Article

Influence of Site Conditions and Quality of Birch Wood on Its Properties and Utilization after Heat Treatment. *Part I—Elastic and Strength Properties, Relationship to Water and Dimensional Stability*

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Abstract: This work deals with the quality of birch (*Betula pendula)* wood from different sites and the impact of heat treatment on it. Two degrees of heat treatment were used, 170 °C and 190 °C. The resulting property values were compared with reference to untreated wood samples. These values were wood density, compressive strength, modulus of elasticity (MOE), bending strength (MOR), impact bending strength (toughness), hardness, swelling, limit of hygroscopicity, moisture content and color change. It was supposed that an increase in heat-treatment temperature could reduce strength properties and, adversely, lead to better shape and dimensional stability, which was confirmed by experiments. It was also shown that the properties of the wood before treatment affected their condition after heat treatment, and that the characteristic values and variability of birch properties from 4 sites, 8 stems totally, were reflected in the properties of the heat-treated wood. Values of static MOR were the exception, where the quality of the input wood was less significant at a higher temperature, and this was even more significant in impact bending strength, where it manifested at a lower temperature degree. Impact bending strength also proved to be significantly negatively affected by heat treatment, about 48% at 170 °C, and up to 67% at 190 °C. On the contrary, the most positive results were the MOE and hardness increases at 170 °C by about 30% and about 21%, respectively, with a decrease in swelling at 190 °C by about 31%. On the basis of color change and other ascertained properties, there is a possibility that, after suitable heat treatment, birch could replace other woods (e.g., beech) for certain specific purposes, particularly in the furniture industry.

Keywords: heat treatment; site conditions; birch; thermowood; density; moisture content; dimensional stability; color; mechanical properties

1. Introduction

With anticipated climate change, tree species with a wide ecological valence are starting to become the focus of forest management. One of these species is birch (*Betula pendula)*. In complex forest management, it is necessary to look at these tree species not only as a substitute from an ecological aspect, but also from a production aspect (i.e., to provide enough material for the processing industry). For the processing industry, not only the quantity of raw materials, but in particular qualitative criteria are important for products with higher added value. There are a lack of

studies from the Czech Republic addressing the issue of birch trees in a comprehensive way, including also wood quality. The aim of this research is to demonstrate the potential of birch wood and provide missing knowledge about this issue.

In the last century, a considerable number of pure or mixed birch stands were established in the Czech Republic in order to evaluate different managing methods on stand microclimates, quantity of leaf-fall, soil conditions and forest regeneration of other tree species. At present there are a relatively large number of studies and contributions available, mostly foreign but also Czech, dealing with this issue [1–17]. These studies, however, predominantly assess only increment and volume production, or the influence of different methods of management on the microclimate and regeneration. The quality of wood is also important for wood processing and its subsequent use. This can be understood differently depending on the wood processing technology and the nature of the final product. Qualitative parameters are mostly understood by the industry as the size and frequency of knots, the presence of a false heartwood, the density of the wood (impact on dry mass yield) and above all strength, toughness and modules of elasticity (MOE) [18].

The selection of optimal habitat, the method of establishing a stand and appropriate silviculture methods are tools of forest managers through which they try to optimize and maximize the volume production of forest stands. This issue is well researched in the Czech Republic as well as for the birch in general, and a large number of works have been devoted to it, such as [19–21]. However, in developed European countries, the issue is dealt with more complexly, mainly in relation to higher efficiency and the use of wood as a major renewable raw material. The subject of interest is also the impact of silviculture methods on wood quality and the possibility of subsequent use [22].

Information on the qualitative parameters of wood is very important to the industry and may vary depending on how it is used. Above all, it is the already-mentioned wood density (volume of dry mass in volume unit) as one of the main indicators of wood quality, which significantly affects other properties, as well as strength or dimensional changes of the wood. Wood density, shrinkage, wood strength and flexibility, false heartwood proportion or rate of knots are all among the highly variable features of wood [23], and depend to a large extent on the distance between trees, their social status, the width of their annual rings and their associated latewood share [24]. Thus, forest management has the tools not only to influence the quantitative but also qualitative parameters of wood, and therefore can affect better evaluation and utilization. The issue of the impact of silviculture methods on the quality of wood has been given considerable attention at the international level. Studies from Scandinavian countries, such Sweden [25,26] and Finland [27], as well as other surrounding countries, especially Poland [16], have primarily been devoted to the influence of the initial number of individuals and silviculture methods on the quality of wood. The importance of adequate thinning intensity, in order to not significantly reduce the quality of wood, is referred to in the literature (e.g., in [28]).

Studies from the Czech Republic that deal with the impact of silviculture on the qualitative characteristics of wood in our economically-important tree species are rather rare and do not address the issue in a comprehensive way. Although there are a considerable number of experimental birch plots in the Czech Republic where different silviculture methods have been applied, there is no relevant assessment of site impact and silviculture methods on the quality of wood.

In the Czech Republic, birch is considered to be an important soil-improving, reinforcing and pioneering tree species, while at the same time it is often considered undesirable due to a rapid initial growth that can adversely inhibit the growth of other tree species. At present, with regard to the decline of spruce stands, an opportunity has arisen to use the "creative forces of nature" and possibly purposefully regulate the development of self-seeded birch trees until their felling age. For example, in Finland, birch is the third main tree species just after spruce and pine, and is often used to produce valuable veneers ("Karelian" birch), but it is also used as solid timber, or to be heat-treated for final use [29]. One of the key research reports on Scandinavian birch is, for example, a study [22] which comprehensively deals with the cultivation of birch, including impact on wood properties.

In terms of processing, birch is a medium-hard timber with good mechanical properties and extensive processing possibilities. It has a low resistance to wood-destroying fungi attacks and

weather conditions, and is therefore not suitable for outdoor use. Due to the aforementioned low durability, typically small dimensions and frequent curvature, the use of birch timber for construction purposes is not considered. When extracting precious varieties for veneering and plywood use, extraction in the winter and fast processing are necessary, as gradual irreversible color change to the wood may otherwise occur, and will degrade the section for use on ornamental veneers [30]. It is clear, however, that birch wood has comparable properties to the tree species currently being used, even after heat treatment [31,32], and can be appreciated in a better way than is currently happening in the Czech Republic (firewood) for which it certainly deserves more attention.

The aim of this paper is at least to contribute to the possibility that forest owners and managers in the Czech Republic obtain important information about the influence and meaningfulness of activities carried out in relation to the quality of birch wood, and consequently its better appreciation [22,30,31,33]. It is through heat treatment that some of the negative features of birch can be reduced. In terms of the heat-treatment process and ThermoWood properties, which are widely used in Finland and other western European countries, much has been described [34–43]. In the context of this paper, which is a free continuation of a 2018 paper by Borůvka et al. [31] that focused on the study of elasticity and strength properties and the dimensional stability of birch wood from different sites before and after heat treatment, there should be another prepared paper. This paper will focus on the surface properties of birch wood in the form of veneers (color, hardness and roughness), and in particular on an economic evaluation of the thermo-treatment process and its possible practical uses in the Czech Republic.

In any case, it is necessary to realize that via the thermal modification of wood many of its properties can be permanently improved, and in regards to birch this includes its low durability in the native state. In addition, high temperature treated wood is naturally friendly as only heat and steam and no additional chemical or other components are used during the production process.

2. Materials and Methods

Samples of birch tree stems were collected in forest stands of the School Forest Enterprise of the Czech University of Life Sciences in Kostelec nad Černými Lesy for analysis (see location in Figure 1) [44].
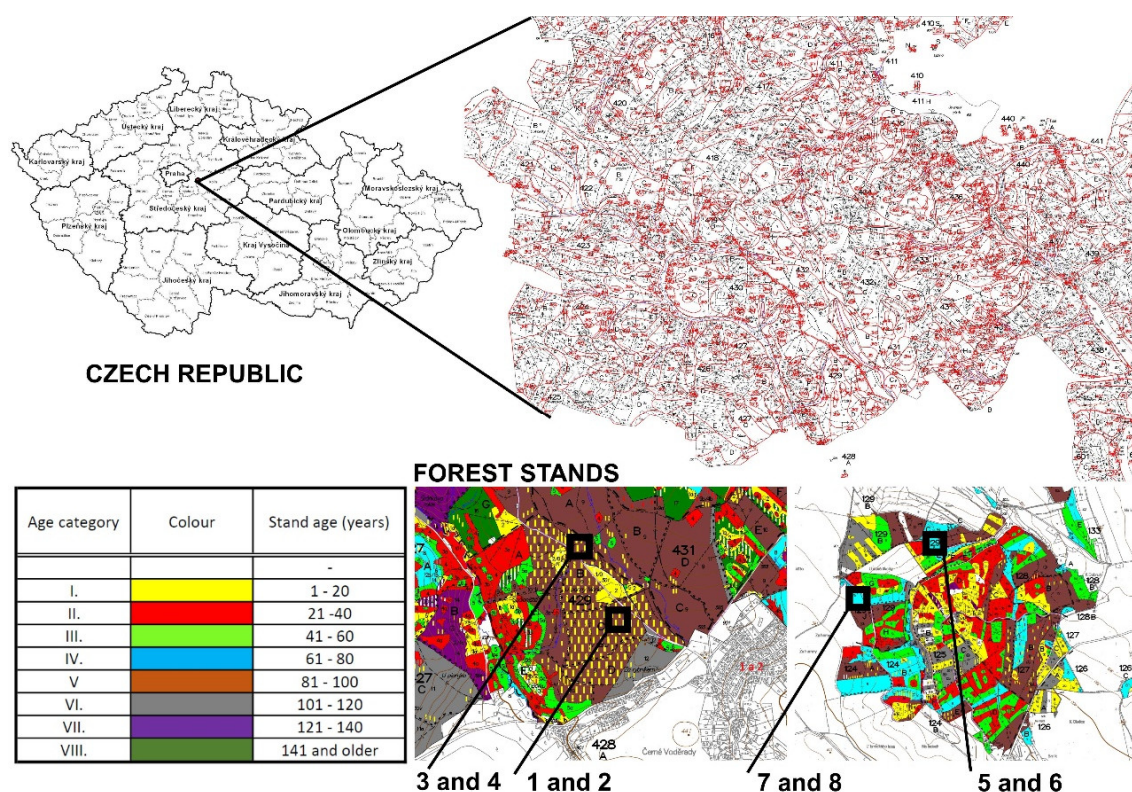

Age category	Colour	Stand age (years)
		-
I.		1 - 20
II.		21 - 40
III.		41 - 60
IV.		61 - 80
V		81 - 100
VI.		101 - 120
VII.		121 - 140
VIII.		141 and older

**Figure 1.** Location of study areas in the Czech Republic and description of particular forest stands.

We cut samples from eight trees in total, coming from four stands. The sections (5 m long) were cut off from the basal part of each sample tree. The diameter of the trees at breast height ranged from 32 to 45 cm, with heights from 24 to 29 m and ages from 58 to 81 years (Table 1). The share of birches in these stands was between 5 and 15%. The characteristics of the area where the samples were taken were as follows: In terms of natural conditions, the territory belonged to Nature Forest Area 10 (Central Bohemian Uplands) [45] and the rock subsoil for stems 1–4 was formed by granite rock, or in the case of stems 5–8 by claystone [46]. Using the Forest Management Institute typological system [47], soil in the case of stems 1, 2, 5 and 6 was characterized by an organic acidic range, and for stems 3, 4, 7 and 8 by an organic range of nutrients. Stems 1–4 were collected at altitudes of 440 to 460 m and stems 5–8 at altitudes of 340–380 m.

Table 1. Parameters of individual trees.

	Height (m)	Dbh* (cm)	Age (year)
1	26	37	68
2	29	34	80
3	28	42	81
4	26	40	65
5	28	34	68
6	27	45	70
7	25	32	58
8	24	36	62
Mean	27	38	69
St. Deviation	2	4	8

* Diameter at breast-height.

A section was made from each stem in the basal section (see the diagram in Figure 2). A disc for the hardness test was cut from the section (see Figure 2c), and the remainder of the section was then cut into planks, followed by prisms measuring $25 \times 50 \times 1000$ mm (R × T × L). From each prism, 6 test pieces of dimensions R × T × L = $20 \times 20 \times 300$ mm were made for a mutual comparison that would ensure the longitudinal parallelism of reference test specimens for the two selected heat treatment steps, and lateral parallelism for the two series of tests (see the cut diagram in Figure 2d). In addition, test specimens with transverse dimensions of 20×100 mm and a 300-mm length in the direction of the fibers were removed from the appropriate remains of the planks, in the amount of 180 pieces, for color measurement and subsequent determination of the most appropriate level of treatment (see the method used for color measurement in the following paragraphs).
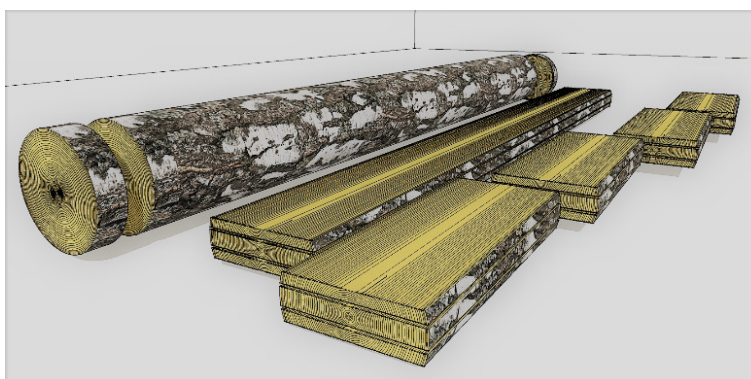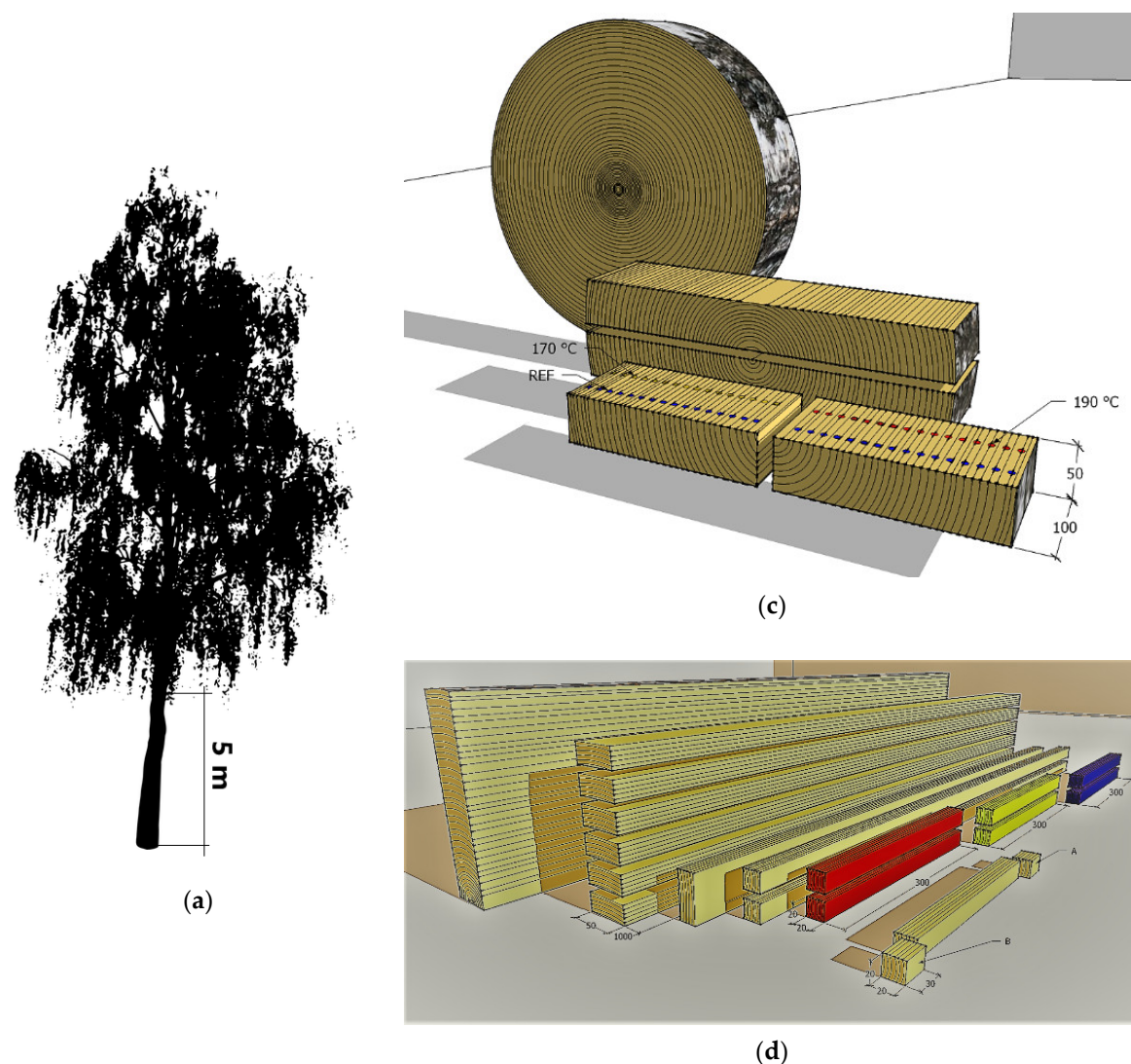

(**b**)

Figure 2. Cutting diagram for test specimen preparation. (**a**) Basal section of the trunk, (**b**) cutting of selected trunk section, (**c**) cutting of the disc and method for the experimental measurement of hardness and (**d**) cutting diagram for preparation of testing samples. Blue coloring = reference, with no treatment; yellow coloring = heat treatment at 170 °C; red coloring = heat treatment at 190 °C; upper set of samples = for the determination of impact bending strength; bottom set of samples = for the determination of dynamic elasticity modulus, static elasticity modulus and bending strength; small samples marked A and B = for determination of density, compressive strength, swelling and moisture content.

A total of 720 primary test specimens were manipulated in the series of 30 pieces using 3 treatment steps, including untreated reference samples, from 8 stems (see the diagram in Figure 2d). Samples for hardness tests were made according to the scheme in Figure 2c. Samples with dimensions of R × T × L = 20 × 20 × 30 mm for density determination, swelling and compressive strength were cut from the ends of 300 mm samples after the end of the bending and impact bending tests. The general condition was that none of the specimens contain knots, cracks or reaction wood, and that the fiber deflection in the longitudinal direction be as small as possible (<5°). The specimens were then conditioned to equilibrium moisture content in climatic chamber CLIMACELL 707 (BMT Medical Technology Ltd., Brno, Czech Republic) with a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C.
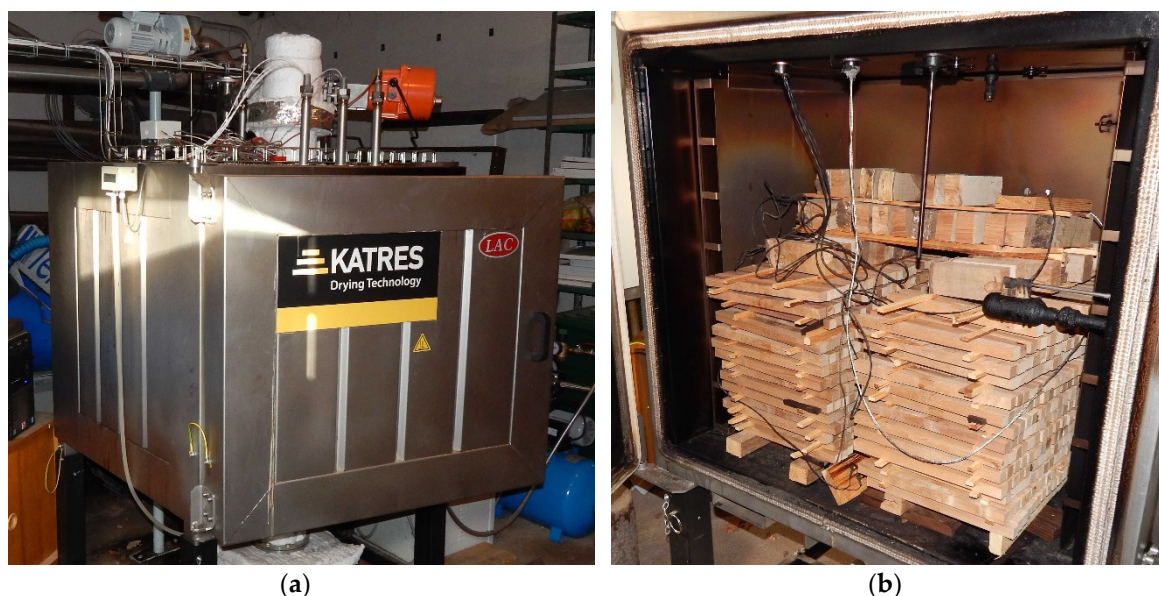
(**a**) (**b**)

Figure 3. (**a**) Photograph of the thermal chamber used for the treatment, (**b**) including the arrangement of the samples inside.

A third of the primary test specimens were subsequently subjected to thermo-treatment in an air atmosphere at 170 °C, then a different third at 190 °C, in accordance with the known Finnish patent for the thermal modification of wood, Pat. EP-0759137 [29,37]. The production was carried out in a laboratory high temperature chamber A type KHT (Katres Ltd., Jihlava, Czech Republic), see Figure 3, with a filling capacity of 0.38 m³, a maximum load capacity of 150 kg, a maximum operating temperature of 250 °C and a power consumption of 3 kWh. During the treatment we used a water curtain spray unlike the steam used in Finnish technology. The detailed course of the production is shown in Figure 4. The thermally modified test specimens were then air conditioned again to equilibrium moisture content in an environment with a relative humidity of 65 ± 5% and a temperature of 20 ± 2 °C.

(**a**) (**b**)
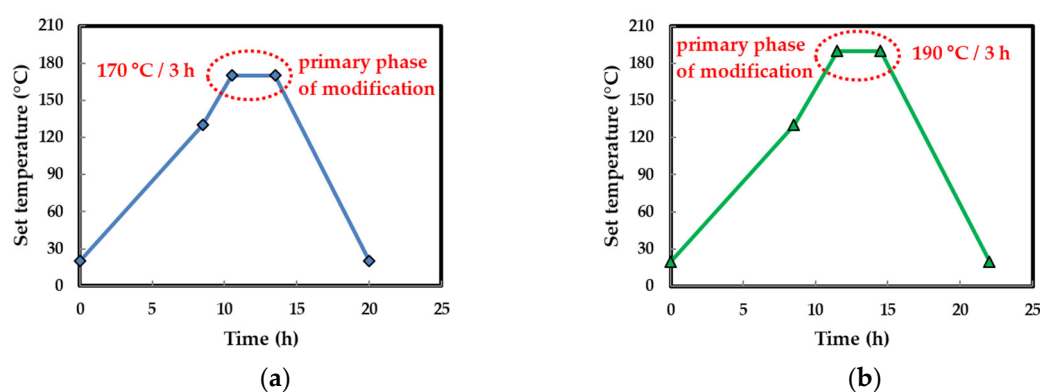
Figure 4. Diagram of the heat-treatment procedure at (**a**) 170 °C and (**b**) 190 °C.

All of the tests were carried out completely according to the testing standards of Czech national standardization [48–58], and the determination of the dynamic elasticity modulus was based on the methodology specified in the Fakopp instrumentation manual [59].

Standard color measurement (CIE*L**a*b*) was carried out on specimens in untreated and heat-treated conditions with a Spectrophotometer CM-600d (Konica Minolta, Osaka, Japan). The total color difference of the wood related to the white color before and after the thermal modification was determined by the colorimetric parameter ΔE, which is calculated as the square root of the sum of the squares of the partial deviations (ΔL* is the difference in the brightness axis, Δa* is the difference in

the green-red axis and Δb* is the difference in the blue-yellow axis). It therefore represents the shortest distance between coordinates of the standard, which in our case is a white color and a sample in the color space. [48,49].

As one of the comparable properties, color was additionally measured on samples of birch with 160 °C, 180 °C and 200 °C heat treatments, and on steamed and native beech samples, for comparison with the selected 170 °C and 190 °C treatment degrees, in order to evaluate the potential of birch wood to substitute beech wood for practical uses. Heat treatments at 160 °C, 180 °C and 200 °C were carried out in the same way as at 170 °C and 190 °C (see Figure 4). This means that up to a temperature of 130 °C, the rate of increase was about 13 °C per hour, and the peak stage was reached at about 20 °C per hour. The final cooling after the end of the primary phase of modification took place at a rate in the range of 20–25 °C per hour.

The sound propagation velocity in the test specimens was determined by measuring the ultrasonic pulse transit time between the two pressure piezoelectric probes of the Fakopp Ultrasonic Timer instrument (Fakopp Enterprise Bt., Ágfalva, Hungary). From the dynamic modulus of elasticity (MOE) in literature [60] arises:

$$E_d = c^2 \cdot \rho \tag{1}$$

where E_d is the dynamic modulus of elasticity in MPa, c is the speed of sound propagation in m.s^{-1} and ρ is the wood density in kg.m^{-3}. [59].

Charpy's hammer (CULS, Prague, Czech Republic) was used to ascertain impact bending strength (toughness). The direction of the hammer impact was tangential. [55].

Static bending strength (MOR) and modulus of elasticity (MOE) were determined on the Tira 50 kN testing machine (Tira GmbH, Schalkau, Germany) under the load of two forces at quarter distances from the supports to eliminate shear stress (see Figure 5). [53,54].
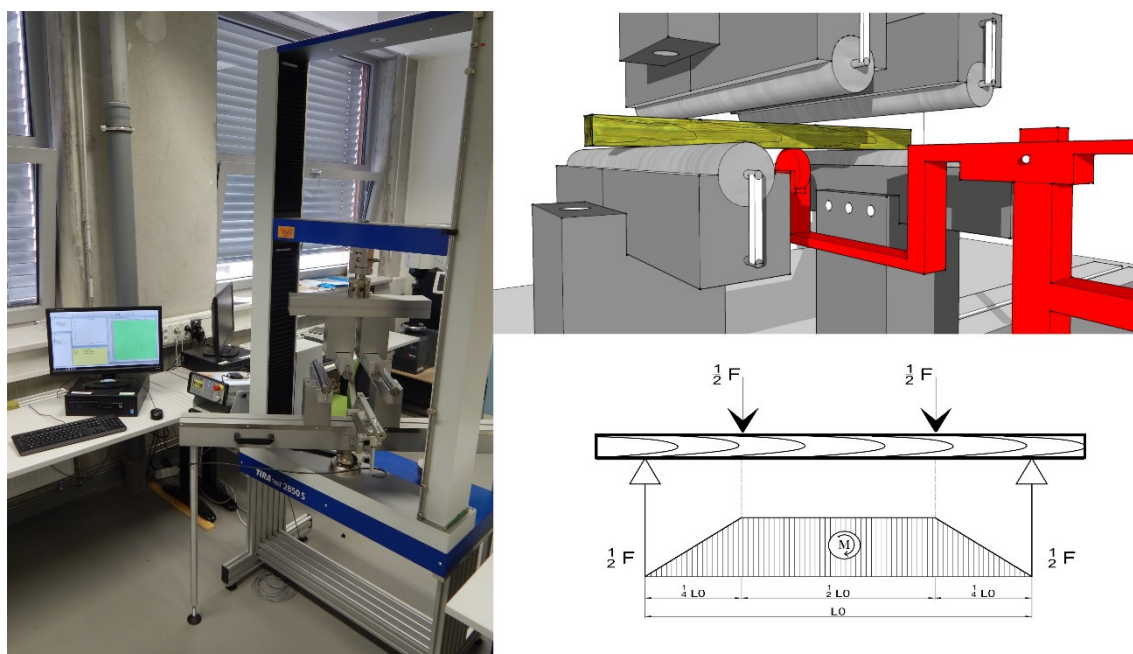
Figure 5. Photo of Tira 50 kN testing machine, detailed picture of loading and schema of bending moment with two load forces.

Brinell hardness the radial plane was measured with the hardness tester DuraVision-30 (Struers GmbH, Willich, Germany) using a force of 500 N. [57,58].

Compressive strength was determined using the Tira 50 kN testing machine, and we also obtained specific strengths in kN.m/kg by relating the acquired values to density. [52].

Swelling was determined in accordance with the standard in such a way that we subjected the samples to two cycles of repetition (swelling–drying). Drying as part of this test and for determination of equilibrium moisture content was done in the Binder FD 115 lab kiln (Binder Inc., Tuttlingen, Germany) at 103 ± 2 °C. [50,56].

Basic density was calculated as the proportion of wood dry mass and volume in the swollen state (maximum volume). Limit of hygroscopicity, or the fiber saturation point (FSP) in %, was also determined via a calculation according to the following relationship:

$$FSP = \left(\frac{1}{\rho_B} - \frac{1}{\rho_0}\right) \cdot \rho_W \cdot 100 \qquad (2)$$

where ρ_0 is the oven-dry density in g.cm⁻³, ρ_B is the basic density in g.cm⁻³ and ρ_W is the density of water in g.cm⁻³. [51].

For statistical analysis, analysis of variance (ANOVA) was used to evaluate the significance of individual factors. Duncan's Multiple Range Test was used to compare the properties of wood among the different treatments and sites (moreover trees and cycles of swelling and shrinkage). A linear regression model was used to set the value of correlation between selected properties. The same significance level of $\alpha = 0.05$ was used for all of the analyses. [61].

3. Results and Discussion

Color measurements were taken of untreated samples and samples with heat treatment at 160 °C, 170 °C, 180 °C, 190 °C and 200 °C, as well as of native and steamed beech samples, in order to select a suitable birch treatment temperature for the purpose of esthetical appearance (see Table 2 and Figure 6). On the basis of the obtained results and previous research [31], the temperature ranges of 170 °C and 190 °C were selected for the main treatment and subsequent evaluation.

Table 2. Color parameters (mean / standard deviation).

	L*	a*	b*	ΔE*	ΔE*/REF
Untreated birch	80.1/0.4	5.9/0.1	19.0/0.2	82.5/0.4	-
Birch treated at 160 °C	69.1/1.4	8.0/0.4	19.9/0.1	72.3/1.3	−12.3
Birch treated at 170 °C	65.7/0.8	7.2/0.2	17.1/0.3	68.3/0.7	−17.2
Birch treated at 180 °C	58.5/1.2	8.6/0.2	21.2/0.4	62.8/1.0	−23.8
Birch treated at 190 °C	49.6/0.3	11.8/0.3	23.8/0.2	56.3/0.3	−31.8
Birch treated at 200 °C	34.7/1.6	8.8/1.0	14.1/1.8	38.5/2.3	−53.3
Untreated beech	73.1/0.8	8.0/0.3	20.3/0.3	76.3/0.7	−7.5
Steamed beech	66.8/0.8	11.5/0.2	21.3/0.5	71.0/1.0	−13.9

Valid *N* = 30 (for all series). L* is brightness, a* is value in the green-red axis, b* is value in the blue-yellow axis, ΔE*/REF is decrease in ΔE* values compared to untreated birch in %.

(**a**)   (**b**)   (**c**)

(**d**)   (**e**)   (**f**)

(**g**)   (**h**)
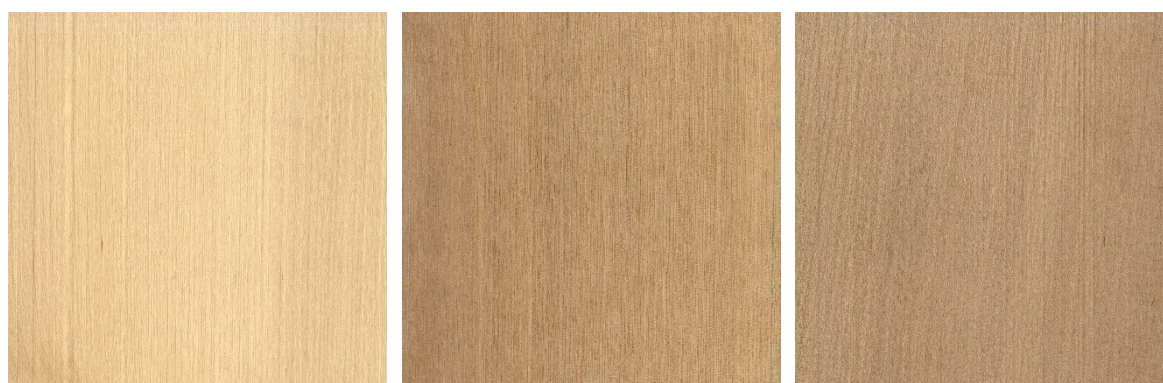
Figure 6. (**a**) Untreated birch, (**b**) birch treated at 160 °C, (**c**) birch treated at 170 °C, (**d**) birch treated at 180 °C, (**e**) birch treated at 190 °C, (**f**) birch treated at 200 °C, (**g**) untreated beech, (**h**) steamed beech.

Table 3 contains a summary of the basic statistical characteristics of all of the tested properties of heat-treated birch wood compared to the native wood, regardless of which stand and stem they came from. Subsequently, the obtained data were subjected to factor analysis (see Figures 7–9) and multiple comparisons (see Duncan´s tests, Table A1–8). A more detailed analysis is included at the end of this chapter, notably a drastic decrease in impact bending strength even at a lower temperature treatment (170 °C), in the case of bending strength at the higher temperature (190 °C), and the almost insignificant influence of heat treatment on the dynamic modulus of elasticity and compressive strength values.

Table 3. Basic statistical analyses of the properties for untreated and heat-treated birch wood.

Properties	Heat Treatment Degree	Minimum	Mean	Maximum	Std.Dev.	Coef.Var. (%)
Density	REF	519	652	814	53	8.1
(kg/m³)	170	492	647	774	52	8.1
	190	461	637	768	58	9.1
Oven-dry density	REF	491	634	775	50	7.9
(kg/m³)	170	470	625	748	52	8.4
	190	445	618	725	55	8.9
Basic density	REF	425	517	628	38	7.3
(kg/m³)	170	414	523	620	40	7.6

		190	414	535	628	43	7.9
Limit of	REF	24	36	45	4	10.8
hygroscopicity	170	23	31	41	3	10.8
(%)	190	12	25	53	5	18.4
Radial swelling	REF	4.0	7.9	13.5	1.4	17.8
(%)	170	3.8	7.2	11.4	1.3	18.5
	190	1.4	5.8	12.7	1.5	26.5
Tangential swelling	REF	6.2	12.5	17.0	1.8	14.5
(%)	170	6.5	11.0	14.6	1.5	13.4
	190	1.2	8.6	21.1	2.1	24.6
Volumetric swelling	REF	14.3	22.5	29.6	2.6	11.4
(%)	170	13.2	19.5	26.8	2.3	12.0
	190	5.9	15.5	31.7	3.3	21.0
Compressive strength	REF	32.0	59.6	80.6	9.2	15.4
(MPa)	170	39.9	62.9	85.8	8.5	13.6
	190	19.2	63.1	89.0	11.6	18.5
Specific	REF	42.8	91.3	112.4	11.5	12.6
compressive strength	170	63.9	97.1	128.0	9.9	10.2
(kN.m/kg)	190	27.0	99.0	134.4	15.3	15.4
Static	REF	3809	10559	36686	2884	27.3
modulus of elasticity	170	6547	13699	25514	3104	22.7
(MPa)	190	2019	12356	23974	2813	22.8
Dynamic	REF	6642	14316	35070	4230	29.5
modulus of elasticity	170	2234	15212	31931	4939	32.5
(MPa)	190	5688	14140	29587	3373	23.9
Modulus of rupture -	REF	16.8	82.0	122.2	17.5	21.4
bending strength	170	17.3	88.2	133.5	23.7	26.9
(MPa)	190	9.9	61.1	123.1	22.6	37.1
Toughness - impact	REF	0.7	8.1	13.2	2.9	35.6
bending strength	170	0.6	4.2	11.1	2.3	53.8
(J/cm^2)	190	0.3	2.7	13.4	2.1	78.6
Hardness	REF	12.0	28.0	71.0	9.9	35.5
in the radial plane *	170	12.0	33.9	68.0	12.9	38.1
(MPa)	190	12.0	29.5	64.0	13.0	44.1
Equilibrium	REF	11.9	12.6	13.0	0.3	2.0
moisture content	170	8.6	10.9	11.5	0.4	3.8
(%)	190	6.1	9.6	10.5	0.7	7.2

Valid N = 240 for all properties within heat treatment degree (* exception: N = 416), REF = reference, with no treatment, 170 = heat treatment at 170 °C, 190 = heat treatment at 190 °C.

The paper includes the results of a single-factor analysis of Figures 7a,c,d, 8a–e, 9a–d,i and 10 (impact of heat treatment), and a two-factor analysis of Figures 7e–h, 8g,h, 9e–h,j–l and 11 (impact of heat treatment and stand, or stem or cycles of repeated swelling and shrinkage), while the connecting line in the graphs between individual stands (sites) or stems are here only for better clarity and trend analysis (in fact, they should not be joined). At the same time, the existing known correlations

between the static and dynamic modulus of elasticity and compressive strength on density (Figure 7b) and swelling on density (Figure 8f) were confirmed, in regards to the dependence of all of the samples (i.e., reference and thermally modified) [62]. It was also shown that elastic properties responded to heat treatment more positively than strength properties; see Figure 9b,c, which exhibited 22% increase in static bending strength at 170 °C, and up to 43% at 190 °C in favor of elasticity. It was also shown that dynamic stress (Figure 9d) was much harder on the heat-treated wood than static stress (Figure 9c) because of the higher brittleness—although the hardness, at least on the surface layers, was relatively higher (see Figure 9i,j). At 170 °C, this difference was approximately 56% and at 190 °C approximately 41%, to the detriment of dynamics.

(**a**)

(**b**)

(**c**)

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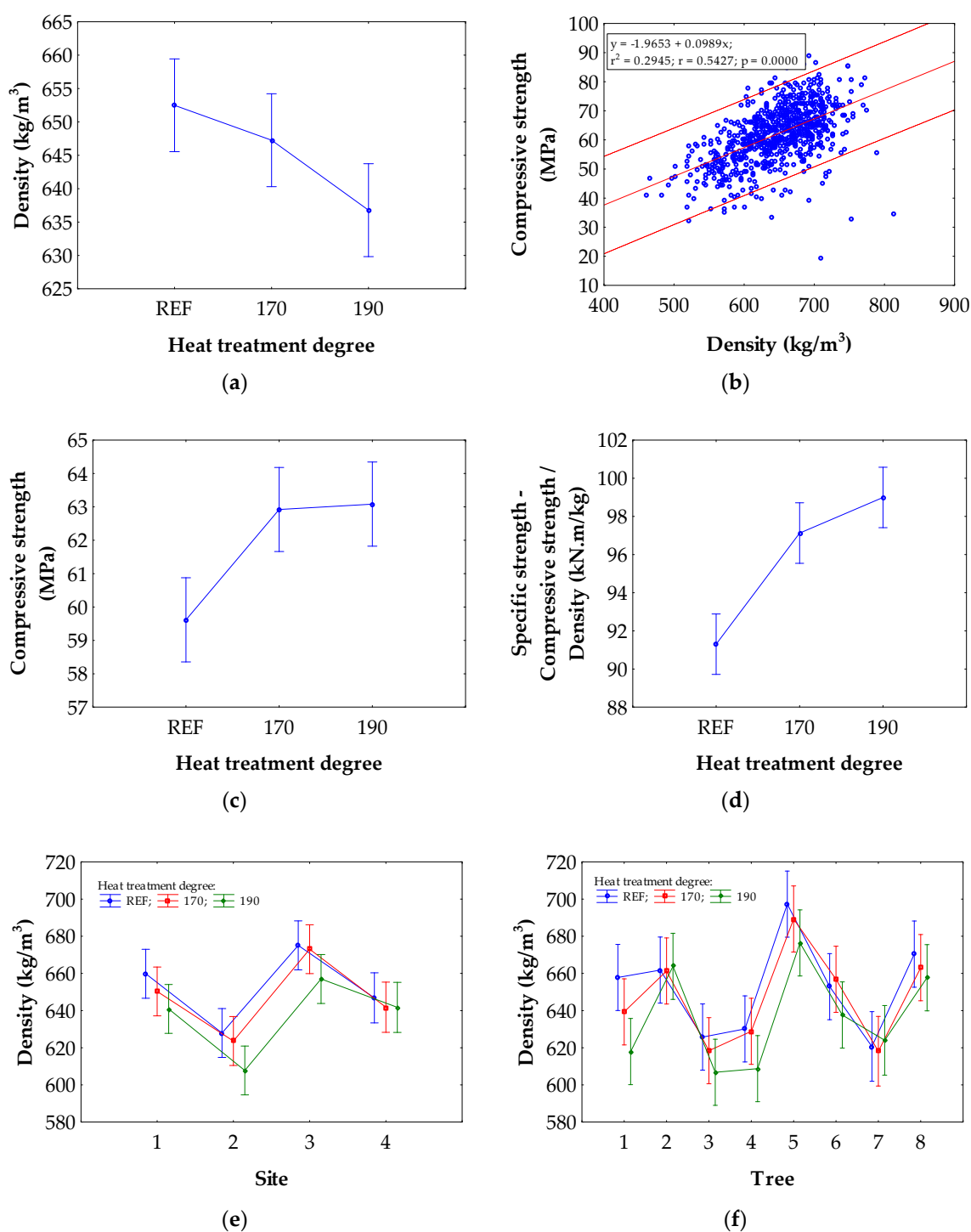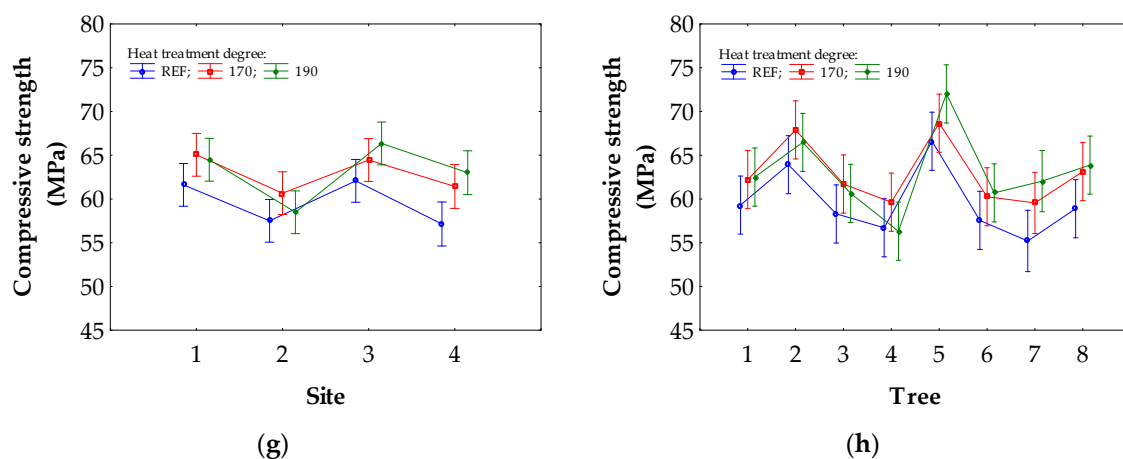
Figure 7. Graphic visualization of the effect of heat-treatment temperature on (**a**) wood density, (**c**) compressive strength and (**d**) specific compressive strength. Graphic visualization of the effect of heat-treatment temperature and site on (**e**) density and (**g**) compressive strength. Graphic visualization of the effect of heat-treatment temperature and tree on (**f**) density and(**h**) compressive strength. The relationship between density and compressive strength, regardless of the heat-treatment degree, is shown in (**b**). Significance level is 95%. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.

Most important of all, and the main objective of this paper, was verification that the properties of wood prior to treatment have an affect on its condition after heat treatment. Their variability, irrespective of any particular stand or stem, was 10–30%, depending on the property and the treatment level. As predicted, it was shown that the characteristic values and variability of the [24] birch wood properties from 4 stands or 8 stems were manifested on heat-treated wood. The exception was static bending strength (Figure 9e), where at a higher temperature (190 °C) the quality of the input wood was not as significant. This was shown even more markedly in regards to impact bending strength (Figure 9g), which manifested itself at a lower temperature (170 °C). Impact bending strength was also negatively affected by the heat treatment most significantly at 170 °C by about 48%, and at 190 °C with a decrease of up to about 67% and a drop of about 26% for MOR (see Table 4). Conversely, the most positive affects were an increase in the modulus of elasticity and hardness at 170 °C by about 30% and 21%, respectively, and a decrease in swelling at 190 °C by about 31%, which was associated with an adequate decrease in the fiber saturation point (see Table 4). The higher shape stability of the heat-treated wood was obviously proven, and the wood was even found to be more resilient to repeated "swelling–shrinkage" cycles, which showed some instability in the native wood compared to the ThermoWood (see Figure 11).

(**a**)

(**b**)
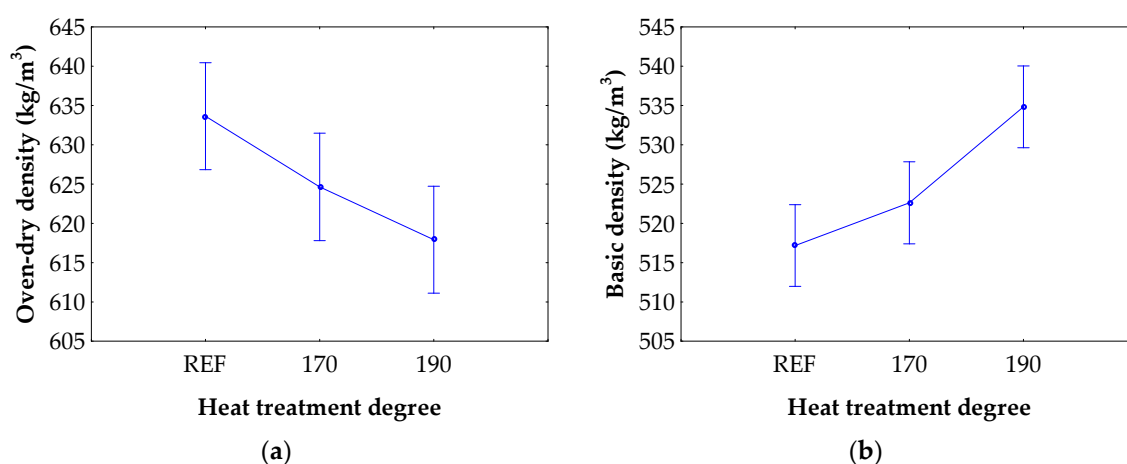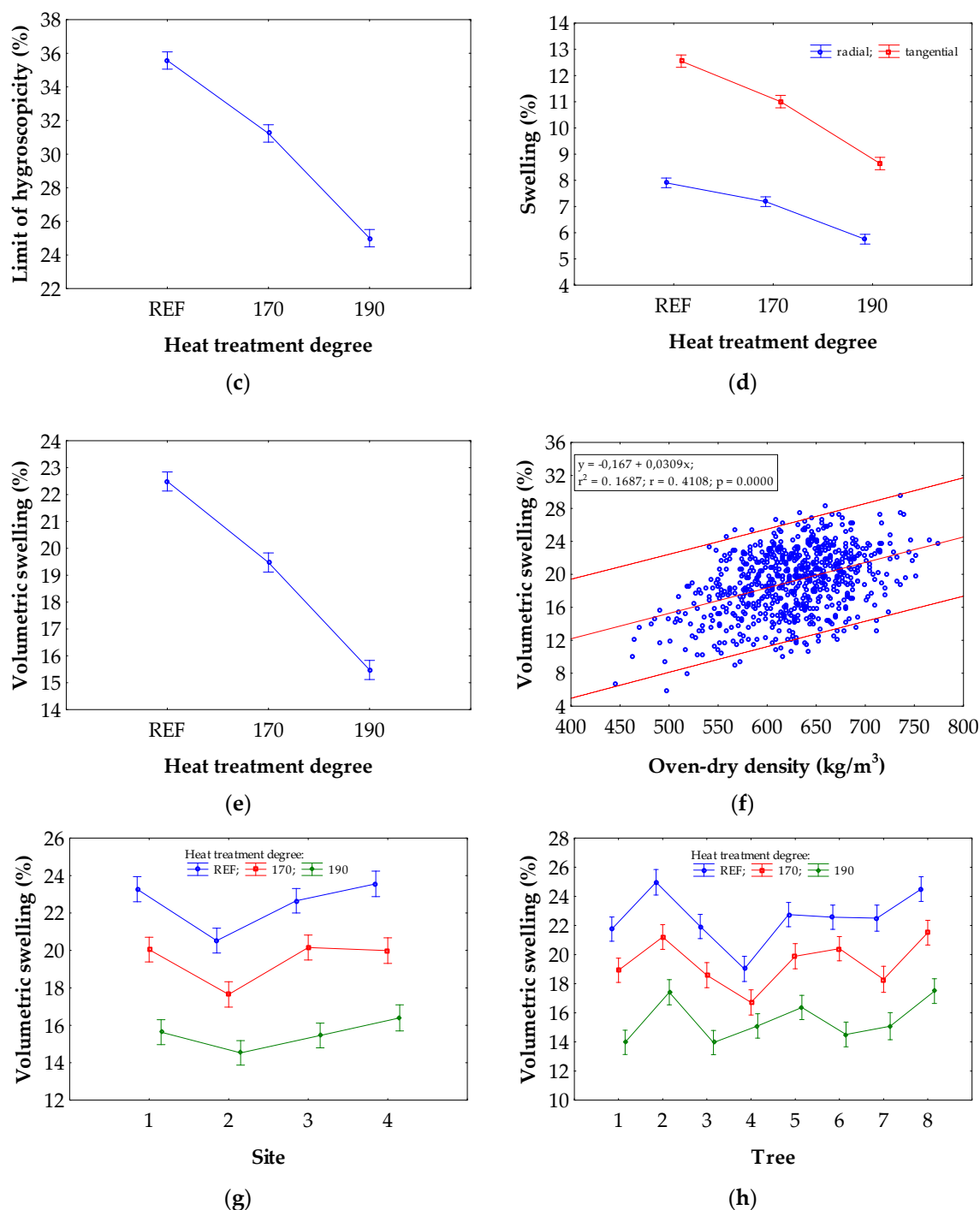
Figure 8. Graphic visualization of the effect of heat-treatment temperature on (**a**) oven-dry density, (**b**) basic density, (**c**) limit of hygroscopicity (fiber saturation point – FSP), (**d**) radial and tangential swelling, and (**e**) volumetric swelling. (**f**) The relationship between density and volumetric swelling, regardless of the heat-treatment degree. (**g**) Graphic visualization of the effect of heat-treatment temperature and site on volumetric swelling. (**h**) Graphic visualization of the effect of heat-treatment temperature and tree on volumetric swelling. Significance level is 95%. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.

In regards to the resulting birch wood properties from individual stands (sites), the research proved that acidic soil at lower altitudes is the best, but this requires more extensive research. This conclusion is quite logical, since birch wood from fertile soils should have bigger growths and hence larger volumes, but also a somewhat lower density. The values of other properties relate to this, such

as the tree number 3. In any case, the priority of this research was mainly to demonstrate the influence of the input material quality with respect to selected treatment levels and the resulting relevant properties.
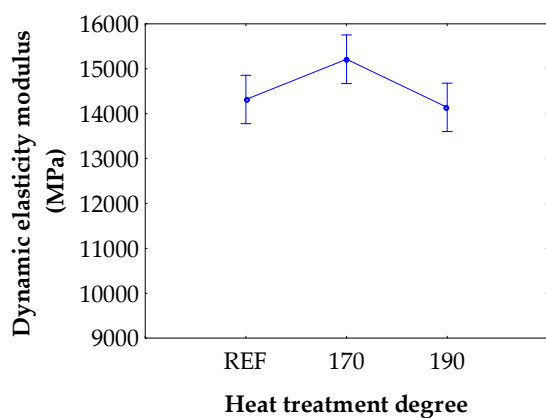
(**a**)
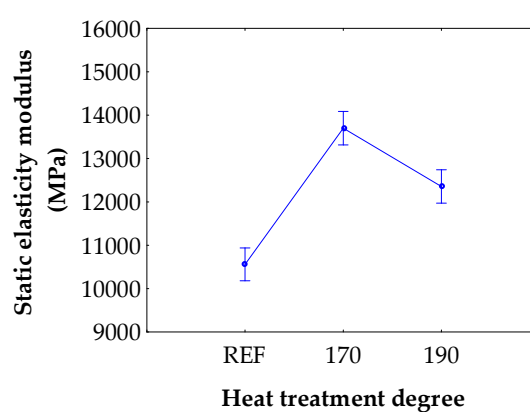
(**b**)
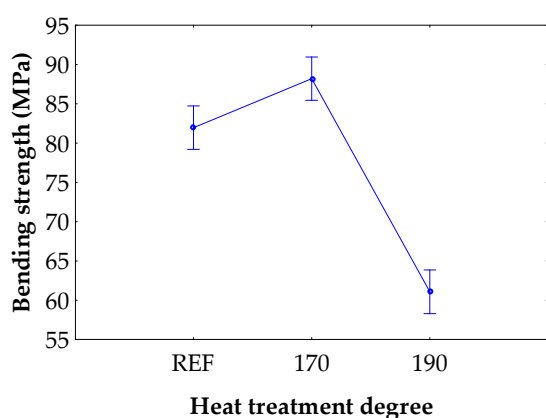
(**c**)
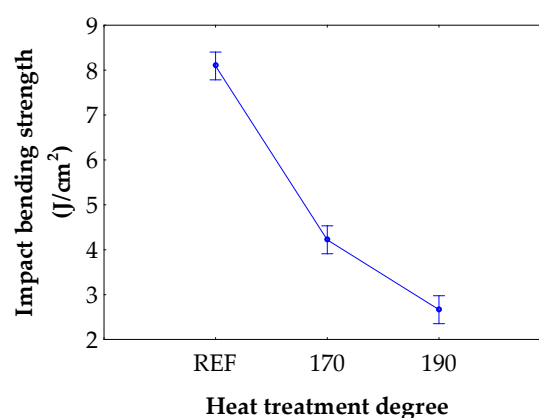
(**d**)
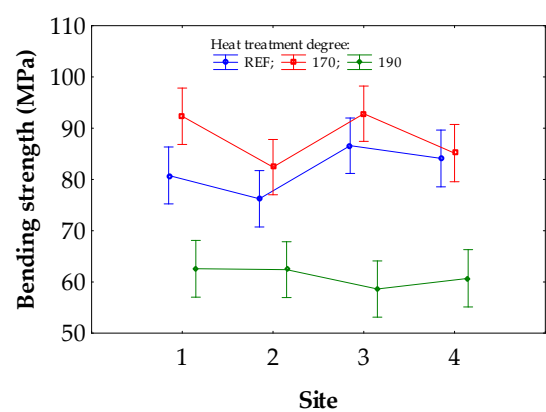
(**e**)
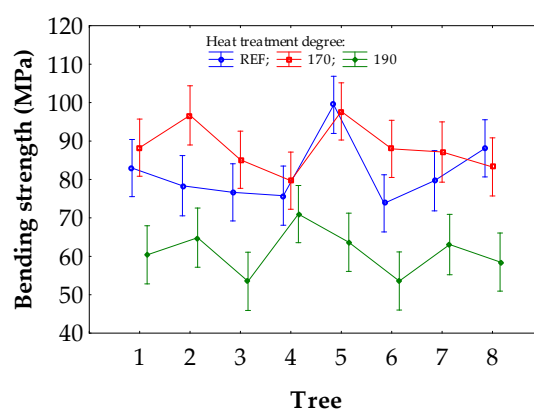
(**f**)
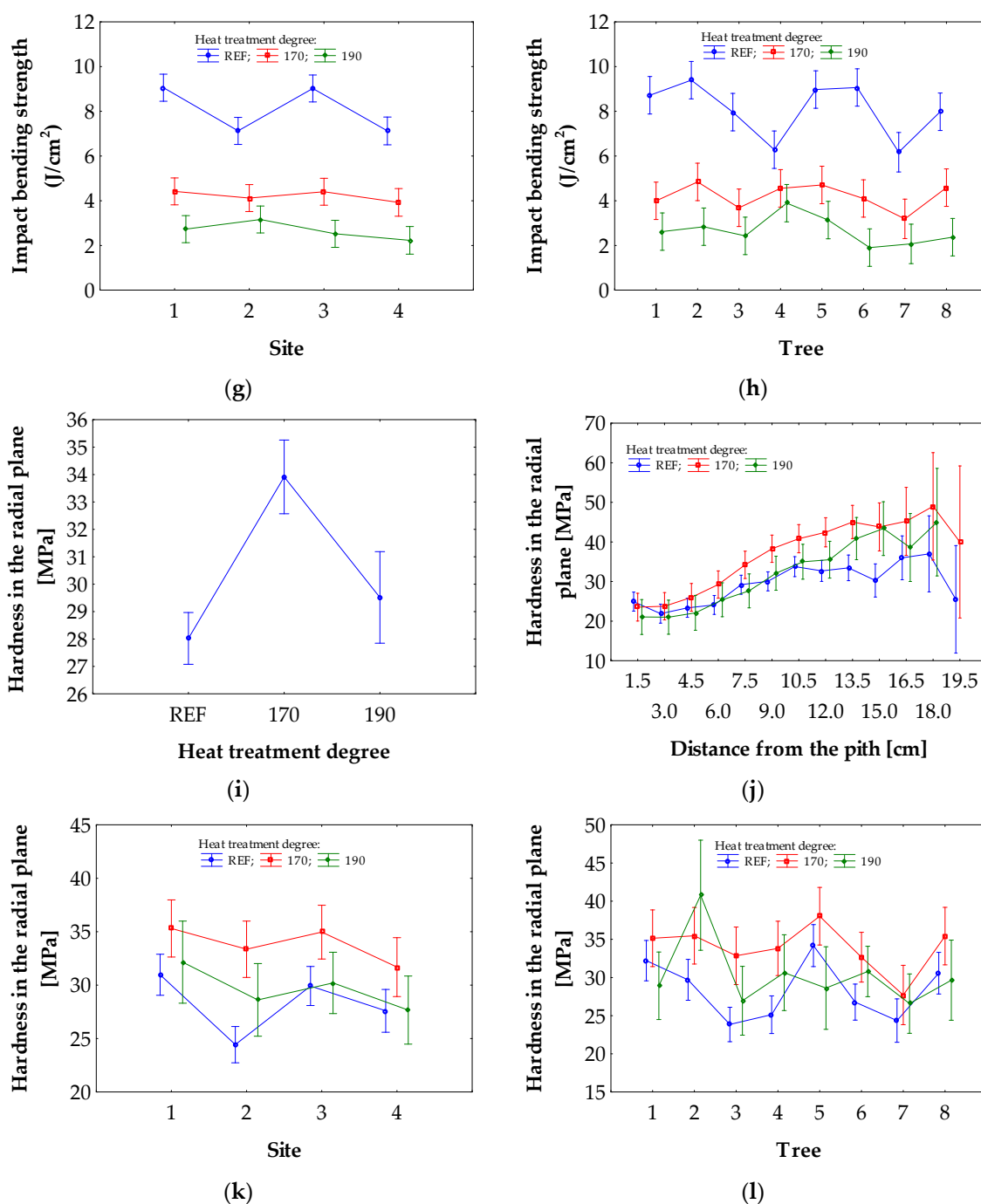
Figure 9. Graphic visualization of the effect of heat-treatment temperature on (**a**) dynamic elasticity modulus, (**b**) static elasticity modulus, (**c**) bending strength, (**d**) impact bending strength and (**i**) hardness in the radial plane. Graphic visualization of the effect of heat-treatment temperature on (**j**) hardness profile in the horizontal direction along the radius of the tree. Graphic visualization of the effect of heat-treatment temperature and site on (**e**) bending strength, (**g**) impact bending strength and (**k**) hardness of the radial plane. Graphic visualization of the effect of heat-treatment temperature and tree on (**f**) bending strength, (**h**) impact bending strength, and (**l**) hardness in the radial plane. Significance level is 95%. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.
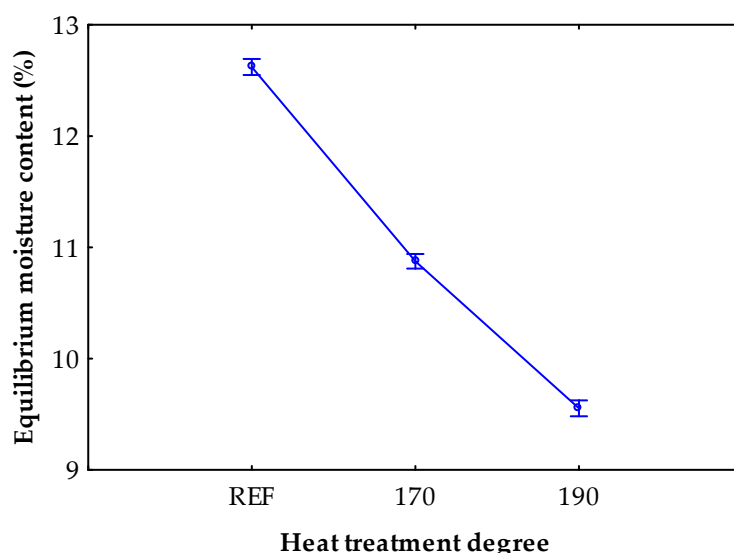
Figure 10. The equilibrium moisture content of birch wood after heat treatment and subsequent air conditioning at temperature 20 ± 2 °C and a relative humidity of 65 ± 5%. Significance level is 95%. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.
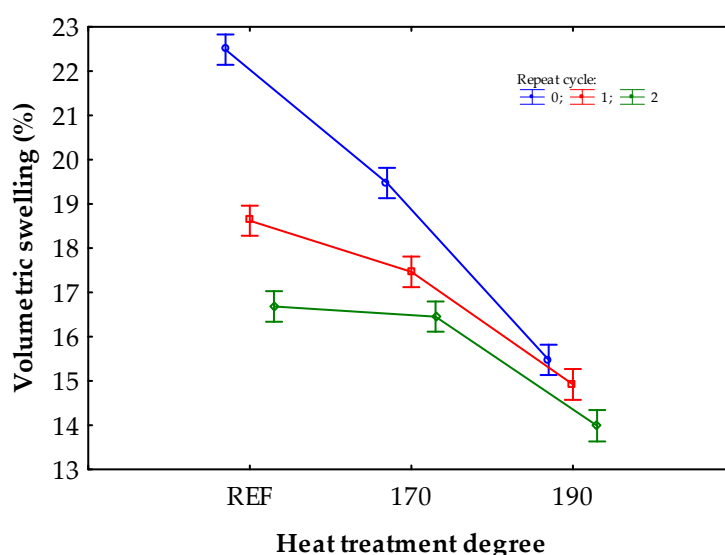
Figure 11. The change of volumetric swelling after repeating one and two cycles of storage under the water surface and re-drying. Significance level is 95%. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.

Regarding the effect of heat treatment on the properties of wood, it was essential that the selected degrees for final treatment caused changes in properties that were relatively on the desired level. The general trend corresponded with the results specified for the example in the handbook from the International ThermoWood Association [37] and others [32,38]. However, it is necessary to realize that hardwoods contain a higher proportion of "fill-type" hemicelluloses (i.e., xylans) [63], and thus are more susceptible to higher treatment temperatures in terms of mechanical properties. The temperature of 170 °C and in particular 190 °C were both acceptable in terms of color and other properties, except for the ability of the treated wood to withstand the dynamic load. This must be taken into consideration, and the wood should not be exposed to this type of load.

Table 4. Changes in the properties of heat-treated birch wood in comparison to the reference (untreated) birch in %.

	170/REF	190/REF
Density	−0.8	−2.3
Oven-dry density	−1.4	−2.5
Basic density	1.2	3.5
Limit of hygroscopicity	−13.9	−30.6
Radial swelling	−8.9	−26.6
Tangential swelling	−12.0	−31.2
Volumetric swelling	−13.3	−31.1
Compressive strength	5.5	5.9
Specific compressive strength	6.4	8.4
Static modulus of elasticity	29.7	17.0
Dynamic modulus of elasticity	6.3	−1.2
Modulus of rupture (bending strength)	7.6	−25.5
Toughness (impact bending strength)	−48.1	−66.7
Hardness in the radial plane	21.1	5.4
Equilibrium moisture content	−13.5	−23.8
Total color change	−17.2	−31.8

Overall, there is a possibility that, after appropriate heat treatment, birch could replace beech for certain specific purposes, particularly in the furniture industry. One of the options is the application of heat-treated veneers, which are also ideal finalization in terms of the economy, and this is likely the most appropriate direction for research in this area. Based on preliminary research, it has been shown that the color potential of heat-treated birch wood veneers is very interesting, and it is important to choose a time limit for the peak stage of a particular treatment step (see Figure 12). Heat treatment produces a uniform color change in wood into warm brown tones across the entire cross-section, and also creates the appearance of exotic wood. As a benchmark, the most suitable properties other than color will be roughness and in particular hardness. These will be important variables for assessing the surface quality of furniture components.

(**a**)	(**b**)

Figure 12. (**a**) Sample of untreated birch veneer. (**b**) Sample of treated veneer under a temperature of 200 °C for 2 hours.

4. Conclusions

It has been proven that the properties of wood prior to treatment have an effect on its condition after heat treatment. The exception was static bending strength, where at a higher temperature (190 °C) the quality of the input wood became less significant, a fact that was even more significant in impact bending strength at an even lower temperature (170 °C). The tested properties demonstrated that sites also play an important role in the properties of wood, and the best results were obtained from acidic soil at lower altitudes.

Impact bending strength proved to be most negatively affected by the heat treatment, about 48% at 170 °C and up to 67% at 190 °C. The most positive effect was the increase in modulus of elasticity and hardness by about 30% and 21% at 170 °C, respectively, with a decrease in swelling at 190 °C by about 31%.

Overall, it can be stated that the higher dimensional stability of heat-treated wood was "redeemed" by degraded strength properties, in particular under dynamic stress. This effect was enhanced with increasing treatment temperatures. Overall, due to both color and other properties, there is the potential for birch to replace beech and other woods for certain specific purposes, in particular in the furniture industry in the form of heat-treated veneers.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Duncan's Multiple Range Test for density.

MS = 2690.2		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
DF = 708													
REF	Site 1												
REF	Site 2	0.003 *											
REF	Site 3	0.131	0.000 *										
REF	Site 4	0.219	0.077	0.007 *									
170	Site 1	0.350	0.038 *	0.018 *	0.718								
170	Site 2	0.001 *	0.650	0.000 *	0.031 *	0.013 *							
170	Site 3	0.165	0.000 *	0.832	0.012 *	0.027 *	0.000 *						
170	Site 4	0.093	0.189	0.001 *	0.597	0.405	0.090	0.003 *					
190	Site 1	0.088	0.175	0.001 *	0.577	0.390	0.087	0.002 *	0.929				
190	Site 2	0.000 *	0.044 *	0.000 *	0.000 *	0.000 *	0.096	0.000 *	0.001 *	0.001 *			
190	Site 3	0.768	0.006 *	0.083	0.319	0.481	0.002 *	0.112	0.148	0.143	0.000 *		
190	Site 4	0.098	0.174	0.002 *	0.617	0.421	0.083	0.003 *	0.994	0.930	0.001 *	0.157	

* Values are significant at $p < 0.05$. Error: Between MS = mean squares, DF = degrees of freedom. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C.

Table A2. Duncan's Multiple Range Test for compressive strength.

MS = 93.018		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
DF = 708													
REF	Site 1												
REF	Site 2	0.036 *											
REF	Site 3	0.793	0.021										
REF	Site 4	0.025 *	0.841	0.014									
170	Site 1	0.090	0.000 *	0.138	0.000 *								
170	Site 2	0.620	0.091	0.477	0.068	0.033							
170	Site 3	0.145	0.000 *	0.207	0.000 *	0.755	0.060						
170	Site 4	0.917	0.041 *	0.733	0.029 *	0.078	0.668	0.131					
190	Site 1	0.152	0.000 *	0.219	0.000 *	0.751	0.062	0.986	0.134				
190	Site 2	0.107	0.580	0.070	0.481	0.001 *	0.217	0.002 *	0.116	0.002 *			
190	Site 3	0.018 *	0.000 *	0.032 *	0.000 *	0.463	0.005 *	0.337	0.015 *	0.325	0.000 *		
190	Site 4	0.464	0.005 *	0.602	0.003 *	0.298	0.249	0.411	0.427	0.433	0.023 *	0.093	

* Significant at $p < 0.05$.

Table A3. Duncan's Multiple Range Test for oven-dry density.

MS = 2477.4		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
DF = 708													
REF	Site 1												

REF	**Site 2**	0.007 *										
REF	**Site 3**	0.040 *	0.000 *									
REF	**Site 4**	0.241	0.116	0.001 *								
170	**Site 1**	0.147	0.198	0.000 *	0.728							
170	**Site 2**	0.000 *	0.353	0.000 *	0.015 *	0.034 *						
170	**Site 3**	0.160	0.000 *	0.451	0.013 *	0.006 *	0.000 *					
170	**Site 4**	0.121	0.213	0.000 *	0.625	0.848	0.038 *	0.004 *				
190	**Site 1**	0.150	0.188	0.000 *	0.714	0.953	0.032 *	0.006 *	0.879			
190	**Site 2**	0.000 *	0.037 *	0.000 *	0.000 *	0.001 *	0.208	0.000 *	0.001 *	0.001 *		
190	**Site 3**	0.903	0.009 *	0.035 *	0.259	0.165	0.000 *	0.150	0.143	0.175	0.000 *	
190	**Site 4**	0.148	0.199	0.000 *	0.718	0.968	0.034 *	0.006 *	0.870	0.982	0.001 *	0.169

* Significant at $p < 0.05$.

Table A4. Duncan's Multiple Range Test for volumetric swelling.

MS = 6.6651 DF = 708		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
REF	**Site 1**												
REF	**Site 2**	0.000 *											
REF	**Site 3**	0.201	0.000 *										
REF	**Site 4**	0.558	0.000 *	0.078									
170	**Site 1**	0.000 *	0.354	0.000 *	0.000 *								
170	**Site 2**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *							
170	**Site 3**	0.000 *	0.444	0.000 *	0.000 *	0.820	0.000 *						
170	**Site 4**	0.000 *	0.321	0.000 *	0.000 *	0.910	0.000 *	0.752					
190	**Site 1**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *				
190	**Site 2**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.029 *			
190	**Site 3**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.718	0.054		
190	**Site 4**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.112	0.000 *	0.065	

* Significant at $p < 0.05$.

Table A5. Duncan's Multiple Range Test for bending strength.

MS = 453.67 DF = 708		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
REF	**Site 1**												
REF	**Site 2**	0.249											
REF	**Site 3**	0.197	0.019 *										
REF	**Site 4**	0.433	0.068	0.558									
170	**Site 1**	0.008 *	0.000 *	0.146	0.056								
170	**Site 2**	0.682	0.141	0.343	0.668	0.023 *							
170	**Site 3**	0.006 *	0.000 *	0.137	0.048 *	0.901	0.018 *						
170	**Site 4**	0.323	0.043 *	0.714	0.794	0.085	0.519	0.075					
190	**Site 1**	0.000 *	0.001 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *				
190	**Site 2**	0.000 *	0.001 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.962			
190	**Site 3**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.369	0.372		
190	**Site 4**	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.660	0.671	0.597	

* Significant at $p < 0.05$.

Table A6. Duncan's Multiple Range Test for impact bending strength.

MS = 5.6569 DF = 708		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
REF	Site 1												
REF	Site 2	0.000 *											
REF	Site 3	0.934	0.000 *										
REF	Site 4	0.000 *	0.999	0.000 *									
170	Site 1	0.000 *	0.000 *	0.000 *	0.000 *								
170	Site 2	0.000 *	0.000 *	0.000 *	0.000 *	0.523							
170	Site 3	0.000 *	0.000 *	0.000 *	0.000 *	0.973	0.515						
170	Site 4	0.000 *	0.000 *	0.000 *	0.000 *	0.309	0.655	0.304					
190	Site 1	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.003 *	0.000 *	0.009 *				
190	Site 2	0.000 *	0.000 *	0.000 *	0.000 *	0.008 *	0.037 *	0.008 *	0.081	0.324			
190	Site 3	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.001 *	0.000 *	0.002 *	0.632	0.168		
190	Site 4	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.284	0.050	0.506	

* Significant at $p < 0.05$.

Table A7. Duncan's Multiple Range Test for hardness in the radial plane.

MS = 126.19 DF = 1236		REF Site 1	REF Site 2	REF Site 3	REF Site 4	170 Site 1	170 Site 2	170 Site 3	170 Site 4	190 Site 1	190 Site 2	190 Site 3	190 Site 4
REF	Site 1												
REF	Site 2	0.002 *											
REF	Site 3	0.612	0.009 *										
REF	Site 4	0.130	0.102	0.280									
170	Site 1	0.048 *	0.000 *	0.015 *	0.000 *								
170	Site 2	0.267	0.000 *	0.123	0.009 *	0.345							
170	Site 3	0.065	0.000 *	0.022 *	0.001 *	0.857	0.407						
170	Site 4	0.711	0.001 *	0.412	0.068	0.096	0.420	0.124					
190	Site 1	0.569	0.000 *	0.313	0.043 *	0.139	0.533	0.172	0.811				
190	Site 2	0.274	0.047 *	0.502	0.622	0.002 *	0.032 *	0.003 *	0.162	0.113			
190	Site 3	0.692	0.007 *	0.883	0.237	0.020 *	0.150	0.029 *	0.474	0.366	0.445		
190	Site 4	0.131	0.115	0.276	0.970	0.000 *	0.010 *	0.001 *	0.069	0.044 *	0.623	0.237	

* Significant at $p < 0.05$.

Table A8. Duncan's Multiple Range Test for Repeat Cycle of Volumetric Swelling.

MS = 6.9927 DF = 2151		REF 0	REF 1	REF 2	170 0	170 1	170 2	190 0	190 1	190 2
REF	0									
REF	1	0.000 *								
REF	2	0.000 *	0.000 *							
170	0	0.000 *	0.001 *	0.000 *						
170	1	0.000 *	0.000 *	0.002 *	0.000					
170	2	0.000 *	0.000 *	0.358	0.000	0.000				
190	0	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *			
190	1	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.026 *		
190	2	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	0.000 *	

* Values are significant at $p < 0.05$. Error: Between MS = mean squares, DF = degrees of freedom. REF = reference, with no treatment; 170 = heat treatment at 170 °C; 190 = heat treatment at 190 °C; 0 = repeat cycle 0; 1 = repeat cycle 1; 2 = repeat cycle 2.

References

1. Balcar, V.; Špulák, O.; Kacálek, D. Tvorba druhové skladby horských lesů na lokalitách extrémně zatížených klimatickými stresy (Restoration of tree species composition on mountain forest sites affected by extreme climatic stress). *Zprávy lesnického výzkumu* **2010**, *55*, 241–250.

2. Fahlvik, N.; Agestam, E.; Ekö, P.M.; Lindén, M. Development of single-storied mixtures of Norway spruce and birch in Southern Sweden. *Scand. J. For. Res.* **2011**, *26*, 36–45, doi:10.1080/02827581.2011.564388.

3. Frivold, L.H.; Frank, J. Growth of Mixed Birch-Coniferous Stands in Relation to Pure Coniferous Stands at Similar Sites in South-eastern Norway. *Scand. J. For. Res.* **2002**, *17*, 139–149, doi:10.1080/028275802753626782.

4. Hansson, K.; Olsson, B.A.; Olsson, M.; Johansson, U.; Kleja, D.B. Differences in soil properties in adjacent stands of Scots pine, Norway spruce and silver birch in SW Sweden. *For. Ecol. Manag.* **2011**, *262*, 522–530, doi:10.1016/j.foreco.2011.04.021.

5. Heräjärvi, H. Technical properties of mature birch (Betula pendula and B. pubescens) for saw milling in Finland. *Silva Fennica* **2001**, *35*, 469–485, doi:10.14214/sf.581.

6. Holmström, E. Regeneration and Early Management of Birch and Norway Spruce Mixtures in Southern Sweden. Ph.D. Thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden, 2015; ISBN 978-91-576-8442-4.

7. Hynynen, J.; Niemistö, P.; Viherä-Aarnio, A.; Brunner, A.; Hein, S.; Velling, P. Silviculture of birch (Betula pendula Roth and Betula pubescens Ehrh.) in northern Europe. *Forestry* **2010**, *83*, 103–119, doi:10.1093/forestry/cpp035.

8. Hynynen, J.; Repola, J.; Mielikäinen, K. The effects of species mixture on the growth and yield of mid-rotation mixed stands of Scots pine and silver birch. *For. Ecol. Manag.* **2014**, *262*, 1174–1183, doi:10.1016/j.foreco.2011.06.006.

9. Johansson, T. Biomass production and allometric above- and below-ground relations for young birch stands planted at four spacings on abandoned farmland. *Forestry* **2007**, *80*, 41–52, doi:10.1093/forestry/cpl049.

10. Maleki, K.; Kiviste, A.; Korjus, H. Analysis of Individual Tree Competition on Diameter Growth of Silver Birch in Estonia. *For. Syst.* **2015**, *24*, 1–13, doi:10.5424/fs/2015242-05742.

11. Martiník, A.; Adamec, Z. Rozdíly ve struktuře mladých březových porostů vzniklých na holině pod porostem v oblasti chřadnoucích smrčin na severní Moravě (Diferences in structure of young silver birch stands regenerated after clearcutting and under declining spruce stands in the north Moravia—Czech Republic). *Zprávy lesnického výzkumu* **2016**, *61*, 271–278.

12. Mäkinen, H. Effect of stand density on the branch development of silver birch (Betula pendula Roth) in central Finland. *Trees* **2002**, *16*, 346–353, doi:10.1007/s00468-002-0162-x.

13. Novotný, P.; Buriánek, V.; Čáp, J.; Dostál, J.; Frýdl, J. Výsledky hodnocení domácích proveniencí břízy bělokoré (Betula pendula Roth) ve věku 26 let (Results of the assessment of silver birch (Betula pendula Roth) provenances from the Czech Republic at the age of 26 years). *Zprávy lesnického výzkumu* **2014**, *54*, 40–50.

14. Špulák, O.; Souček, J.; Bartoš, J.; Kacálek, D. Potenciál mladých porostů s dominancí břízy vzniklých sukcesí na neobhospodařované orné půdě (Potential of young stands with birch dominance established by succession on abandoned agricultural land). *Zprávy lesnického výzkumu* **2010**, *55*, 165–170.

15. Valkonen, S.; Ruuska, J. Effect of Betula pendula admixture on tree growth and branch diameter in young Pinus sylvestris stands in Southern Finland. *Scand. J. For. Res.* **2003**, *18*, 416–426, doi:10.1080/02827581.2003.9610645.

16. Zasada, M.; Bijak, S.; Bronisz, K.; Bronisz, A.; Gaweda, T. Biomass dynamics in young silver birch stands on postagricultural lands in central Poland. *Drewno* **2014**, *57*, 30–39, doi:10.12841/wood.1644-3985.S07.02.

17. Zâlîtis, T.; Zâlîtis, P. Growth of young stands of Silver birch (Betula pendula Roth.) depending on pre-commercial thinning intensity. *Balt. For.* **2007**, *13*, 61–67.

18. Kurjatko, S. Vlastnosti dreva ako parametre jeho kvality (Wood properties as a parameters of its quality). In *Parametre kvality dreva určujúce jeho finálne použitie (Wood quality parameters determining its end use)*, 1st ed.; TU: Zvolen, Slovakia, 2010; pp. 11–23, ISBN 978-80-228-2095-0.

19. Martiník, A. Obnova lesa síjí břízou—Zkušenosti ze smrkového porostu po větrné kalamitě (Regeneration of birch by seeding – experience from windthrown spruce stand). *Zprávy lesnického výzkumu* **2014**, *59*, 35–39.

20. Pulkrab, K.; Remeš, J.; Sloup, M. Modelová studie přímých nákladů holosečného a podrostního hospodářského způsobu (Model evaluation of management economic efficiency in the application of alternative silvicultural systems). *Zprávy lesnického výzkumu* **2010**, *55*, 16–27.

21. Špulák, O.; Souček, J.; Leugner, J. Nadzemní biomasa, živiny a spalné teplo v mladém sukcesním porostu přípravných dřevin (Aboveground biomass, nutrients and combustion heat of young successional forest stand of pioneer species). *Zprávy lesnického výzkumu* **2016**, *61*, 132–137.

22. Lundqvist, S.-O.; Grahn, T.; Olsson, L. *Properties of Materials from Birch—Variations and Relationships*; Part 1: Growth, wood density and biomass; Innventia Report No. 390; Innventia AB: Stockholm, Sweden, 2013; p. 52.

23. Barnett, J.R.; Jeronimidis, G. *Wood Quality and Its Biological Basis*; Blackwell Publishing: Oxford, UK, 2003; p. 226, ISBN 978-1-84127-319-8.

24. Zobel, B.J.; Buijtenen, J.P. *Wood Variation: Its Causes and Control*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 1989; p. 363, ISBN 978-3-642-74071-8.

25. Fahlvik, N.; Ekö, P.M.; Petersson, N. Effects of precommercial thinning strategies on stand structure and growth in a mixed even-aged stand of Scots pine, Norway spruce and birch in southern Sweden. *Silva Fennica* **2015**, *49*, 1–17, doi:10.14214/sf.1302.

26. Johansson, T. *Growth and Yield in Shelter Stands of Silver Birch and Norway Spruce*; Report/Rapport 068; SLU: Upsala, Sweden, 2014; p. 32.

27. Valkonen, S.; Valstra, L. Productivity and economic of mixed two-storied spruce and birch stands in Southern Finland simulated with empirical models. *For. Ecol. Manag.* **2001**, *140*, 133–149, doi:10.1016/S0378-1127(00)00321-2.

28. Vanhellemont, M.; Acker, J.V.; Verheyen, K. Exploring life growth pattern in birch (Betula pendula). *Scand. J. For. Res.* **2016**, *31*, 561–567, doi:10.1080/02827581.2016.1141978.

29. Viitaniemi, P.; Ranta-Maunus, A.; Jämsä, S.; Ek, P. Method for Processing of Wood at Elevated Temperatures. Patent EP-0759137 VTT, 11 May 1995.

30. Reisner, J.; Zeidler, A. Možnosti využití dřeva břízy (Possibilities of using birch wood). *Lesnická práce* **2010**, *89*, 30–31.

31. Borůvka, V.; Zeidler, A.; Holeček, T.; Dudík, R. Elastic and Strength Properties of Heat-Treated Beech and Birch Wood. *Forests* **2018**, *9*, 1–18, doi:10.3390/f9040197.

32. Poncsak, S.; Kocaefe, D.; Bouazara, M.; Pichette, A. Effect of high temperature treatment on the mechanical properties of birch (Betula papyrifera). *Wood Sci. Technol.* **2006**, *40*, 647–663, doi:10.1007/s00226-006-0082-9.

33. Heräjärvi, H. Static bending properties of Finnish birch wood. *Wood Sci. Technol.* **2004**, *37*, 523–530, doi:10.1007/s00226-003-0209-1.

34. Borůvka, V.; Zeidler, A.; Holeček, T. Comparison of Stiffness and Strength Properties of Untreated and Heat-Treated Wood of Douglas Fir and Alder. *BioResources* **2015**, *10*, 8281–8294, doi:10.15376/biores.10.4.8281-8294.

35. Esteves, B.M.; Pereira, H.M. Wood modification by heat treatment: A review. *BioResources* **2009**, *4*, 370–404.

36. Garrote, G.; Domínguez, H.; Parajó, J.C. Hydrothermal processing of lignocellulosic materials. *Holz als Roh- und Werkstoff* **1999**, *57*, 191–202, doi:10.1007/s001070050039.

37. ITA (International Thermowood Association). *Thermowood Handbook*; International Thermowood Association: Helsinki, Finland, 2003. Available online: https://asiakas.kotisivukone.com/files/en.thermowood.palvelee.fi/downloads/tw_handboo k_080813.pdf (accessed on 21 November 2018).

38. Johansson, D. Heat Treatment of Solid Wood (Effects on Absorption, Strength and Color). Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden, 2008.

39. Kubojima, Y.; Okano, T.; Ohta, M. Bending strength and toughness of heat-treated wood. *J. Wood Sci.* **2000**, *46*, 8–15, doi:10.1007/ BF00779547.

40. Navi, P.; Sandberg, D. *Thermo-Hydro-Mechanical Wood Processing*, 1st ed.; CRC Press: Lausanne, Switzerland, 2012; p. 280, ISBN 978-1439860427.

41. Reinprecht, L. *Wood Deterioration, Protection and Maintenance*, 1st ed.; John Wiley & Sons: Oxford, UK, 2016; p. 376, ISBN 978-1119106531.

42. Sandberg, D.; Kutnar, A.; Mantanis, G. Wood modification technologies—A review. *iForest* **2017**, *10*, 895–908, doi:10.3832/ifor2380-010.

43. Xie, Y.; Liu, Y.; Sun, Y. Heat-treated wood and its development in Europe. *J. For. Res.* **2002**, *13*, 224–230, doi:10.1007/BF02871703.

44. Lesprojekt Stará Boleslav. ŠLP Kostelec nad Černými lesy. Lesní hospodářský plán 2011–2020—Lesnické mapy (SFE Kostelec nad Černými lesy. Forest Management Plan 2011–2020—Forest Maps); Lesprojekt Stará Boleslav: Brandýs nad Labem-Stará Boleslav, Czech Republic, 2011.

45. Lesprojekt Stará Boleslav. ŠLP Kostelec nad Černými lesy. Lesní hospodářský plán 2011–2020—Textová část (SFE Kostelec nad Černými lesy. Forest Management Plan 2011–2020—Text Part); Lesprojekt Stará Boleslav: Brandýs nad Labem-Stará Boleslav, Czech Republic, 2011; p. 202.

46. Česká geologická služba. Geovědní mapy 1:50 000. Číslo mapového listu 1331 (Geo-Science Maps 1:50,000. Map Sheet Number 1331). Available online: https://mapy.geology.cz/geocr50/ (accessed on 6 August 2018).

47. Plíva, K. *Typologický klasifikační systém ÚHÚL (FMI Typological System)*; Forest Management Institute: Brandýs nad Labem, Czech Republic, 1987; p. 52. Available online: http://www.uhul.cz/images/typologie/Typologicky_klasifikacni_system_UHUL_Pliva_198 7.pdf (accessed on 6 August 2018).

48. ČSN EN ISO 11664-4. *Kolorimetrie—Část 4: Kolorimetrický prostor CIE 1976 L*a*b* (Colorimetry—Part 4: CIE 1976 L*a*b* Color Space)*; Czech Office for Standards, Metrology and Testing: Prague, Czech Republic, 1 November 2011.

49. ČSN EN ISO 11664-6. Kolorimetrie—Část 6: CIEDE2000 vzorce výpočtu barevného rozdílu (Colorimetry—Part 6: CIEDE2000 Color-Difference Formula); Czech Office for Standards, Metrology and Testing: Prague, Czech Republic, 1 March 2017.

50. ČSN 49 0103. Drevo. Zisťovanie vlhkosti pri fyzikálnych a mechanických skúškach (Wood. Determination of moisture content at physical and mechanical testing); Office for Standardization and Measurement: Prague, Czech Republic, 1 December 1979.

51. ČSN 49 0108. *Drevo. Zisťovanie hustoty (Wood. Determination of the Density)*; Czech Standards Institute: Prague, Czech Republic, 1 March 1993.

52. ČSN 49 0110. Drevo. Medza pevnosti v tlaku v smere vlákien (Wood. Compression Strength Limits Parallel to the Grain); Office for Standardization and Measurement: Prague, Czech Republic, 1 January 1980.

53. ČSN 49 0115. Drevo. Zisťovanie medze pevnosti v statickom ohybe (Wood. Determination of Ultimate Strength in Flexure Tests); Office for Standardization and Measurement: Prague, Czech Republic, 1 December 1979.

54. ČSN 49 0116. Drevo. Metóda zisťovania modulu pružnosti pri statickom ohybe (Wood. Determination of the Modulus of Elasticity in Static Bending); Office for Standardization and Measurement: Prague, Czech Republic, 1 January 1982.

55. ČSN 49 0117. *Drevo. Rázová húževnatosť v ohybe (Wood. Impact Strength in Flexure)*; Office for Standardization and Measurement: Prague, Czech Republic, 1 January 1980.

56. ČSN 49 0126. Skúšky vlastností rastlého dreva. Metóda zisťovania napúčavosti (Testing of Growth Wood Properties. Method for Determination of Swelling); Office for Standardization and Measurement: Prague, Czech Republic, 1 July 1989.

57. ČSN 64 0128. Zkoušky tuhých nekovových materiálů. Tvrdost podle Brinella (Testing of Rigid Non-Metallic Materials. Hardness According to Brinell); Czech Office for Standardization: Prague, Czech Republic, 1 May 1953.

58. ČSN EN 1534. Dřevěné podlahoviny—Stanovení odolnosti proti vtisku—Metoda zkoušení (Wood Flooring—Determination of Resistence to Indentation—Test Method); Czech Office for Standards, Metrology and Testing: Prague, Czech Republic, 1 May 2011.

59. FAKOPP Ultrasonic Timer User's Guide. Available online: http://fakopp.com/docs/products/ultrasonic/UltrasonicGuide.pdf (accessed on 21 November 2018).

60. Požgaj, A.; Chovanec, D.; Kurjatko, S.; Babiak, M. *Štruktúra a Vlastnosti Dreva (Structure and Properties of Wood)*, 1st ed.; Príroda: Bratislava, Slovakia, 1993; p. 485, ISBN 80-07-00600-1.

61. TIBCO Statistica™ 13.4.0. Available online: https://docs.tibco.com/products/tibco-statistica-13-4-0 (accessed on 21 November 2018).

62. Dinwoodie, J.M. *Timber: Its Nature and Behavior*, 2nd ed.; CRC Press: New York, NY, USA, 2000; p. 272, ISBN 978-0419235804.

63. Fengel, D.; Wegener, G. *Wood: Chemistry, Ultrastructure, Reactions*, 2nd ed.; Walter de Gruyter: Berlin, Germany, 1989; p. 613, ISBN 978-0899255934.