **	22756 **	427 **	1203 **	2264 **	18568 **	11527 **	16274 **
B: relative humidity	2690 **	1263 **	7689 **	38 **	5.5 **	123 **	2536 **	1749 **	2827 **
C: velocity	14 **	14 **	241 **	1	2.57	7.46 **	176 **	154 **	275 **
AB interaction	895 **	339 **	2088 **	12	0.001	10.1 **	20 **	21 **	53 **
AC interaction	2.36	0.61	19 **	0.04	0.73	0.03	13 **	12 **	16 **
BC interaction	0.59	5.45 **	9.8 **	0.002	0.27	0.03	0.83	1.6	3.3
A^2 : quadratic effect	788 **	397 **	2020 **	4.34	25 **	48.3 **	162 **	78 **	92.81 **
B^2: quadratic effect	463 **	225 **	1093 **	44.49 **	80 **	97.07 **	10 **	8.6 **	21.71 **
C^2: quadratic effect	0.16	1.4	4.71	0.11	0.36	0.15	3.65	8.6 **	14.38 **

*** statistically significant at $\alpha = 0.01$ level ** statistically significant at $\alpha = 0.05$ level the values without asterisk are not statistically significant

Table 4. Regression coefficients of the polynomial models for process variables (in coded factors)

Variables / Factors	Estimated coefficients								
	R_1: Drying time			R_2: Energy consumption			R_3: Relative stress		
	30%	60%	90%	30%	60%	90%	30%	60%	90%
Constant	28.01	31.99	35	85.99	182.6	279.39	0.36	0.36	0.35
T	-22.46	-23.64	-23.05	-11.79	-20.26	-28.59	-0.057	-0.056	-0.05
RH	12.93	13.11	13.40	3.54	-1.38	-6.67	-0.021	-0.022	-0.02
V	-0.96	-1.40	-2.38	-0.59	-0.94	-1.64	0.005	0.006	0.006
T x RH	-9.75	-8.88	-9.12	-2.59	-0.02	2.50	0.002	0.003	0.004
T x V	0.50	0.38	0.88	0.16	0.65	-0.15	-0.002	-0.002	-0.002
V x RH	-0.25	-1.12	-0.63	-0.037	-0.40	-0.15	0.0005	0.0008	0.001
T^2	6.82	7.15	6.69	1.16	2.85	4.07	0.005	0.004	0.003
RH^2	5.22	5.39	4.92	3.70	5.10	5.76	-0.001	-0.0015	-0.0019
V^2	0.098	0.44	0.32	0.18	0.34	0.23	-0.0007	-0.0015	-0.0015
Predicted R^2	**0.99**	**0.98**	**0.99**	**0.85**	**0.94**	**0.97**	**0.99**	**0.99**	**0.99**

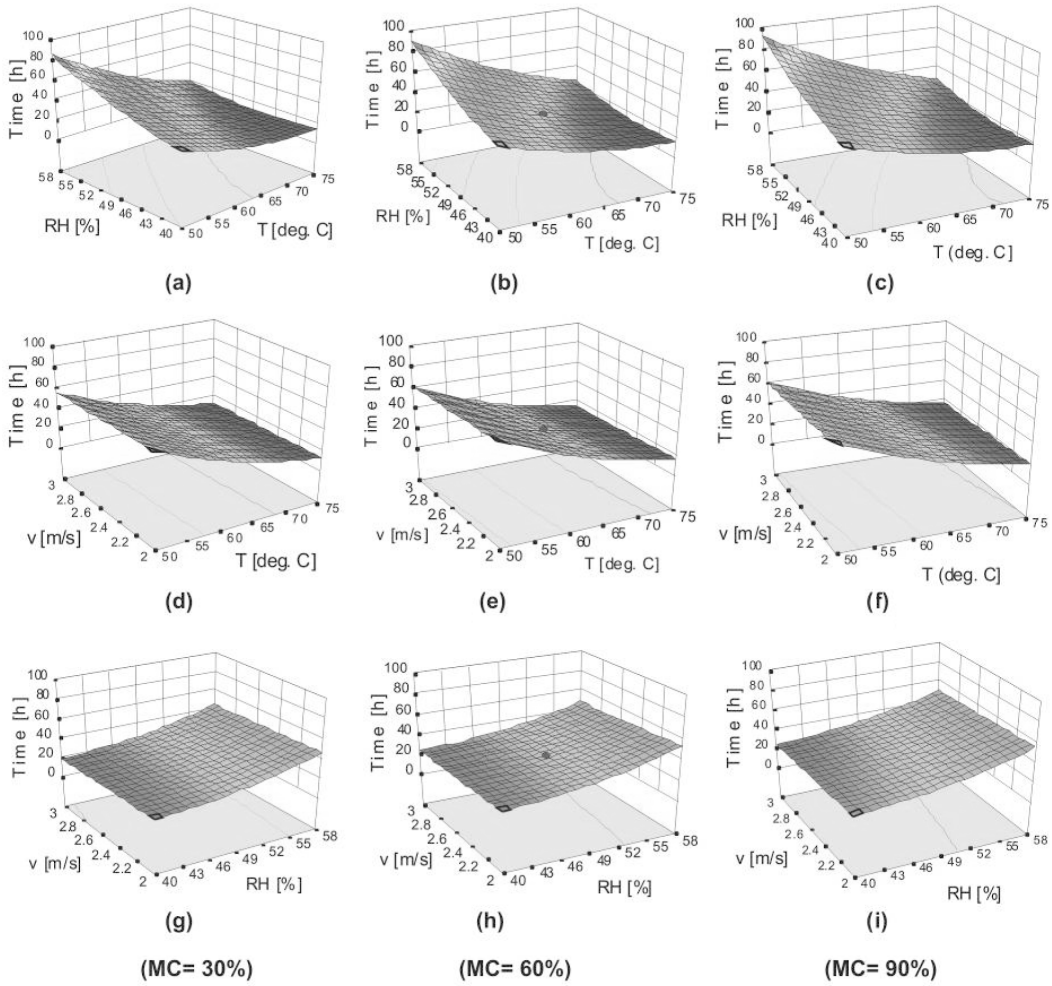

Figure 3. Response surface plot showing effects of drying parameters on drying time: (a, b and c) temperature and relative humidity at 2.5 m/s air velocity; (d, e and f) temperature and velocity at 49 % air relative humidity; (g, h and i) velocity and relative humidity at 62.5 °C air temperature

research show that fast drying is achieved in kilns by using temperatures as high as possible and relative humidities as low as possible, as also concluded by Bergman (2010).

The results for energy consumption show also an important effect of temperature on energy consumption through its high coefficient value, decreasing with increasing process temperature, more evidently at higher relative humidity than at lower relative humidity (Figure 4). The decrease is more obvious at 30 % initial moisture content. Contrarily to drying time, the energy consumption slightly decreased with increasing relative humidity at 60 % and 90 % initial moisture contents. At 30 % initial moisture content, energy consumption sharply decreased with relative humidity decrease. The latter is in agreement with the statement that low relative humidity stimulates diffusion by lowering the moisture content at the surface, increasing the diffusion rate (Bergman 2010). As the moisture evaporation slows down, the heat required for moisture evaporation decreases. Both, temperature and relative humidity influenced the energy consumption due to the quadratic effects. Velocity was not a significant parameter for energy consumption

The analysis of the process parameters on relative stress indicated that temperature had important influence on relative stress, while velocity and relative humidity were not important parameters. Drying stress decreased with increasing temperature, more obviously at higher relative humidity than at lower relative humidity, at all initial moisture contents (Figure 5). The results are in agreement with the statement that temperature is the most important processing factor because it can be responsible for defects in each defect category (Bergman 2010).

Optimization

The Design-Expert Software generated a hierarchical range of process parameters and responses, where all responses were equally weighed. The optimal solutions with the highest calculated overall desirability are shown in Table 5. A new TORKSIM simulation was performed with the optimal parameters and the results were comparable to those predicted by the model, confirming good predictability and validity of the model applied in the experimental design.

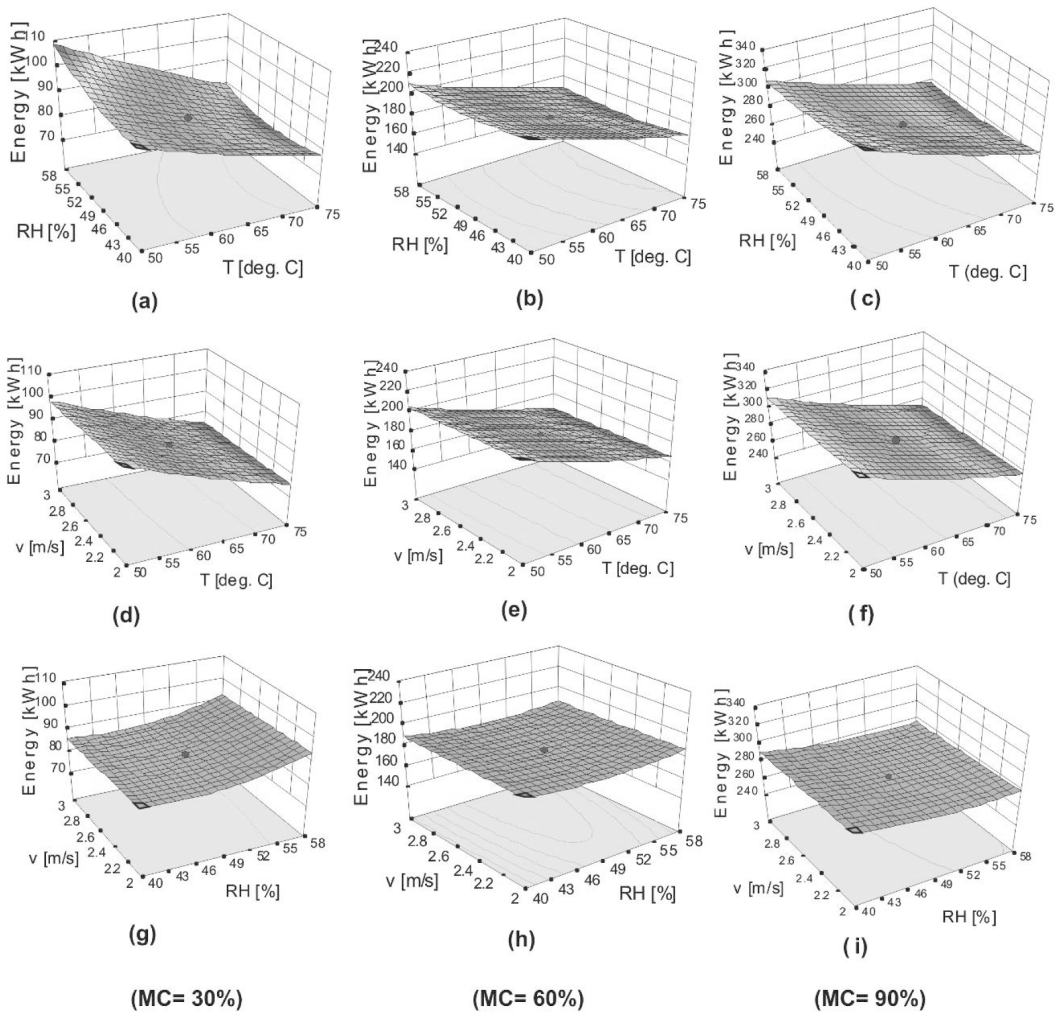

Figure 4. Response surface plot showing effects of drying parameters on energy consumption: (a, b and c) temperature and relative humidity at 2.5 m/s air velocity; (d, e and f) temperature and velocity at 49 % air relative humidity; (g, h and i) velocity and relative humidity at 62.5 °C air temperature

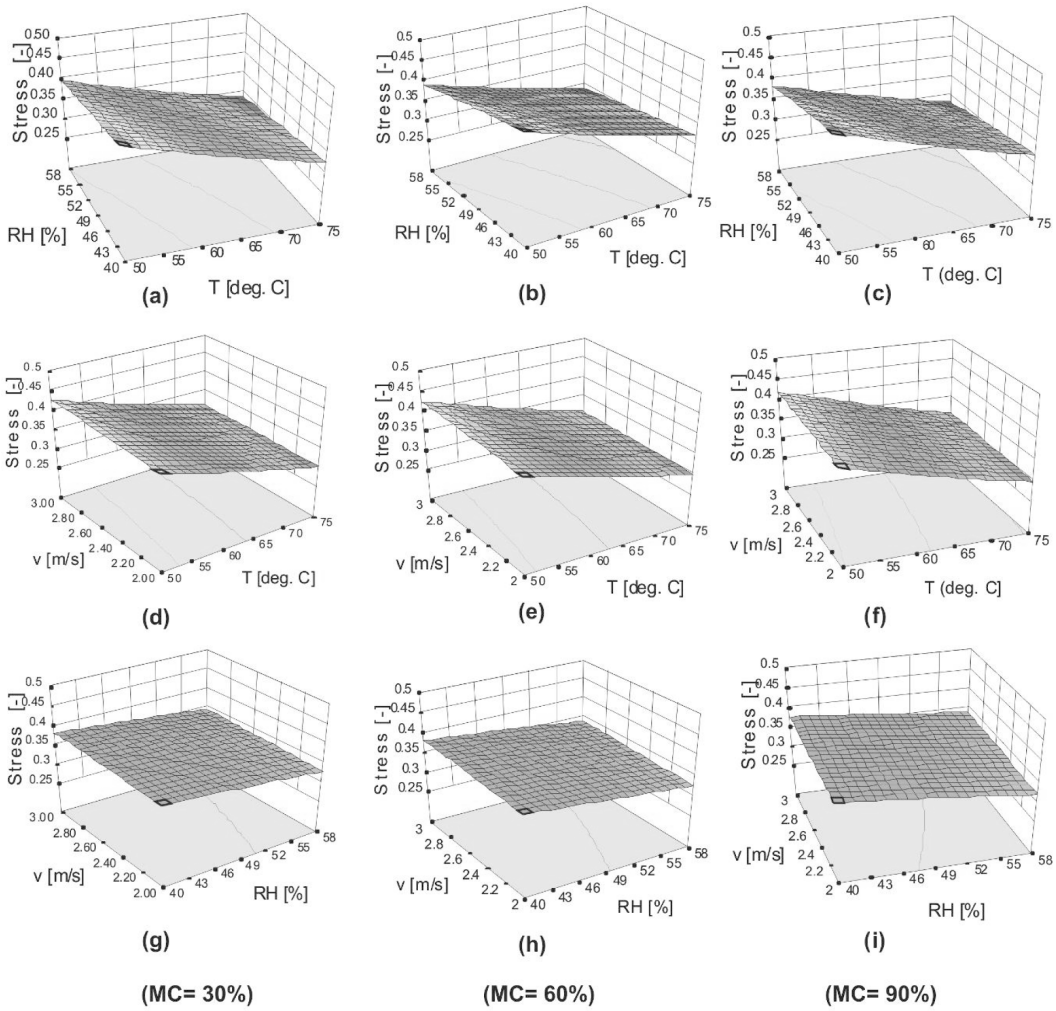

Figure 5. Response surface plot showing effects of drying parameters on relative stress: (a, b and c) temperature and relative humidity at 2.5 m/s air velocity; (d, e and f) temperature and velocity at 49 % air relative humidity; (g, h and i) velocity and relative humidity at 62.5 °C air temperature

Table 5. Optimal air parameters and responses

MC		Air temperature (°C)	Air relative humidity (%)	Air velocity (m/s)	Drying time (hours)	Energy consumption (kWh/m³)	Relative stress (-)	Desirability (-)
30%	Polynomial model prediction	72.74	43.82	3	12.76	77.26	0.330*	0.94
	TORKSIM simulation				16	77.6	0.329	-
	Relative error (%)				20	0.4	0.3	-
60%	Polynomial model prediction	71.96	44.60	2.96	16.21	170.85	0.330*	0.92
	TORKSIM simulation				20	171.6	0.333	-
	Relative error (%)				19	0.44	0.9	-
90%	Polynomial model prediction	71.44	44.38	3	18.59	263.6	0.330*	0.91
	TORKSIM simulation				22	265	0.330	-
	Relative error (%)				15.5	0.52	0	-

*The relative stress requirement was to be equal with 0.33

Conclusions and Discussion

Drying simulations of spruce were performed for a pilot-scale kiln by varying the process variables: air velocity (2-3 m/s), air temperature (50-75 °C) and air relative humidity (40-58 %), according to the Box-Wilson Central Composite Design. The drying parameters were optimized based on three optimization criteria, namely, minimization of drying time, energy consumption and drying stress. The air temperature had the most significant effect on all drying results. The temperature increase resulted in the decrease of all drying responses. The velocity played a minor role. Also, the interaction between temperature and relative humidity on responses was stronger than the other interactions. The nonlinear effect of temperature was more important than the effect of relative humidity for drying time and stress. For energy consumption, the nonlinear effect of relative humidity was more important than the effect of temperature. The average air parameters of 3 m/s velocity, 72 °C temperature and 44 % relative humidity were found optimum for convective drying of spruce, when the initial moisture contents were 30 %, 60 % and 90 %, respectively. The optimum response values obtained from simulation and polynomial model prediction were very close, showing that RSM provides valuable information, which improves the understanding of the process developed in a pilot-scale model.

Acknowledgement

We acknowledge the National University Research Council for its support through the research project PNII-PCE, ID_851: The application of the irreversible processes thermodynamics method to the optimization of the capillary-porous materials drying process.

References

Anderson, **J.-O**. 2012. Improving energy use in sawmills: from drying kilns to national impact. Licentiate thesis, December 2012, Luleå University of Technology, Sweden. 67 pp.

Bergman, R. 2010. Drying and control of moisture content and dimensional changes. In: R.J. Ross (Editor) Wood handbook– Wood as an engineering material. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, p. 13.1-13.20.

Dalvand, M. J., Mohtasebi, S. S. and Rafiee, S. 2014. Modeling of electrohydrodynamic drying process using response surface methodology. *Food Science and Nutrition*. 2(3): 200-209.

Diamante, L. M. and Yamaguchi, Y. 2012. Response surface methodology for optimisation of hot air drying of blackcurrant concentrate infused apple cubes. *International Food Research Journal* 19 (1): 353-362.

Kumar, D., Prasad, S. and Murthy, G. S. 2014. Optimization of micro-wave-assisted hot air drying conditions of okra using response surface methodology. *Journal of Food Science and Technology* 51(2): 221-232.

Miletić, T., Ibrić, S., and Đurić, Z. 2014. Combined application of experimental design and artificial neural networks in modeling and characterization of spray drying drug: cyclodextrin complexes. *Drying Technology* 32 (2): 167-179.

N**ekkanti**, **V., Muniyappan, T., Karatgi, P., Hari, M.S., Marella, S. and Pillai, R.** 2009. Spray-drying process optimization for manufacture of drug-cyclodextrin complex powder using design of experiments. *Drug Development and Industrial Pharmacy* 35(10): 1219-1229.

NIST/SEMATECH. e-Handbook of Statistical Methods.
Available online at: http://www.itl.nist.gov/div898/handbook/. (Last updated: 10/30/2013).

Ofori, J. and Brentuo, B. 2010. Drying characteristics and development of kiln drying schedules for the wood of *Alstonia boonei*, *Antrocaryon micraster*, *Bombax buonopozense*, *Dialium aubrevillei* and *Sterculia rhinopetala. Ghana J. Forestry* 26:50-60. Available online at: https://www.fornis.net/system/files/drying_characteristics.pdf.

Perre, P. **and Keey, R**. 2006. Drying of wood: principles and practice. In: A.J. Mujumdar (editor) Handbook of Industrial Drying, 3rd ed., Dekker, New York, p. 821-877.

Pérre, P. and Olek, W. 2007. From fundamentals to practice: the interaction chain. In: P. Pérre (Editor) Fundamentals of Wood Drying. A.R.BO.LOR., Nancy, p. 1-20.

Salin, **J. G.** 2010. Problems and solutions in wood drying modeling: history and future. *Wood Material Science and Engineering* 5(2): 123-134.

Salin, J.-G. 1999. Simulation models: from a scientific challenge to a kiln operator tool. In: 6th International IUFRO Wood Drying Conference, Stellenbosch, South Africa, p. 177-185.

Simpson, **W.T**. 1991. Kiln Schedules. In: Boone and Simpson (editors) USDA Agricultural Handbook AH-188: Dry Kiln Operator's Manual, Forest Product Laboratory, Madison, P. 133-177. Available online at: http://www.fpl.fs.fed.us/documnts/usda/ah188/chapter07.pdf.

Sova, D., Ungureanu, V.B. and Postelnicu, A. 2012. The laboratory wood drier. From theory to practice. *Pro Ligno* 8 (1): 15 – 27.

Stanish, **M.A.** 2008. Application of wood drying simulation models in commercial lumber manufacturing. *Drying Technology* 26 (9):1089-1096.

Tamme, V., Muiste, P., Mitt, R. and Tamme, H. 2011. Determination of effective diffusion coefficient stress of pine wood during convective drying. *Baltic Forestry* 17(1):110-117.

Tratek. 2008. TORKSIM v.5.0. User manual and instructions for evaluation of calculated results, SP Technical Research Institute of Sweden, 32 pp.

Truebswetter, **T**. 2006. Holztrocknung [Wood drying]. Fachbuchverlag, Leipzig, 204 pp. (in German).

Whitcomb, P.J. and Anderson, M.J. 2005. RSM Simplified. Optimizing processes using response surface methods for designing of experiments. CRC Press, Taylor & Francis Group, Boca Raton, USA. 304 pp.

Received 20 April 2015
Accepted 30 September 2016