Norway Spruce (*Picea abies* [L.] Karst.) as a Bioresource: Evaluation of Solid Wood, Particleboard, and MDF Technological Properties and Formaldehyde Emission

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Norway spruce (*Picea abies* [L.] Karst.) is an important forest species, comprising approximately 55.9% of the growing stock of Czech forests. The variations in the wood densities from three different locations were evaluated with respect to their mechanical and physical properties. Also, mechanical properties and formaldehyde emission of particleboard (PB) and medium-density fibreboard (MDF) panels produced from Norway spruce wood were investigated. The overall average density of the spruce wood was 509.22 kg/m^3, ranging from 400.95 ± 27.92 to 617.50 ± 29.91 kg/m^3 by location. Most of the panels exceeded the requirements of EN standards for the measurements of MOE, MOR, and the internal bond. Furthermore, the results showed highly significant differences ($p < 0.001$) among the panels for PB and MDF, which could be related to inter-panel variations. The formaldehyde emissions of PB and MDF were below the E1 emission limits. Moreover, positive correlations were found between the formaldehyde emissions (perforator and gas analysis methods) and board density. The results of this study verify our knowledge of wood density variation as affected by location as well as the age of trees and their relationship to mechanical and physical properties. Consequently, the variation in mechanical properties of the produced panels as well as the formaldehyde emission can further contribute to creating models to predict the quality of the product.

Keywords: Czech Republic; Formaldehyde emission; MDF; Norway spruce; Particleboard; Solid wood

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INTRODUCTION

Norway spruce (*Picea abies* [L.] Karst.), a large, conifer belonging to the family Pinaceae, is the most important commercial species in the Czech Republic. It comprises approximately 44.8% of the area and 55.9% of the growing stock of Czech forests, as reported by the Czech Ministry of Agriculture (2009). Norway spruce is used extensively in particleboard (PB) and medium-density fibreboard (MDF) panels. These products are used widely in the manufacturing of furniture, floor underlayment, and interior decoration (wall and ceiling panelling) for kitchen worktops, refrigerator cabinets, computer tables, shower cabinets, and external cladding.

Previous studies have focused on the properties of spruce wood. For example, Trendelenburg (1937) analysed the distribution of density and compression strength over the stem of wood, finding that spruce had smaller changes in density within its stem than other coniferous woods and that the differences among multiple stems were greater than those within a single stem. Additionally, the strength increased with increasing density, late wood content, and distance from the pith, as well as with decreasing altitude, annual ring width, and height in the stem (Vorreiter 1954). Teischinger and Müller (2006) investigated the effect of an increase in density and decrease in knot area ratio with increasing distance from the pith on the quality of large diameter round spruce wood. The mechanical and physical properties of spruce and their relationship with density have been studied. A clear radial trend was observed for selected wood properties: the density, MOE, and bending MOR increased with increasing distance from the pith and decreasing annual ring width (Sonderegger *et al.* 2008).

Spruce particles and fibres are used in the industrial production of PB and MDF panels. These wood-based panels have been cited throughout the wood industry as a major source of formaldehyde emissions in domestic dwellings. Formaldehyde is considered a dangerous substance, and its concentration in indoor environments is restricted in many countries because of its reactivity, toxicity, and pungent odour (Wang *et al.* 2008; Nemli and Ozturk 2006). With increasing standards of living, concerns about human health and the environment have been raised due to the increasing demand for wood-based panels (Nemli *et al.* 2008; Kim 2009). The International Agency for Research on Cancer (IARC) has established that formaldehyde is undetectable by smell at concentrations of less than 0.1 ppm. At concentrations above 1.0 ppm however, exposure to formaldehyde will produce extreme discomfort (IARC 2004).

Referenced and secondary methods, among others, are used for estimating and measuring formaldehyde emissions from PB, MDF, and other wood-based products, as described in many works (Risholm-Sundman and Wallin 1999; Salem *et al.* 2011a). In previous studies measuring the emission of formaldehyde from wood-based products, a good correlation was found between formaldehyde emissions values obtained from different test methods (Que *et al.* 2007; Park *et al.* 2010; Kim *et al.* 2010; Kim and Kim 2005; Salem *et al.* 2012a).

The E1 emission class adopted in Europe for PB and MDF is ≤0.1 ppm, ≤8 mg/100 g, and ≤3.5 mg/m^2 h as measured by chamber (EN 717-1 2004), perforator (EN 120 1993), and gas analysis (EN 717-2 1994) methods, respectively. However, previous studies demonstrated that low-emission adhesives were insufficient in the production of E1 type PB or MDF (Salem *et al.* 2011a). Thus, all production parameters, including resin type, molar ratio, raw material type or wood species, moisture content (MC) of the board, drying temperature, board density, formaldehyde scavengers, aging, hardener type and amount, coatings, and laminates should be accounted for in the technological properties of the E1 emission class for PB and MDF panels (Salem *et al.* 2011a,b; Nemli and Çolakoğlu 2005; Nemli and Öztürk 2006; Roffael *et al.* 2010; Böhm *et al.* 2012). Other studies have focused on the variations in the measurements of formaldehyde emissions between laboratories, and the results indicated that most of the significant variations were due to differing chamber conditions, such as volume, materials, sampling air, and specific differences in test conditions (Yrieix *et al.* 2010; Salem *et al.* 2012a). However, the differences between measurements from different laboratories remain an important element in determining formaldehyde emissions (Risholm-Sundman and Wallin 1999; Salem *et al.* 2012b).

In this work, the mechanical and physical properties and variations in the wood density for Norway spruce wood from different locations in the Czech Republic were studied. Additionally, the mechanical properties of the PB and MDF panels manufactured using Norway spruce wood were evaluated. The formaldehyde emissions were evaluated using three different test methods: perforator (EN 120 1993), gas analysis (EN 717-2 1994), and European small-scale chamber (EN 717-1 2004).

EXPERIMENTAL

Site Description and Wood Density Measurement

The *P. abies* testing material was sourced from the Černokostelecko region, located approximately 30 km east of Prague, Czech Republic. The forest district belongs to the Czech University of Life Sciences and occupies over 9,986 ha. Its elevation ranges from 210 to 528 m above sea level. The mean annual temperature is 6 to 9 °C, and the mean annual precipitation is 600 to 650 mm. Nine sample trees were selected from three different sites (location 1- approx. 350 m a.s.l., loc. 2- 420 m a.s.l., loc. 3- 320 m a.s.l.; three trees per site). The localities differed in elevation, soil fertility, and tree size.

The first stand, near Jevany village, featured fertile soils and the following tree species composition: 95% spruce, 2% pine, 2% larch, and 1% oak. The average breast-height diameter was 35 cm, and the average height was 31 m. The average age of the felled trees was 106 years.

The second stand, near Krymlov village, was characterised by gley soils and was entirely made up of spruce (100%). The average breast-height diameter was 26 cm, and the average height was 24 m. The average age of the felled trees was 94 years. The third stand, near Stříbrná Skalice village, was primarily characterized by gley soils and pure spruce. The average breast-height diameter was 33 cm, and the average height was 31 m. The average age of the felled trees was 109 years. All selected trees were representative of the stands, free of any defects.

To prepare the testing samples, the bottom portion of each tree was cut about a half inch to an inch off from the trunk end to avoid any cracks caused by felling the trees. These sections were cut into boards, which were used for sample preparation after seasoning. Clear samples (20 × 20 × 30 mm) were produced in accordance with ČSN 49 0101 (1980). The samples were stored in an air-conditioned room (20 °C and 65% according to ČSN 49 0103 (1979) until the MC equilibrated. Thereafter, the wood density for 12% MC was set according to ČSN 49 0108 (1993). The density was determined by use of the following formula,

$$\rho_{12} = \frac{m_{12}}{V_{12}} \quad [kg.m^{-3}] \tag{1}$$

where m_{12} is the sample weight with 12% MC (in kg) and V_{12} is the sample volume with 12% MC (in m^{-3}).

In total, 756 testing samples were produced to evaluate the wood density, corresponding to 252 pieces for each site. The remaining wood from all nine trees as well as after measuring the mechanical and physical properties of wood was transferred to chips for the production of PB and MDF panels. The chips were divided into two groups, the first group for the production of PB and the second one for MDF panels, as described below.

Physical and Mechanical Measurements of Spruce Solid Wood

Twelve samples (20 × 20 × 30 mm) were used to evaluate the shrinkage (α). The total shrinkage (α_{max}) from the green to the oven-dried conditions in radial (α_r) and tangential (α_t) directions and the volumetric shrinkage (α_V) were tested following the Czech national standard ČSN 49 0128 (1989),

$$\alpha_i \max = \frac{l_i \max - l_i \min}{l_i \max} \times 100[\%] \tag{2}$$

$$\alpha_v \max = \frac{V \max - V \min}{V \max} \times 100[\%] \tag{3}$$

where i is the radial or tangential direction, l_{max} is the size at a moisture content above the fibre saturation point, l_{min} is the size of the oven-dried samples, V_{max} is the volume at a moisture content above the fibre saturation point, and V_{min} is the volume of the oven-dried samples. For the mechanical properties, 12 samples were used for each of the following tests: bending strength (MPa), impact strength (J/cm^2), and compression strength in radial and tangential direction and parallel to grain (MPa).

Production of Particleboard Panels

The PB panels (16 mm thickness) were produced from 100% Norway spruce particles. The particles were divided into two layers, coarse (1.2 to 1.18 mm) and fine (0.4 to 0.8 mm), based on their size, which were then dried to 3% MC. The wood particles were placed in a rotating drum-type blender, and three-layer mats were formed using 17.5% fine particles for each face and back layer and 65% coarse particles for the core layer. MUF adhesive with 62% solid content was used in the blending process (Table 1). The adhesive was applied to the particles over 5 min at levels of 11% and 7%, based on the oven-dry weight of the particles in the face and core layers, respectively.

Table 1. Composition of Melamine-Urea-Formaldehyde Adhesive Resin and Pressing Conditions Used for the Production of Particleboard and MDF Panels

Parameter	MUF		Pressing conditions	Material	
	PB	MDF		PB	MDF
Resin content [a]	Face: 11%, Core: 7%	8 %	Pressure (MPa)	3.25	3.4
Solid resin content	62%		Temperature (°C)	195	200
Melamine content (wt% to MUF resin)	4 % (in powder form)		Pressing factor (s/mm)	10	14-16
Viscosity (mPa.s at 20 ºC)	150-600				
pH at 20 °C	9.0-11				
Density	1150-1250 kg/m³				
Wax (%)	0.5				
Hardener % (NH_4NO_3)[b]	3 % (57-63% urea as solid content)	(0 %)[c]			
F/(M + U) molar ratio	< 1.1 (< 1.1:1)				
Free formaldehyde	< 0.2%				

[a] Percent based on oven-dry weight of wood raw material; [b] % based on solid content of MUF;
[c] MDF only- pH value of wood fibers was sufficient to start the curing reaction (pH value of the fibers was approximately 4.5)

Production of Fibreboard Panels

The wood fibre was made from *P. abies* after pre-steaming the chips (Hua *et al.* 2012) using a disc refiner with the following conditions: MC = 50%, temperature = 160°C, and pressure = 120 psi. The MDF was manufactured using 8 % MUF adhesive, based on the oven-dried weight of the fibres. The wood fibre was placed in a rotary drum mixer, and the MUF resin was sprayed onto the wood fibre during rotation. The fibre and resin mixture was cold pressed at 0.196 MPa for 2 min to improve the stability of the mat and to obtain the proper density gradient before hot pressing. The temperature, pressure, and specific press time used to manufacture the PB and MDF panels are presented in Table 1. The density of the PB and MDF panels was calculated as the ratio of the mass of the panel to the volume after the panel was conditioned at 23 °C and 65% RH for 48 h.

Mechanical Testing Method of Particleboard and MDF Panels

Six PB and MDF panels were randomly selected for mechanical testing. The dimensions of the rectangular specimens were a length of 20 times the nominal thickness plus 50 mm (370 ± 1 mm for PB and MDF) and a width of 50 ± 1 mm. The cutting was performed according to EN 326-1 (1997). MOR and MOE measurements were performed in parallel and perpendicular directions to grain orientation (Buyuksari 2012) for the six panels. The MOE was evaluated using a UTS 100K instrument (measuring range 5 to 100 kN) according to EN 310 (1999).

The modulus of elasticity in bending was calculated using the following equation,

$$E_m = \frac{(F_2 - F_1)l_1^3}{4bt^3(a_2 - a_1)} \tag{4}$$

where l_1 is distance between the support centres (240 mm), b is the width of the test piece (mm), t is the thickness of the test piece (mm), $F_2 – F_1$ is the increment of load on the straight-line portion of the load-deflection curve (N), F_1 and F_2 are approximately 10% and 40% of the maximal load, respectively, and $a_2 – a_1$ is the deflection increment at the mid-length of the test piece (mm), corresponding to a load increment $F_2 – F_1$. The MOR was also calculated according to the following formula (EN 310 1999):

$$f_m = \frac{3F_{\max} l_1}{2bt^2} \tag{5}$$

The Brinell hardness for all three sections – transverse, radial, and tangential – was tested using 20 × 20 × 30 mm samples. The hardness was computed according to the following formula,

$$HB = \frac{P}{\pi.d.h}[MPa] \tag{6}$$

where P is the load pressing of the ball into the samples, d is the ball diameter, and h is the depth of the indentation.

Square samples (5.1 cm × 5.1 cm) were used for internal bond (IB) measurement (EN 319 1999). Samples were conditioned at 65% RH at 23 °C for 48 h before testing. The reported values are the average of six specimens from each board.

We should note here that the physical properties of PB and MDF panels have not been evaluated because the panels will be subjected to the next production process (lamination) to evaluate the different types of laminates.

Formaldehyde Emission Measurement

Free formaldehyde measurements from PB and MDF panels [(36 replicates for the EN 717-2 (1994) and EN 120 (1993) methods and three replicates for EN 717-1 2004)] were conducted in the laboratory of the Timber Research and Development Institute, Prague, Czech Republic.

Small-scale chamber method (EN 717-1)

In the referenced method (EN 717-1 2004), two test pieces (0.2 m × 0.28 m × 16 mm) with a total area of 0.225 m^2 were used to measure formaldehyde emissions. The samples were not conditioned before testing. The loading factor was 1 m^2/m^3. The temperature and RH were 23 ± 0.5 °C and 45 ± 3%, respectively. The formaldehyde emitted from the tested samples mixed with the air in the chamber and was periodically measured until the formaldehyde concentration in the chamber reached steady-state. An E1 class emission of ≤0.1 ppm (0.124 mg/m^3) was used as the standard limit measured by the EN 717-1 (2004) method. To avoid contaminating the solid wood samples with formaldehyde from the ambient air, the compressed air was dried and cleaned before entering the chamber.

Gas analysis method (EN 717-2)

A 400 mm × 50 mm × 16 mm sample was placed in a 4 L chamber under controlled temperature (60 ± 0.5 °C), RH ≤ 3%, airflow (60 ± 3 L/h), and pressure. The emitted formaldehyde was measured in duplicate using two different pieces, and the reported value was the average of the two pieces after 4 h. E1 class emissions of ≤3.5 mg/m^2 h was used as the standard limit measured by the EN 717-2 (1994) method.

Perforator method (EN 120)

The formaldehyde contents of the samples from the manufactured particleboard (36 samples) and MDF (36 samples) panels were measured by the perforator method (EN 120 1993) most commonly used in industry as a production control. Approximately 110 g of the 25 × 25 mm specimens were extracted in the perforator apparatus using boiling toluene (600 mL) for 2 h under reflux. The total operation and analysis time is approx.-imately 3 h, which has led to its widespread use for production control in the wood-based panel industry, especially in Europe and China. The formaldehyde content is expressed as mg HCHO/100 g of dry board (mg/100 g o.d.). The E1 emission limit was ≤8 mg/100 g o.d. The EN 120 (1993) values for PB and MDF with different MCs were corrected to boards conditioned to an MC of 6.5%, as previously described (Salem *et al.* 2012a). The formaldehyde released from the three methods was absorbed in water and determined photometrically by the acetylacetone method (Nash 1953).

Statistical Analysis

The mechanical properties and formaldehyde emissions from particleboard and MDF panels were statistically analysed using the general linear model (GLM) procedure in SAS version 8.2 (2001), using a completely randomised design to test the differences among factors and levels. A comparison among the least square (LS) means with 95%

confidence intervals (CI) was performed using Duncan's multiple-range test to identify significant differences and to compare the means between boards. Linear correlations were applied to the values of EN717-2 (1994), EN 120 (1993), and the density of boards. Additionally, the normality of the formaldehyde values (mg/m^2 h and mg/100 g o.d.) from PB and MDF panels and that of the density of the boards was performed using a normal probability plot (normal P-plot). All of the values are presented as the mean ± standard deviation (SD).

RESULTS AND DISCUSSION

Density Variation in Spruce Wood

Density data for the spruces from three different locations in the Czech Republic are presented in Table 2. The overall average density of the spruce wood was 509.22 kg/m^3, ranging from 400.95 ± 27.92 to 617.50 ± 29.91 kg/m^3 by location. Tree number 3 in loc. 2 had the highest density, 556.54 ± 29.91 kg/m^3, and tree number 1 in loc. 1 had the lowest density, 451.70 ± 27.92 kg/m^3. It could be suggested that the variations in the densities are related to the tree age within different locations. However, the same tree species of similar tree age can differ due to site-specific growing conditions including forest structure (Pokorný *et al.* 2012). Additionally, within two even-aged monocultures of Norway spruce located at mountain and highland localities of the Czech Republic with similar stand age and tree size, mountain trees comparing to them from highland showed less/tapering stems and lower stem wood density as a result of different early to late wood proportion (Pokorný *et al.* 2012; Jyske *et al.* 2008).

Table 2. Results of Basic Statistical Variations in the Density of Spruce Wood Among the Different Locations

Location	Tree No.	Density (kg/m^3)							
		Mean	Min.	Max.	Lower quartile	Upper quartile	SD	CV%	SE
1	1	451.7	400.95	539.22	427.81	472.9	27.92	6.18	3.05
	2	472.37	419.22	527.77	463.57	486.22	22.05	4.67	2.41
	3	505.24	444.53	572.74	496.28	516.85	23.63	4.68	2.58
2	1	501.1	434.71	599.94	466.96	533.83	43.37	8.66	4.73
	2	532.38	473.26	598.28	498.06	560.26	36	6.76	3.93
	3	556.54	478.84	617.5	538.92	578.74	29.91	5.37	3.26
3	1	517.26	463.94	572.33	501.27	532.38	24.06	4.65	2.62
	2	525.79	471.88	594.52	504.26	550.61	28.67	5.45	3.13
	3	520.63	450.72	614.43	496.73	548.31	37.65	7.23	4.11
Overall value		509.22	448.67	581.86	488.21	531.12	30.36	5.96	3.31

The spruce wood density varied with high statistical significance ($P < 0.001$) by location (Fig. 1). Figure 1 shows that there were significant differences in the density means among the trees in loc. 1 and loc. 2 ($P < 0.001$), but not loc. 3. The trees from loc. 2 and loc. 1 had the highest and lowest densities, respectively. On the other hand, mountain trees showed significantly lower stem wood density values compared to trees from lower altitude (Pokorný *et al.* 2012).

Gryc *et al.* (2011) found that the average basic density was 576 kg/m^3 for spruce branch wood from different testing areas in the Czech Republic and that the mean stem basic density for the same testing areas was 430 kg/m^3 (it was 509.22 kg/m^3 in the present study). Previous studies have reported that the increase in density seems to be mainly due to the decreased early wood content (Romagnoli *et al.* 2003), as expressed in both mean wood density and minimum wood density. The variation in the density of spruce wood could be attributed to an anomaly in the growth pattern of annual rings, known as indented rings (Hakkila and Uusvaara 1968).

Additionally, Ziegler and Merz (1961) reported a highly disturbed cell arrangement, a greater number of trabeculae, and shorter, irregularly shaped tracheids. Moreover, a significant temperature dependence for both ring width and latewood density and its effects on the cambial activity of spruce have been observed by Götsche-Kühn (1988) and can be explained by pollution-induced inhibition of photosynthesis and hormonal growth regulator synthesis, which are dependent on the development of buds and shoots (Kozlowski and Pallardy 2002). Another study (Požgaj *et al.* 1997) revealed that, if early to late wood properties are compared, differences in cell size, cell wall thickness, cell wall to lumen area ratio, and wood density become apparent.

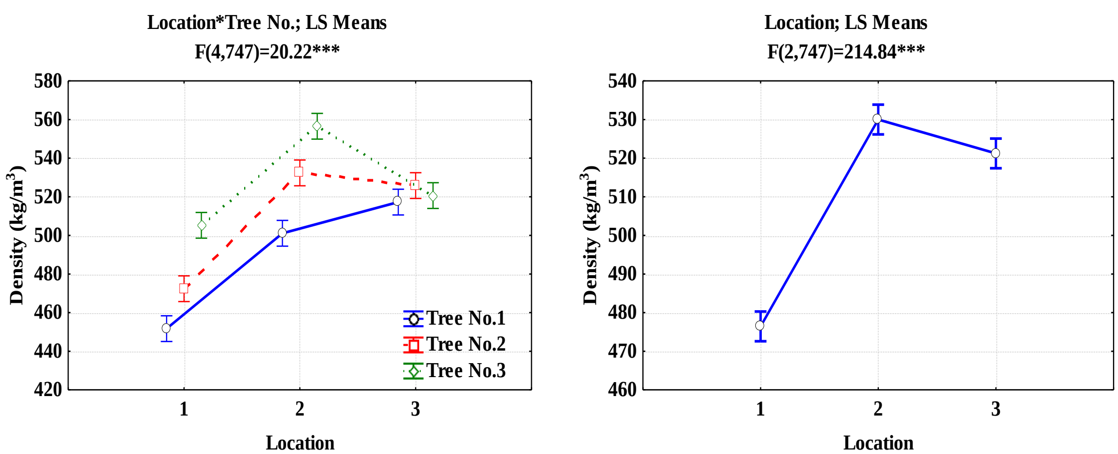
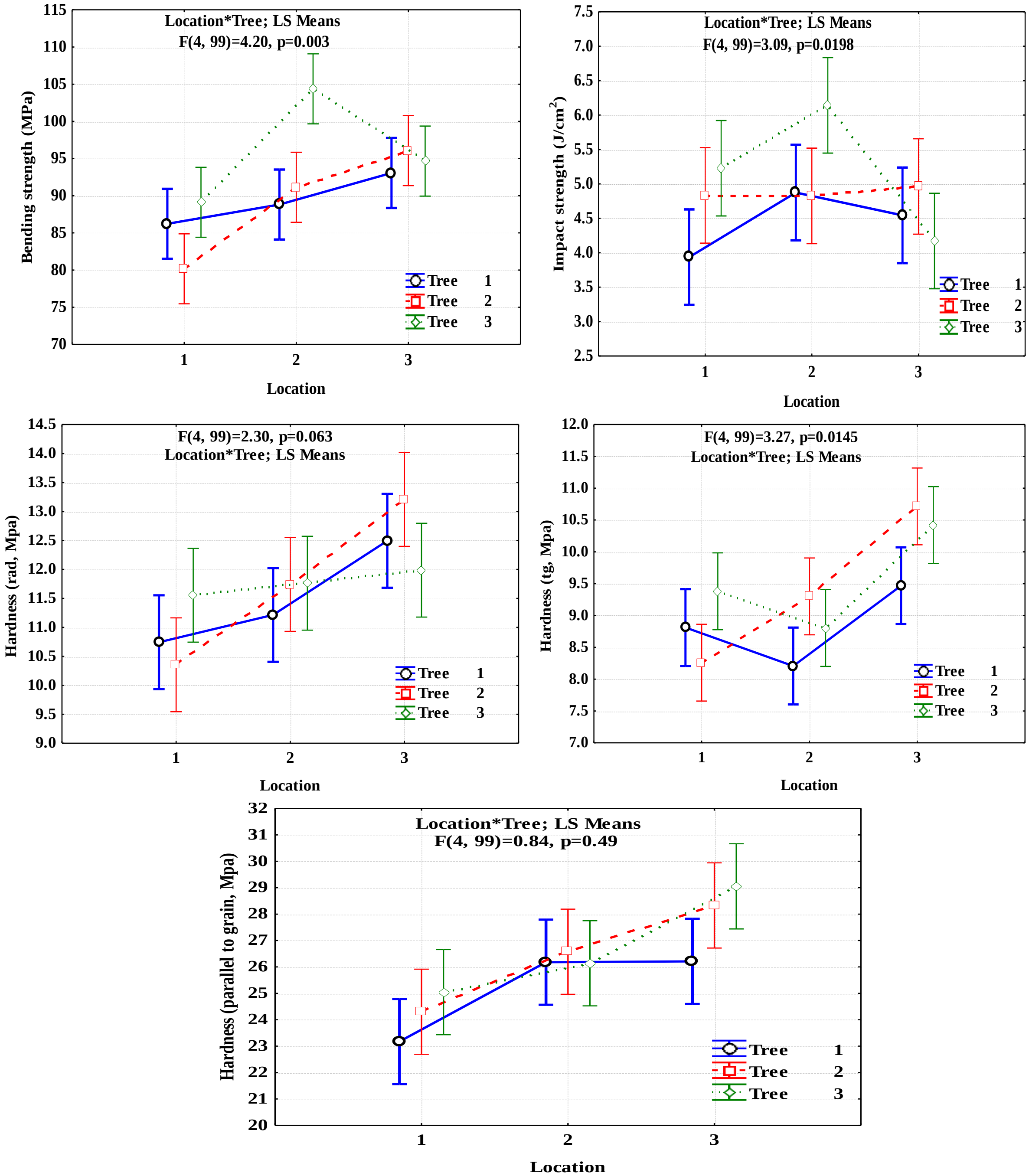


Fig. 1. Variations in the density of spruce wood among the different locations

Mechanical and Physical Properties of Spruce Wood

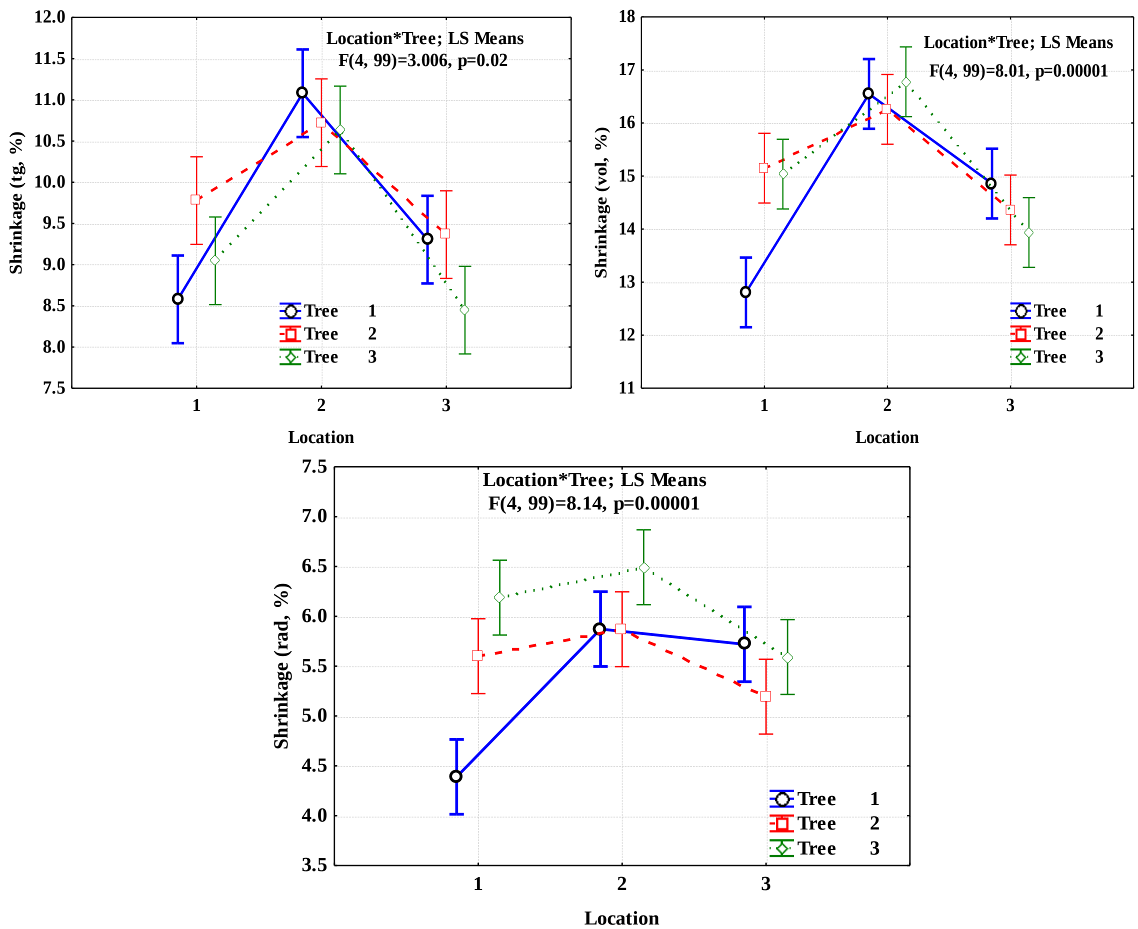
The results for some of the mechanical and physical properties measured from nine trees from different locations are presented in Table 3. The bending strength ranged from 80.16 ± 8.03 to 104.38 ± 9.08 MPa, which was reflected in the modulus of elasticity (*ca.* 9-24 GPa) of spruce logs (Edlund *et al.* 2006). The impact strength ranged from 3.94 ± 0.70 to 6.14 ± 1.13 J/cm^2. The hardness (MPa) ranged from 10.71 ± 0.99 to 8.25 ± 0.57 (tangential), 10.35 ± 1.43 to 13.21 ± 1.43 (radial), and 29.05 ± 2.28 to 23.18 ± 3.26 (parallel to grain). The shrinkage (%) ranged from 8.45 ± 1.09 to 11.08 ± 0.62 (tangential), 4.39 ± 0.38 to 6.49 ± 0.61 (radial), and 12.81 ± 1.02 to 16.78 ± 0.60 (volumetric).

The variations among the measured mechanical and physical properties of spruce solid wood from nine trees within three different locations are shown in Figs. 2 and 3. Analysis of variance revealed significant differences ($p < 0.001$) between the trees within each location in terms of bending strength, impact strength, hardness (tangential), and shrinkage (tangential, radial, and volumetric). Significant differences were not found for parallel to grain hardness ($p < 0.49$) and radial hardness ($p < 0.063$).



rad- radial; tg- tangential to the grain

Fig. 2. Some mechanical properties of spruce solid wood from the three different locations and the test results of ANOVA



rad- radial; tg- tangential; vol- volumetric

Fig. 3. Some physical properties of spruce solid wood from the three different locations and the test results of ANOVA

Table 3. Mechanical and Physical Properties of Spruce Wood Tested from Nine Trees from Three Locations

Loc.	Tree	Bending strength (MPa)	Impact strength (J/cm^2)	Hardness (Mpa) Tangential	Radial	Parallel	Shrinkage (%) Tangential	Radial	Volume
1	1	86.22 ± 8.53	3.94 ± 0.70	8.81 ± 0.99	10.74 ± 1.36	23.18 ± 3.26	8.58 ± 0.83	4.39 ± 0.38	12.81 ± 1.02
	2	80.16 ± 8.03	4.83 ± 0.85	8.25 ± 0.57	10.35 ± 1.43	24.30 ± 1.69	9.77 ± 0.75	5.60 ± 0.60	15.14 ± 1.07
	3	89.12 ± 7.58	5.23 ± 1.08	9.38 ± 0.82	11.55 ± 1.17	25.05 ± 1.84	9.05 ± 1.31	6.19 ± 0.79	15.04 ± 1.33
2	1	88.81 ± 11.97	4.87 ± 0.85	8.21 ± 0.96	11.21 ± 1.37	26.18 ± 3.08	11.08 ± 0.62	5.87 ± 0.69	16.55 ± 0.64
	2	91.13 ± 5.03	4.83 ± 1.20	9.30 ± 1.18	11.74 ± 1.65	26.58 ± 2.73	10.72 ± 1.00	5.87 ± 0.79	16.26 ± 1.50
	3	104.38 ± 9.08	6.14 ± 1.13	8.80 ± 0.84	11.76 ± 1.27	26.14 ± 4.18	10.63 ± 0.45	6.49 ± 0.61	16.78 ± 0.60
3	1	93.06 ± 9.47	4.54 ± 1.97	9.47 ± 1.02	12.49 ± 1.56	26.21 ± 2.30	9.30 ± 0.60	5.72 ± 0.36	14.86 ± 0.68
	2	96.07 ± 6.05	4.96 ± 1.46	10.71 ± 0.99	13.21 ± 1.43	28.33 ± 3.09	9.36 ± 1.28	5.19 ± 0.73	14.36 ± 1.74
	3	94.66 ± 5.94	4.17 ± 1.16	10.42 ± 1.72	11.99 ± 1.42	29.05 ± 2.28	8.45 ± 1.09	5.59 ± 0.77	13.94 ± 1.17

Values are the average of 12 replicates (mean ± SD)

Mechanical Properties of Particleboard and MDF Panels

The density of the PB boards ranged from 598 to 708 kg/m^3, and the MC ranged from 4.15 to 7.56%. The results of the statistical analysis of variance and Duncan's multiple-range test for the mechanical properties of PB panels and comparisons among the means are presented in Table 4, revealing a highly significant effect ($P < 0.001$). The average MOR (21.44 N/mm^2) ranged from 20.40 ± 0.45 to 22.40 ± 1.37 N/mm^2 (bending parallel to grain) and from 18.10 ± 0.22 to 20.80 ± 0.63 N/mm^2 (bending perpendicular to grain). The MOE ranged from 3655 ± 1.36 to 3452 ± 2.23 N/mm^2 (bending parallel to grain) and from 2839 ± 1.86 to 3148 ± 2.38 N/mm^2 (bending perpendicular to grain). The IB values ranged from 0.401 ± 0.01 to 0.45 ± 0.01 N/mm^2.

The density of MDF ranged from 673 to 810 kg/m^3 and the MC ranged from 3.36 to 5.97%. Table 5 shows the mechanical properties of MDF made from Norway spruce wood fibres and the ANOVA results ($P < 0.001$). The MOR values ranged from 39.10 ± 0.38 to 43.50 ± 1.18 N/mm^2 (parallel to grain) and from 37.5 ± 1.04 to 43.2 ± 0.67 N/mm^2 (perpendicular to grain). The MOR values ranged from 3602 ± 2.82 to 3919 ± 2.19 N/mm^2 (parallel to grain) and from 3518 ± 2.60 to 3929 ± 2.19 (perpendicular to grain). The IB values ranged from 0.83 ± 0.01 to 0.95 ± 0.01 N/mm^2.

To evaluate the differences among the boards made from the same type of wood product and thickness (16 mm thick), an analysis of variance was used. The mean values of the studied parameters of the boards were statistically significant ($P < 0.001$) (Table 4 and 5). Figures 4 and 5 present the evaluation of the differences among the MOR, MOE, and IB observed from the six panels of PB and MDF, respectively.

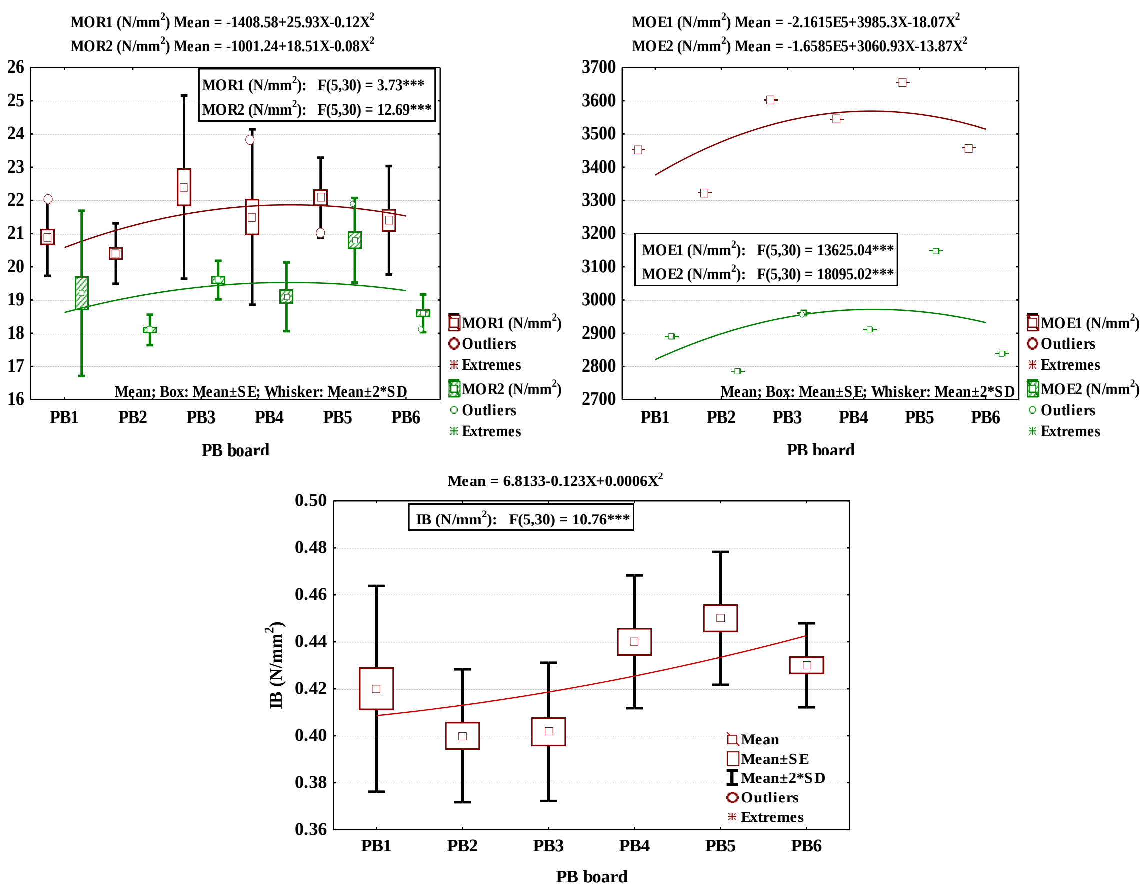


Fig. 4. Box-whiskers plot of MOR, MOE, and IB variation among particleboard panels (16 mm); MOR1, MOE1: Values are parallel to grain; MOR2, MOE2: Values are perpendicular to grain

Based on EN 312 (2003), an MOR of 12.5 N/mm^2 and 13 N/mm^2 are the minimum requirements of PB for general use and furniture manufacturing, respectively. There is no minimum MOE requirement for general use, whereas the minimum for furniture manufacturing is 1800 and 2300 N/mm^2 for interior grade type and load bearing in dry conditions, respectively. Particleboards made from spruce particles had MOR and MOE values that exceeded the requirements for general use and furniture manufacturing as well as load bearing in dry conditions. Previously, it was reported that panels with the highest densities had the highest MOR and MOE, suggesting that the PB density plays a very important role in the bending strength (García-Ortuño *et al.* 2011). Particleboards PB1, PB2, PB3, PB4, and PB6 (Table 4) had IB values below the requirements for load bearing use (0.45 N/mm^2). All panels achieved the internal bond requirements for general purpose and interior grade. Similar to the results above, the MDF panels exceeded the EN 622-5 (2009) requirements as shown in Table 5. The variation in the tested panels could be related to inter-panel variations (Salem *et al*. 2012b).

Figure 4 shows that the MOR values for PB1, PB4, and PB5 (parallel to grain) and PB5 and PB6 (perpendicular to grain) each included one outlier. In contrast, the IB values did not include any outliers. For the MOE values, only PB3 (perpendicular to grain) included an outlier.

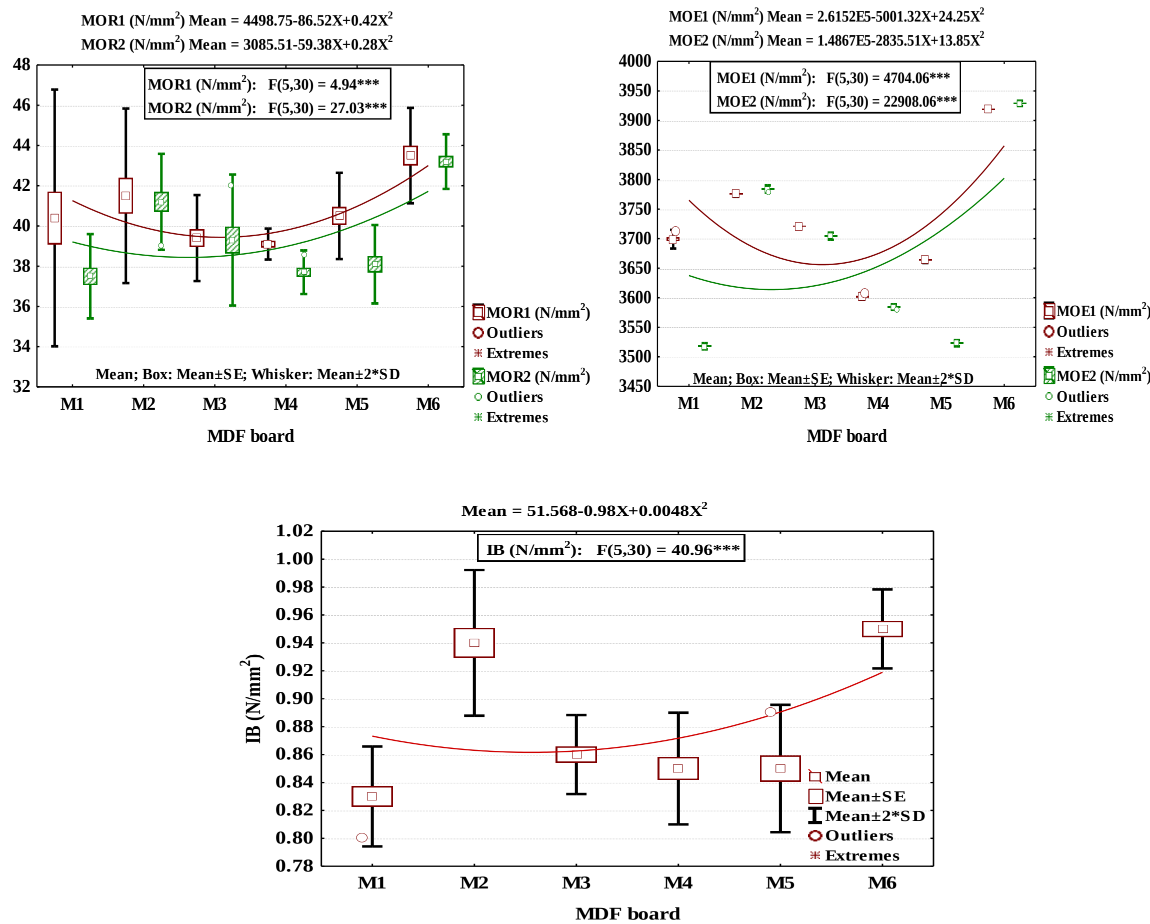


Fig. 5. Box-whiskers plot of MOR, MOE, and IB value variation among the MDF panels (16 mm); MOR1, MOE1: Values are parallel to grain;
MOR2, MOE2: Values are perpendicular to grain.

Figure 5 presents the variations among MOR, MOE, and IB values from MDF panels. The MOR (perpendicular to grain) from M2, M3, and M4 had one outlier for each panel, whereas the MOR values (parallel to grain) did not include any outliers. The MOE (parallel and perpendicular to grain) included outliers of M1 and M4 and of M2 and M4. M1 and M5 had one outlier in terms of IB values.

An outlier value, *i.e.*, a value far from the central mean, indicates faulty data. The measured MOR, MOE, and IB values for spruce PB and MDF included outliers among panels, even for the same type of board, resin, manufacturing conditions, and the test conditions. This finding indicates that some boards exhibited unusual properties.

In this study, the variations in MOR, MOE, and IB may be attributed to sample heterogeneity, despite the random distribution of the tested samples throughout the PB and MDF panels. Additionally, the high density variation of the panels (PB, MDF) might be attributed to the variation of spruce wood densities within three different locations (the localities differed in elevation, soil fertility, and tree size) with different tree ages.

Table 4. Mechanical Properties of Particleboards Made from Norway Spruce

Board No.	MOR (N/mm^2)*		MOE (N/mm^2)*		IB (N/mm^2)*	Board density (kg/m^3)
	//	⊥	//	⊥		
PB1	20.90 ± 0.58^{bc}	19.20 ± 1.24^{b,c}	3452 ± 2.23^{e}	2890 ± 2.36^{d}	0.42 ± 0.02^{c}	635.67
PB2	20.40 ± 0.45^{c}	18.10 ± 0.22^{d}	3323 ± 2.89^{f}	2786 ± 1.85^{f}	0.40 ± 0.01^{d}	653.17
PB3	22.40 ± 1.37^{a}	19.60 ± 0.28^{b}	3602 ± 4.00^{b}	2961 ± 3.06^{b}	0.401 ± 0.01^{d}	660.33
PB4	21.50 ± 1.32^{a,b,c}	19.10 ± 0.51^{b,c}	3544 ± 0.77^{c}	2911 ± 1.97^{c}	0.44 ± 0.01^{a,b}	668.67
PB5	22.08 ± 0.60^{a,b}	20.80 ± 0.63^{a}	3655 ± 1.36^{a}	3148 ± 2.38^{a}	0.45 ± 0.01^{a}	675.83
PB6	21.40 ± 0.81^{a,b,c}	18.60 ± 0.28^{c,d}	3458 ± 2.44^{d}	2839 ± 1.86^{e}	0.43 ± 0.008^{b,c}	693.50
Overall value	21.44	19.23	3505.67	2922.5	0.42	
R^2	0.38	0.67	0.99	0.99	0.64	
P value	0.0096	<0.001	<0.001	<0.001	<0.001	
CV%	4.35	3.31	0.07	0.07	3.57	
A	12.5		N/A		0.28	
B	13.0		1800.00		0.40	
C	15.0		2300.00		0.45	

Different letters in the same column represent statistical significance ($P < 0.05$), in accordance with Duncan's multiple-range test
* The results are an average of 6 replicates; (mean ± SD).
[A] For general uses according to EN 312 (2003) standard.
[B] For interior grade type (including furniture), according to EN 312 (2003) standard.
[C] For load bearing under dry conditions, according to EN 312 (2003) standard.

Free Formaldehyde Values

The formaldehyde emissions from the spruce solid wood were previously measured, obtaining values of 0.0055 ± 0.001 ppm and 0.069 ± 0.011 mg/m^2 h as measured by EN 717-1 (2004) and EN 717-2 (1994), respectively (Böhm *et al.* 2012). The formaldehyde emission values from PB and MDF panels are presented in Table 6. The formaldehyde content ranged from 3.93 to 7.07 mg/100 g o.d. with an average of 5.68 mg/100 g o.d. and from 0.41 to 0.89 mg/m^2 h with average of 0.62 mg/m^2 h. Additionally, the chamber values were 0.097 mg/m^3 (PB) and 0.12 mg/m^3 (MDF). The measured free formaldehyde contents varied for each sample for PB and MDF panels.

These phenomena suggested that the most important source of variation is the heterogeneity of the board samples.

Table 5. Mechanical Properties of MDF Made from Norway Spruce Wood Fibers

Board No.	MOR (N/mm²)*		MOE (N/mm²)*		IB (N/mm²)*	Board density (kg/m³)
	//	⊥	//	⊥		
M1	40.40 ± 3.18^{b,c}	37.5 ± 1.04^{c,d}	3699 ± 7.92^{d}	3518 ± 2.60^{f}	0.83 ± 0.01^{c}	736.00
M2	41.50 ± 2.16^{a,b}	41.2 ± 1.19^{b}	3776 ± 2.60^{b}	3784 ± 3.03^{b}	0.94 ± 0.02^{a}	760.00
M3	39.40 ± 1.06^{b,c}	39.3 ± 1.62^{b,c}	3721 ± 1.43^{c}	3704 ± 3.01^{c}	0.86 ± 0.01^{b}	768.50
M4	39.10 ± 0.38^{c}	37.7± 0.54^{c,d}	3602 ± 2.82^{f}	3584 ± 2.28^{d}	0.85 ± 0.02^{b,c}	776.67
M5	40.50 ± 1.07^{b,c}	38.1 ± 0.97^{c,d}	3664 ± 2.60^{e}	3523 ± 2.60^{e}	0.85 ± 0.02^{b,c}	781.33
M6	43.50 ± 1.18^{a}	43.2 ± 0.67^{a}	3919 ± 2.19^{a}	3929 ± 2.19^{a}	0.95 ± 0.01^{a}	794.67
Overall value	40.73	39.5	3730.17	3673.67	0.88	
R^2	0.45	0.81	0.99	0.99	0.87	
P value	0.002	<0.001	<0.001	<0.001	<0.001	
CV%	4.33	2.71	0.104	0.07	2.23	
A	20 (EN 310 1999)		2200 (EN 310 1999)		0.55 (EN 319)	
B	24		2400		0.75	
C	25		2500		0.60	
D	30		2700		0.75	

Different letters in the same column represent statistical significance ($P < 0.05$), in accordance with Duncan's multiple-range test
* The results are an average of 6 replicates
[A] For general use in dry conditions
[B] For general use in wet conditions
[C] For load bearing in dry conditions
[D] For load bearing in wet conditions

Table 6. Values of the Emitted Formaldehyde from Particleboard and MDF as Measured by Chamber, Perforator, and Gas Analysis Methods

Parameter	PB			MDF		
	(mg/100 g o.d.)^{a}	(mg/m² h)^{a}	(mg/m³)^{b}	(mg/100 g o.d.)^{a}	(mg/m² h)^{a}	(mg/m³)^{b}
Mean	5.68	0.62	0.097	6.37	1.46	0.12
Minimum	3.93	0.41		3.25	0.6	
Maximum	7.07	0.89		9.22	2.12	
Lower quartile	5.01	0.53		5.99	1.21	
Upper quartile	6.34	0.73		6.67	1.86	
SD	0.86	0.13		0.93	0.40	
CV%	15.13	21.54		14.63	27.52	

[a] The values are mean of 36 replicates
[b] The value is from 3 measurements; At 23 ºC and 1013 hPa, the following relationship exists for formaldehyde measured by EN 717-1 (2004): 1 ppm = 1.24 mg/m³ or 1 mg/m³ = 0.81 ppm

Obvious variations in formaldehyde emission were found among the panels and within panels of the same type of PB and MDF, which was in agreement with previous investigations (Wiglusz *et al.* 2000; Salem *et al.* 2012b; Roffael *et al.* 1979). Additionally, Aydin *et al.* (2006) reported that poplar and spruce plywood formaldehyde emissions decreased with increasing veneer moisture content.

The different test conditions (temperature, RH, loading factor, *etc.*) among the test methods used (perforator, gas analysis, and chamber) explained the variations among the formaldehyde values. For example, the perforator formaldehyde values were higher than those obtained using gas analysis and the chamber method. Many studies have investigated these variations, finding that the strongest factors affecting formaldehyde emission (gas analysis and chamber values) and formaldehyde content (perforator method) for the panels are air exchange rate, loading ratio, and temperature (Risholm-Sundman *et al.* 2007), as well as the anatomy of the respective wood species (Meyer and Boehme 1997; Böhm *et al.* 2012).

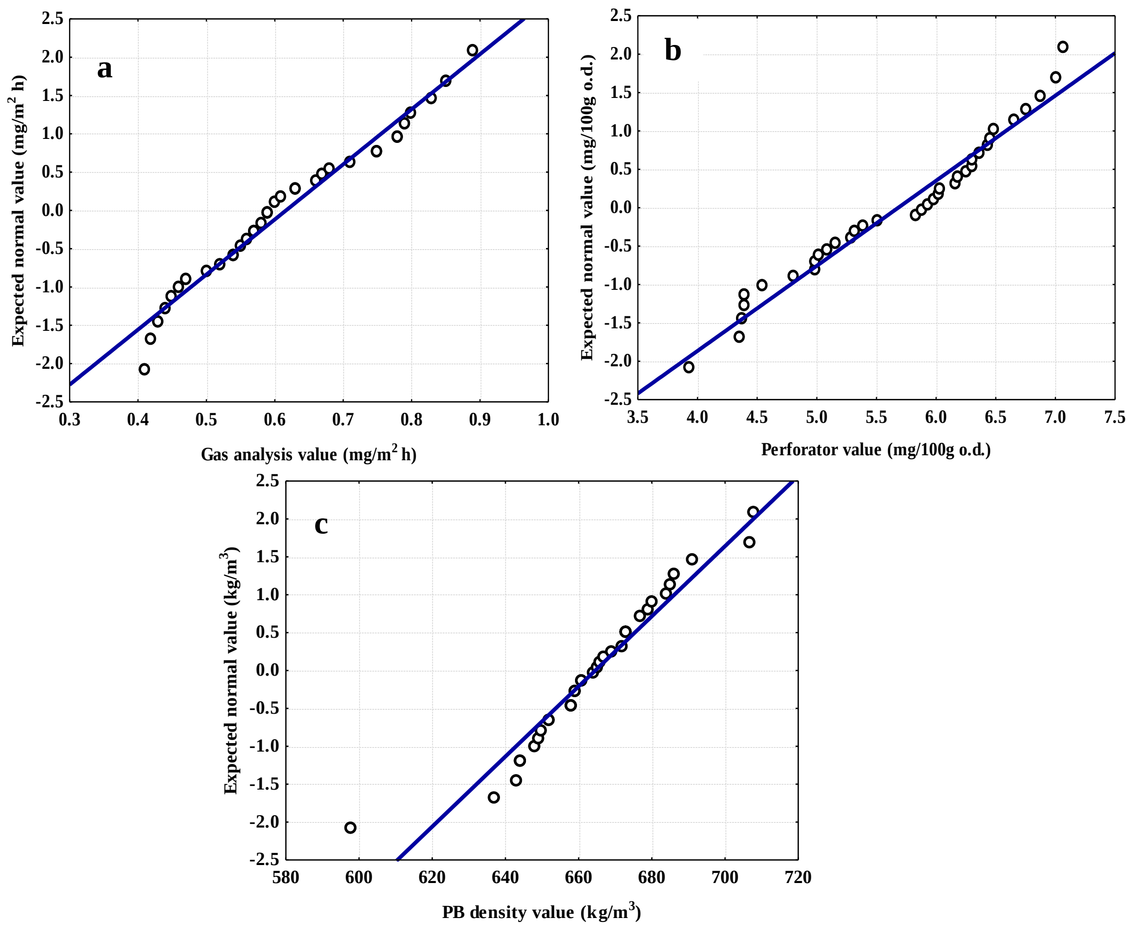


Fig. 6. Normal P- Plot for the formaldehyde emission values of perforator and gas analysis methods and the density values of PB

The perforator method measures the total extractable formaldehyde content present in the samples, whereas the other two methods measure the formaldehyde released from the sample surfaces. To overcome the overestimation of formaldehyde content measured by the extraction method (perforator), recently developed methods were adopted to rapidly determine the parameters required to predict the formaldehyde emission from building and furniture materials (Wang and Zhang 2009; Xiong *et al.* 2009; Xiong *et al.* 2011; Yao *et al.* 2011). Furthermore, boards were used as the testing samples, which are used extensively in furniture. The literature reports that the formaldehyde emissions from the building materials measured by the perforator method are the total formaldehyde concentration, containing both the free emittable formaldehyde and formaldehyde that is difficult to emit under normal conditions (Xiong and Zhang 2010). Considering that the perforator method is carried out at a high temperature (approximately 110.8 °C) relative to 60 °C for EN 717-2 (1994) and 23 °C for the chamber method, the building material cannot emit the total measured formaldehyde concentration at room temperature.

Despite these differences in the formaldehyde emission values among the boards and methods, a good positive correlation was found among the formaldehyde emission values measured by EN 717-2 (1994) and EN 120 (1993) and their relationship with the board density. Figure 6 shows the normal P-plot of the perforator and gas analysis methods and the density values for PB (Figure 6a, b, c) and MDF (Figure 7a, b, c) panels, respectively. The measured values were normally distributed, and most of the values lay near the average value.

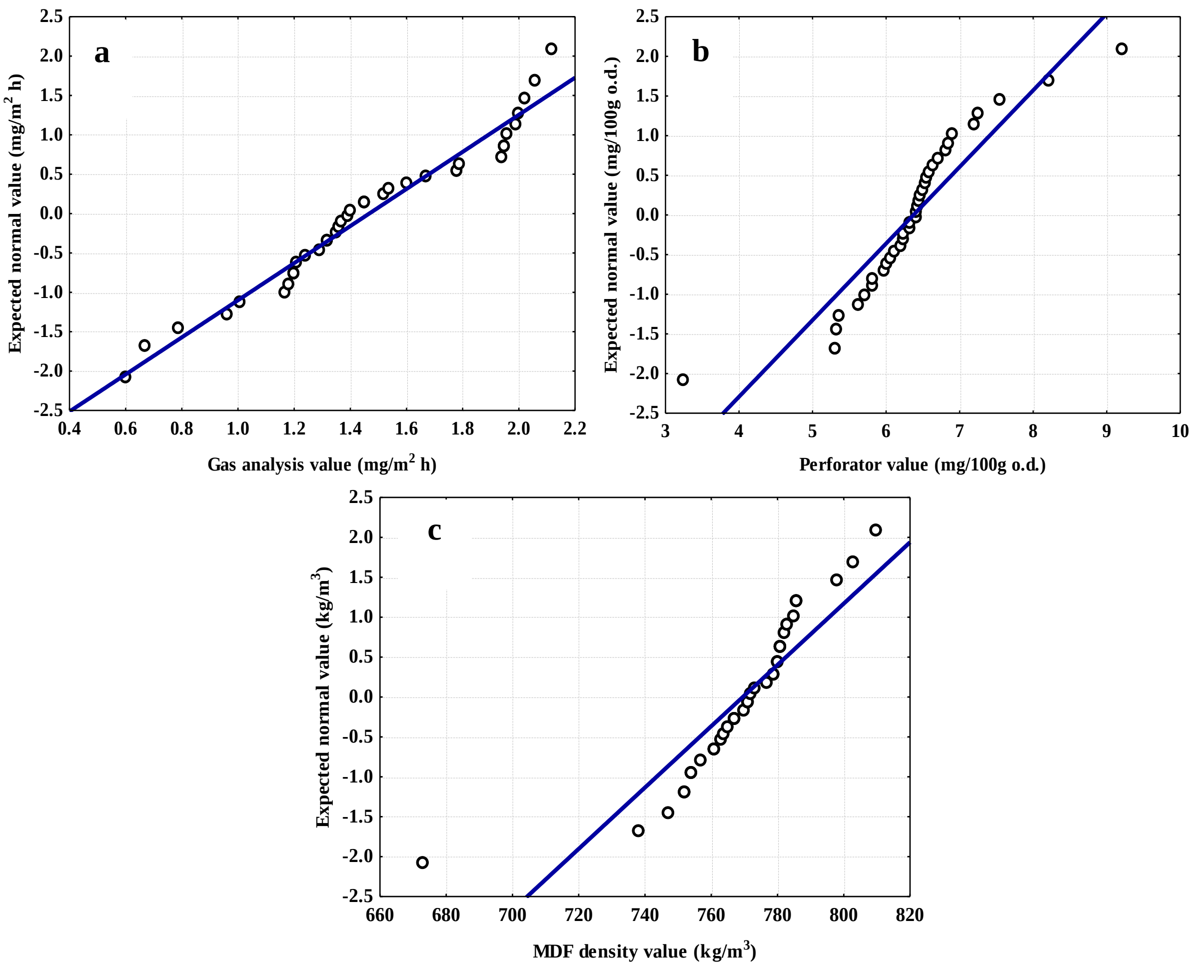


Fig. 7. Normal P- Plot for the formaldehyde emission values of perforator and gas analysis methods and the density values of MDF

The formaldehyde emissions measured by perforator and gas analysis methods from PB panels with 16 mm thickness fitted with the board density had an R^2 value of

0.88 and 0.86, respectively (Fig. 8a). Additionally, there was a good correlation between the emitted formaldehyde measured from PB panels by the two methods, with an R^2 value of 0.93 (Fig. 8b).

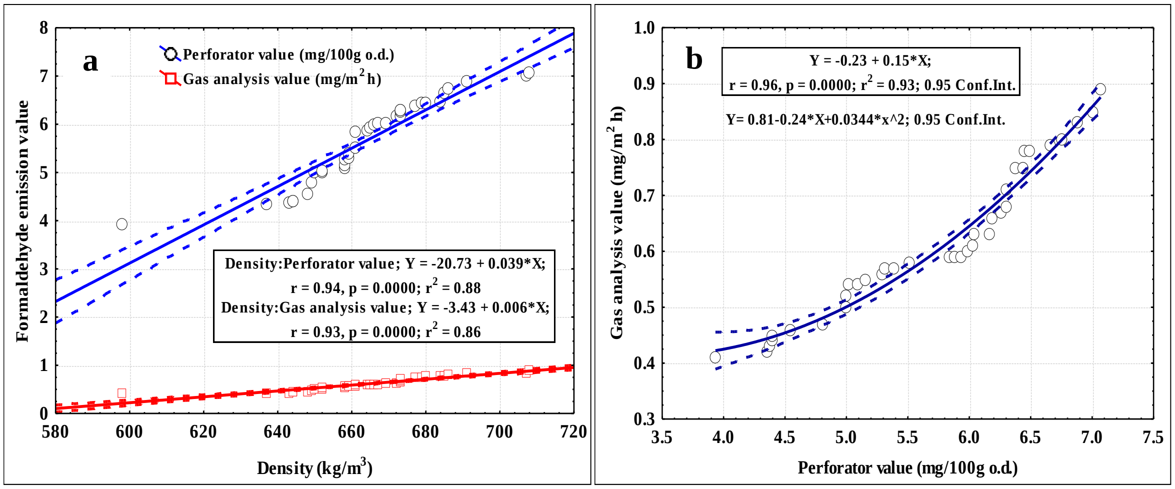


Fig. 8. The correlation between the formaldehyde emission values of perforator and gas analysis methods and the density values of PB

Figure 9a presents the correlation between the MDF board density and formaldehyde emissions measured by the perforator and gas analysis methods, with R^2 values of 0.91 and 0.76, respectively. The value of R^2 for the gas analysis in correlation with the board density was poor, which can be explained by its lack of a normal distribution in Fig. 7a. On the other hand, the linear regression did not obtain a convincing relationship between the gas analysis and perforator (R^2 = 0.77); thus, quartic regression was used to find the acceptable agreement of the correlation relationship (Fig. 9b).

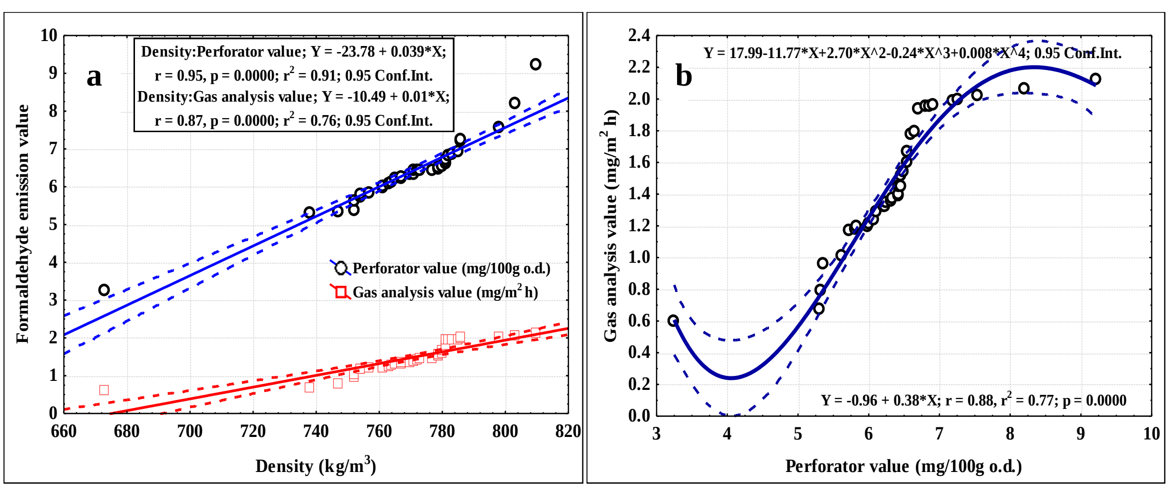


Fig. 9. The correlation between the formaldehyde emission values of perforator and gas analysis methods and the density values of MDF

The California Air Resources Board adopted new standards (CARB 2007) to reduce formaldehyde emissions from PB and MDF in two phases: P1 extends to 2009 [≤0.18 (PB) and ≤0.21 (MDF) ppm] and P2 extends through 2010-2011 [≤0.09 (PB) and 0.11 (MDF) ppm]. Furthermore, this new regulation requires that wood-based panels be certified by a "third-party" laboratory approved by CARB.

The mean formaldehyde emission from the spruce PB panels measured by EN 717-1 (2004) was 0.097 mg/m^3 (0.078 ppm), which is lower than the requirements of the CARB regulations for Phase 2 (≤ 0.09 ppm). The mean formaldehyde emission from the MDF boards was 0.12 mg/m^3 (0.097 ppm), which is lower than the Phase 2 limit (0.11 ppm).

The anatomy of spruce wood is simple, with a low specific gravity (0.51), which affects formaldehyde emissions from the boards. It was previously reported that the PB and MDF panels produced from spruce wood with low specific gravity resulted in lower formaldehyde values in perforator testing due to high formaldehyde release during hot pressing. Moreover, the amount of resin was related to the particle amount. Subsequently, a higher specific gravity corresponds to higher resin usage for panel production (Salem *et al.* 2012b).

CONCLUSIONS

Data from Norway spruce wood was collected from three different locations in the Czech Republic. The variations in the wood densities were reported as well as mechanical and physical properties. Mechanical properties and formaldehyde emission of particleboards and medium-density fibreboard panels produced from Norway spruce wood in a commercial plant in the Czech Republic were investigated. The following conclusions were drawn:

1. The overall average density of the spruce wood was 509.22 kg/m^3, ranging from 400.95 ± 27.92 to 617.50 ± 29.91 kg/m^3 by location.
2. For particleboard panels, The average MOR (21.44 N/mm^2) ranged from 20.40 ± 0.45 to 22.40 ± 1.37 N/mm^2 (bending parallel to grain) and from 18.10 ± 0.22 to 20.80 ± 0.63 N/mm^2 (bending perpendicular to grain). The MOE ranged from 3655 ± 1.36 to 3452 ± 2.23 N/mm^2 (bending parallel to grain) and from 2839 ± 1.86 to 3148 ± 2.38 N/mm^2 (bending perpendicular to grain). The IB values ranged from 0.401 ± 0.01 to 0.45 ± 0.01 N/mm^2.
3. For MDF panels, the MOR values ranged from 39.10 ± 0.38 to 43.50 ± 1.18 N/mm^2 (parallel to grain) and from 37.5 ± 1.04 to 43.2 ± 0.67 N/mm^2 (perpendicular to grain). The MOR values ranged from 3602 ± 2.82 to 3919 ± 2.19 N/mm^2 (parallel to grain) and from 3518 ± 2.60 to 3929 ± 2.19 (perpendicular to grain). The IB values ranged from 0.83 ± 0.01 to 0.95 ± 0.01 N/mm^2.
4. The results showed significant differences ($P < 0.001$) among the spruce panels (particleboard and medium-density fibreboard) with 16 mm thickness bonded with MUF resin. The MOR, MOE, and IB exceeded the requirements of European standards.

5. The formaldehyde emissions measured from particleboards and MDF by the European small-scale chamber (EN 717-1), gas analysis (717-2), and perforator (EN 120) methods were below the limits of the standards.

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