Musical Instrument Lumber Recovery from Romanian Resonance Spruces

Cristian Teofil Albu,[a] Florin Dinulică,[b] Szilard Bartha,[c,]* Maria Magdalena Vasilescu,[b]
Cristian Cornel Tereșneu,[b] and Ioana Andra Vlad [d]

Increasing demand for resonance spruce has led to gradual depletion of resources in traditional areas. Consequently, to meet the need for raw material to manufacture musical instruments, sorting has become the key operation of exploitation. This study was completed on the largest Romanian resonance wood resource, to maximize outputs of flitches for violin, cello, and double bass instruments by optimizing traditional requirements regarding quality of raw material with its current level. Ten resonance spruces were felled and gradually turned into semi-manufactured musical instruments. The material was analysed for defects in all stages of conversion. The frequency of zero defective samples was 60%. Evolution of defects along the trees indicated the tree section from 1 m to 12 m above the ground for musical instruments manufacturing. Output in terms of flitches ranged from one tree to another: between 19 and 32% if calculated from logs volume, and between 13 and 30% if calculated from volume of the standing trees. The results advocated for relaxing traditional requirements on resonance logs, at least regarding buttress and knottiness. Thus, recommendations are made, from the perspective of increasing efficiency, on the admissibility of defects and size diversification of musical instruments.

Keywords: Cello; Double bass; Knots; Lumber recovery; Norway spruce; Resin pockets; Strings; Tree butress; Violin

*Contact information: a: Gurghiu Forestry High Scool, Gurghiu, 547295 Romania; b: Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Transilvania University of Brașov, Brașov, 500123 Romania; c: Department of Forestry and Forest Engineering, University of Oradea, Bihor, 410048 Romania; d: Department of Food Engineering, University of Oradea, Bihor, 410048 Romania; *Corresponding author: barthaszilard10@yahoo.com*

INTRODUCTION

Over time, wood has ennobled the existence of humanity in all aspects thereof: family, professional, artistic, spiritual, *etc.*, and it remains the preferred material for musical instruments manufacturing (Bucur 2006; Wegst 2006). For this purpose, it must have an architecture that ensures the undistorted and, at the same time, amplified transmission of sound emitted by the strings (Kolneder 1998). This architecture develops under certain conditions, and not all trees or tree species can provide such material, which is called "resonance wood" (Domont 2000). Its texture strives towards perfection in terms of fineness and regularity. This explains the multiple set of qualitative restrictions imposed on the raw material (Table 1). Given the environmental constraints plus physiological and genetic determinism, the likelihood of a tree to meet all these requirements simultaneously is low, and the wood that satisfies them is recognized as being the most valuable on Earth (Schmidt-Vogt 1981).

Table 1. Criteria for Selecting Spruce Wood for Manufacturing Strings Instruments Top Plate

Restrictions on Resonance Wood	Information Source
Logs / Sawn Timber	
Under-bark top diameter ≥ 34 cm	SR 1294 (1993)
Length ≥ 2 m	SR 1294 (1993)
Straightness excellency (no crookedness or forking)	SR 1294 (1993)
Minimal out-of-roundness and cylindrical shape	SR 1294 (1993)
Torse fibre wood twisted to the left ≤ 3 cm/m to 4 cm/m	Pașcovici (1930)
No compression wood	Zugliani and Dotta (2009b)
Frequency of uncovered knots: ≤ 3 pcs/2 m length per sample (preferably without knots)	Krzysik (1968)
Maximum diameter of knots ≤ 2 cm	Sonderegger *et al.* (2008)
Checks ≤ ½ of sample diameter	SR 1294 (1993)
Smallest number of resin pockets	Zugliani and Dotta (2009b)
No biological attacks	Zugliani and Dotta (2009b)
Ring width ≤ 4 mm	Krzysik 1968
High regularity of annual growth	Ghelmeziu and Beldie (1972)
Width of resonance wood ≥ 15 cm	Sonderegger *et al.* (2008)
Flitches for Musical Instruments	
No seasoning checks	Zugliani and Dotta (2009b)
No knots, straight grain	Haines (1979)
Ring width = 0.8 mm to 2.5 mm for violins, 3 mm to 4 mm for cello, and up to 5 mm for the double bass and guitar	Ghelmeziu and Beldie (1972); Bucur (1980a)
Difference in width between consecutive rings ≤ 1.0 mm	Sonderegger *et al.* (2008)
Average latewood proportion = 14% to 30%	Ghelmeziu and Beldie (1970)

The defects invoked (Table 1) have a detrimental effect on the vibrational properties (Norimoto *et al.* 1983; Brémaud 2006; Brémaud *et al.* 2013) *via* elasticity properties (Kuprevicius *et al.* 2013). Stem structural defects, *e.g.*, eccentricity, sweep, twisting, and fluting, enhance the internal stresses (Mattheck and Kubler 1997) and can result in degradation when the timber is dried or sawn.

The continuous decrease of wood quality in the last century, from which the spruce is not excepted (Rozenberg and Cahalan 1997), as well as increasing pressure on high-quality wood resources (Zaițev 1969), make it difficult to find resonance spruce in forests once famous for it (Holz 1967; Rădulescu 1969). To produce musical instruments, it is now possible to use less-pruned, root-swelled stems, which therefore have higher knottiness and content of latewood and compression wood (Ille 1975; Albu 2010). However, the knots must be grouped into whorls, the distance between whorls must exceed the length of flitches for the violin (Krzysik 1968; Albu 2010), and the compression wood and biological attacks must be concentrated in the area lacking acoustic expectation (Grapini and Constantinescu 1968; Dinulică *et al.* 2015).

Under these circumstances, the role of sorting in the selection and processing of raw material has greatly increased, especially with the sorters' financial bonus for increasing yield of resonance flitches (Krzysik 1968). Through this research, the authors proposed (a) to determine the output of musical instruments from the current resonance spruce stands in the Romanian Carpathians, by an accurate and judicious sorting, and (b) to find ways to improve the output. To this end, the authors proceeded to: (1) find and measure all visible defects, starting with logs and ending with flitches, and (2) optimize the cutting pattern in relation to the quality of material and the demand to maximize output.

EXPERIMENTAL

To quantify the output of musical instruments, the raw material was tracked from the standing timber to the flitches stored for seasoning (Fig. 1).

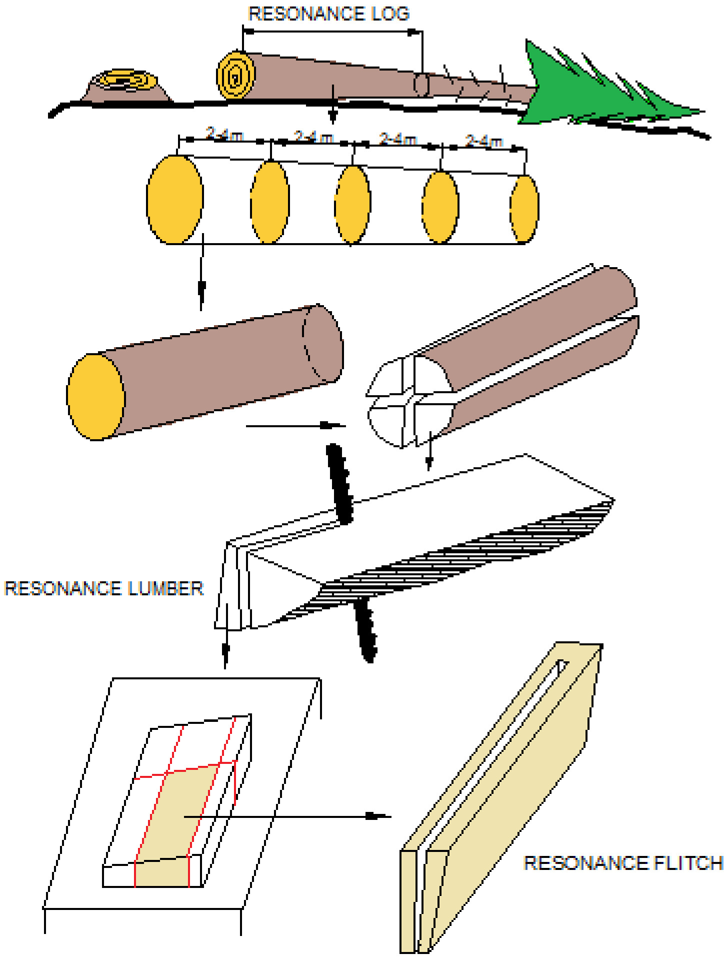

Fig. 1. Flowchart of the study

Materials

The raw material came from a spruce stand with resonance wood from the eastern chain of the Romanian Carpathians (Table 2), sheltered in the caldera of a former volcano (Reghin, Romania). The forest site is protected from wind, and the volcanic substrate, which is unique for spruce resonance (Domont 2000), supports a constant soil moisture regime, and balanced nutrition for spruce trees (Albu 2010). The sampled trees aged up to 240 years (Table 2) and they came exclusively from natural forests.

Table 2. Resource Characterization

Site Features	
Geographic coordinates	25° 13' 26.19" N ; 46° 50' 18.08" E / 1550 m a.s.l
Facing	NE, upper third of the slope
Slope (°)	17
Soil substratum	Andesite with amphiboles and pyroxenes
Soil type (classified according to FAO 1998)	Lepti-dystric Cambisols
Average annual rainfall (mm/yr)	1100
Average thickness of snow layer (cm)	60
Tree Features	
Stand composition (%)	100 Norway spruce
Diameter at breast height of sampled trees (cm)	42 to 62
Sampled trees height (m)	28 to 35
Sampled trees age (yr at breast height)	95 to 240
Distance from neighbouring trees (m)	4.1 to 8.5

Resource Sampling and Processing

Ten trees, whose phenotype corresponded to the established portrait of resonance spruce, were selected (Geambașu 1995; Zugliani and Dotta 2009a). The chosen trees were mechanically felled during the inactive vegetative season, to avoid the flow of sap and to minimize resin content (Schelleng 1982), during a temperature ranging between 3 °C to 5 °C and with a layer of snow, to avoid cracking when felling.

The felled trees were trimmed and cut according to the position of the critical defects for resonance wood (curvature, knots, and biological attacks). The measurement of defects followed the requirements of EN 1310 (1997). Eighteen logs complied with the qualitative requirements outlined in Table 1 and were further converted into flitches for musical instruments (Tables 3 and 4), at the premises of Gliga Company (Reghin, Romania), one of the largest producers of bowed string instruments in Europe. Logs had lengths that ranged between 8.2 m to 12.6 m and small-end diameters of 15 cm to 46 cm without bark.

Table 3. Technological Flow when Converting Resonance Wood into Logs

<table>
<tr><th>Technical Operations</th><th colspan="4">Content / Sampling</th></tr>
<tr><td>Log cutting at lengths of 2 m to 4 m</td><td colspan="4">The logs were cross-sectioned, through whorls with at least 2 or 3 uncovered knots. The minimum length of 2 m was chosen to provide double bass flitches (1.25 m long). On this occasion, a disc from the butt and small-ends of each log were sampled. The discs supplemented the measurements made on logs. A total of 66 discs were sampled.</td></tr>
<tr><td>Quarter sawing</td><td colspan="4">Logs were subject to quarter sawing by the band saw.</td></tr>
<tr><td rowspan="5">Quarters sorting</td><td colspan="4">This operation involved grouping logs according to the musical instrument to which they were dedicated. The sorting criteria were as follows:</td></tr>
<tr><td>Class</td><td>Radius (cm)</td><td>Annual rings</td><td>Wood defects</td></tr>
<tr><td>Quarter for violin or viola</td><td>13 to 24</td><td rowspan="3">To meet the requirements in Table 1.</td><td rowspan="3">The knots are particularly targeted. Clear wood shall be longer than the length of the flitch of the corresponding to the instrument in question.</td></tr>
<tr><td>Quarter for cello</td><td>24 to 37</td></tr>
<tr><td>Quarter for double bass</td><td>≥ 37</td></tr>
</table>

Table 4. Technological Flow when Converting Logs into Flitches for Musical Instruments

<table>
<tr><th>Technical Operations</th><th colspan="5">Content / Sampling</th></tr>
<tr><td>Ripping quarters to the thickness of the flitches</td><td colspan="5">The quarters were radially cut, at the inner thickness of 2.5 cm and the outer thickness of 5.5 cm (Fig. 2).</td></tr>
<tr><td>Splitting quarters to the length of the flitches</td><td colspan="5">It was completed with the band saw. On this occasion, the outer edge was straightened and the juvenile wood was removed.</td></tr>
<tr><td rowspan="7">Calibration of resonance wood lumber</td><td colspan="5">The lumber was rip-sawed to the exact thickness of the flitch:</td></tr>
<tr><td rowspan="2">Instrument</td><td colspan="4">Flitches dimensions (mm)</td></tr>
<tr><td>Length</td><td>Width</td><td>Large parallel side *</td><td>Small parallel side *</td></tr>
<tr><td>Violin, viola</td><td>410</td><td>130</td><td>50</td><td>25</td></tr>
<tr><td>Cello</td><td>850</td><td>240</td><td>45</td><td>20</td></tr>
<tr><td>Double bass</td><td>1250</td><td>370</td><td>55</td><td>20</td></tr>
<tr><td colspan="5">* The flitches have a trapezoidal section.</td></tr>
<tr><td>Edging of flitches</td><td colspan="5">The radial sections and the large thickness of the flitches were adjusted.</td></tr>
<tr><td>Radial rip-sawing of flitches</td><td colspan="5">The flitches for violin and viola were incompletely ripped through the middle, at the circular or with the band saw. This resulted in pairs for the top plates. For cello and double bass, the pairs were obtained by cutting two flitches, one next to the other, from the same quarter of the log.</td></tr>
<tr><td rowspan="8">Sorting of flitches</td><td colspan="5">The flitches for violin and viola were graded by the following criteria:</td></tr>
<tr><td rowspan="3">Class</td><td colspan="4">Sorting criteria</td></tr>
<tr><td rowspan="2">Wood colour</td><td colspan="3">Wood defects</td></tr>
<tr><td>Resin pockets</td><td>Knots</td><td>Anatomical irregularities</td></tr>
<tr><td>Maestro</td><td rowspan="2">Yellowish-white</td><td rowspan="3">Not allowed</td><td rowspan="3">Not allowed</td><td rowspan="4">Indented rings are allowed</td></tr>
<tr><td>Professional</td></tr>
<tr><td>Student</td><td rowspan="2">Yellowish-white or reddish</td></tr>
<tr><td>School</td><td>Only one non-penetrating resin pocket with a thickness < 1 mm and a length < 1 cm is allowed.</td><td>1 to 2 pin knots are allowed (with a diameter < 3 mm) or 1 to 2 shades of small knots, to be placed on the gluing edge of the soundboard with the ribs.</td></tr>
</table>

Pair flitches were calibrated to the dimensions required for the cello, and they were glued and pressed on the peripheral edge, then the outline of the instrument plate was shaped using the template.

Fig. 2. Snapshot from the quarter splitting

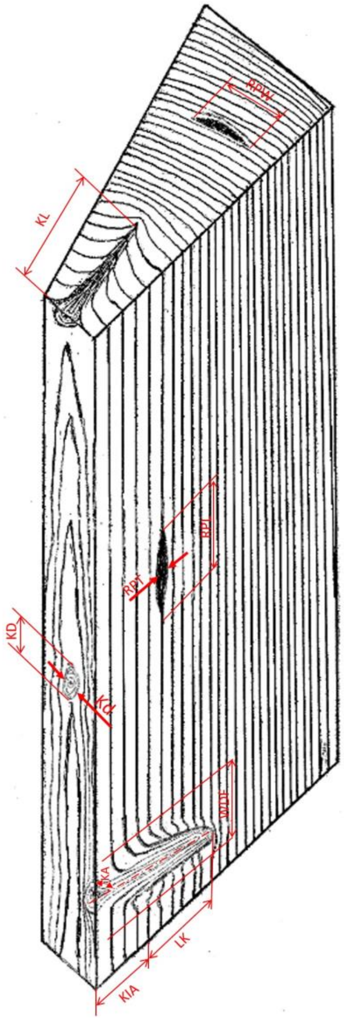

Fig. 3. Measurements of wood features: KA - cutting angle of the knot, KD - maximum diameter of a knot, Kd - minimum diameter of a knot, KIA – length of the intergrown area, LK - length of the loose knot, KL - length of knot, WDF - width of deflected fibre area, RPL - length of resin pocket, RPW - width of resin pocket, and RPT- thickness of resin pocket

Methods

Data acquisition

In the logs with resonance wood and in the discs, all visible qualitative characteristics were measured (Table 5). The eccentricity was measured at the butt end of the logs (Richter 2015), and the ovality at the small end. The highest value measured in the log was retained for the ring shake.

For resonance lumber, the defects measured were the knots and resin pockets (Table 5), which were the only ones allowed for cutting musical instrument flitches (Tables 3 and 4).

To not disrupt the technological flow from the factory, measurements on wood defects in flitches were performed only on the cello ones (62 pairs of flitches). The measurements were performed on both radial and tangential sides.

Because the knots usually have an elliptical section, the diameter was averaged from their values on minor and major axes (Table 5). The ellipticity of the knot was calculated as a dimensionless ratio between its extreme diameters. The knots produce the local distortion of the annual rings, which was why the authors measured near the knot and the width of the affected area, which was further related to the diameter of the knot that resulted in the following variable: influence of the knot area ratio.

For the pair flitches, the mirror pockets were measured at both flitches, and the resulting values were used to reconstruct the 3D geometry of the sectioned pocket.

Thus, the length and thickness of the original pocket were assimilated to the maximum sizes of the measurements from the pair pockets, and the width of the original pocket resulted from the addition of the width of the pair pockets and the addition of the wood cutting thickness (the thickness of the blade plus the double set of the saw). In this study, the cut of the band saw used was 3 mm.

Table 5. Measuring the Wood Qualitative Features

Feature	Measurement Method
Measurements on Round Wood	
Ovality	Determined as a relative percentage difference of the under-bark of the extreme diameters (Richter 2015).
Eccentricity	The deviation of the pith from the geometric center, identified as the center of the largest diameter, was measured. This was reported as a percentage of the average diameter of the section (EN 1310 1997).
Ring shake	Determined as a ratio between the diameter of the circle (ellipse) on which it developed and the average diameter of the log end (EN 1310 1997).
Buttress	Determined only on the logs from the base of the tree, as a difference between the average diameter over-bark of the butt end (the section of tree felling) and the average diameter over-bark at 1 m from the butt end (Beldeanu 2008).
Length of buttress	Measured (in m) from the butt end of the butt-logs to the point where the diameter stabilizes (Albu 2010).
Measurements on Sawn Timber	
Knots	The following were quantified (Albu 2010; Fig. 3): ✓ Frequency of knots, by the total number of knots on the side of the sample, ✓ Diameter of the knots, maximum and minimum size under bark, ✓ Ellipticity of knots, ✓ Length of the knots, measured on the radial side, ✓ Length of the intergrown area and loose knot area (radial side only), ✓ Knot angle towards the edge (only on the radial side), ✓ Width of the deflected fibre area (only on the radial side).
Resin pockets	The following were quantified (Albu 2010; Fig. 3): ✓ Length of the pocket, ✓ Thickness of the pocket, measured at half its length, ✓ Width of the pocket, measured at half of its length, using a metal rod inserted into the depth of the pocket.

Data analyses were performed using Statistica 12.0 software (StatSoft, Inc., Tulsa, OK, USA).

Kruskall-Wallis test and t test were used to check the significance of the differences in defects size between the values of ordinal variables.

Computing the Lumber Recovery

The recovery of musical instruments flitches (in this case: violins, violas, cello, and double bass) was calculated in two variants, dividing the cumulative volume of the instruments obtained either by the log volume input or the volume of the standing trees (Eq. 1 and Eq. 2, respectively), as follows,

$$RFRF_{\mathrm{L}} = \frac{FV}{LV} \cdot 100 \tag{1}$$

where $RFRF_{\mathrm{L}}$ is the resonance flitches recovery factor from logs (%), FV is the total volume of logged flitches (m^3), and LV is the total volume of logs (m^3) and,

$$RFRF_{\mathrm{T}} = \frac{FV}{TV} \cdot 100 \tag{2}$$

where $RFRF_{\mathrm{T}}$ is the resonance flitches recovery factor from standing trees (%), FV is the total volume of logged flitches (m^3), and TV is the total volume of standing trees (m^3). The total volume of the flitches was calculated by multiplying the volume of the flitches corresponding to each instrument with the number of samples obtained for the respective instrument and then by summing the values. The volume of the standing timber was calculated using Eq. 3 (Leahu 1994; Giurgiu *et al.* 2004; Vasilescu *et al.* 2017),

$$V_{\mathrm{T}} = 0.7854 \cdot DBH^2 \cdot TH \cdot f \tag{3}$$

where V_{T} is the volume of the tree (m^3), DBH is the diameter at breast height (m), TH is the tree height (m), and f is the false form factor of the spruce tree (Giurgiu *et al.* 1972).

The recovery was calculated separately for each felled tree.

RESULTS AND DISCUSSION

Log Shape Defects

The log sample was quite heterogeneous in terms of qualitative characteristics subject to analysis (Table 6), even if they originated in biometrically similar trees. Log roundness corresponded to most of the first grade requirements of softwood. The extreme values of the ovality were recorded in the butt-end of the felled trees (which would be rectified before sawing), and, accidentally, in the wood from the base of the crown.

Table 6. Basic Statistic of Resonance Log Qualitative Features

Log Feature	Mean	Median	Min	Max	Coefficient of Variation Between Logs (%)	Significance of the Differences* Between:	
						Trees	Butt-end Log and Top-end Log
Ovality (%)	8.20	6.84	0.00	38.3	87.75	0.07	0.42
Eccentricity (%)	4.64	4.00	0.00	17.90	85.29	0.04	0.04
Butress (cm)	14.20	15.50	5.00	20.00	34.77	0.44	-**
Length of root swelling (m)	0.65	0.68	0.45	0.79	16.63	0.44	-

* p from Kruskall-Wallis test (0.05 is the threshold value for statistical significance); ** Butress was determined only for butt-end logs.

The eccentricities that exceeded the first grade threshold were only 8% of the measurements that also belonged to the butt end of the felled trees. Measurements showed a logarithmic decay of both the ovality and the eccentricity (Fig. 4). Starting already with 1 m from the felling section of the trees, both defects dropped below the first quality threshold. This result fueled the distrust of the luthiers with respect to the base stem (Hutchins 1978). Additionally, the eccentricity was a strong indication of the internal tensions of the wood, which could be released after felling by cracking.

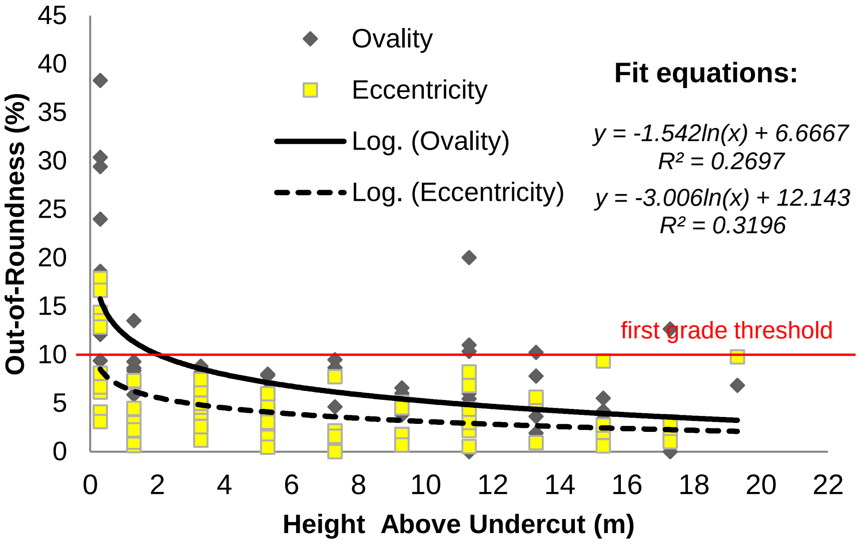

Fig. 4. Variation of the ovality and eccentricity along the resonance spruce trees

The timber obtained by radial cutting of the logs with pronounced eccentricity had fibre deviations, with negative acoustic implications. To mitigate these negative effects, the authors recommend that the quartering or halving of logs should follow the position of the pith. In the past, raw material with moderately eccentric pith was used only for the musical instrument keyboard (Albu 2010).

Approximately 70% of the buttress values exceeded the limit required on spruce wood first grade, which is 10 cm (SR 1294 1993). The forest site and rooting conditions forced the spruce trees to fortify the trunk base, with inevitable effects in terms of stem shape and of the wood architecture. The resonance spruces ensured their stability in the wind through 3 to 5 counterforts (Geambașu 1995). The buttress wood had an irregular structure, and consequently the timber cut from this wood had an anomalous grain (Fig. 5). In this study, tree buttresses occupied the first 0.5 m to 0.8 m of the butt-log (Table 6), which were actually removed from the technological flow of musical instruments manufacturing. It was more efficient to remove the buttress when trimming the logs than to remove the distorted fibre area from the lumber. Because all the trees felled in this study were finally processed into musical instruments, the authors support the relaxation of restrictions on buttress on the first grade spruce (SR 1294 1993) by accepting root-swelled trees, if there are objective acoustic arguments and the length of the root-swelling is reasonable.

Six of the 18 resonance logs had a ring-shake, with a relative diameter of 3% to 13%, which meant that they occupied the core of the trees. This wood was not used in making musical instruments. Considering an average width of 4 cm to 10 cm of the central area without acoustic qualities (Albu 2010), it turned out that ring-shakes sizing up to 20% of the diameter of the wood could be accepted in the case of resonance logs. If they occurred outside the juvenile wood, the partial ring-shakes could be accepted in terms of resonance, provided they appear at one end of the sample that otherwise does not show any other defects. The cutting model will be adapted so that the ring-shake is removed. The size of the ring-shake found in this study was not related to its position along the tree.

Fig. 5. Timber from resonance tree buttress (arrow indicates fibre deviations)

The ingrown bark was rare (in only two of the 18 resonance logs surveyed). It was found only in the root-swelled section of the trunk and was superficial, *i.e.*, in the first 1.5% to 2.5% of log diameter.

Knots Biometrics

Of the 62 pairs of cello flitches surveyed, 37 presented zero defects; the others had knots and/or resin pockets.

The position of flitches for musical instruments was established after the distribution of knots along the resonance timber. The large number of uncovered knots found (Table 7) might seem daunting. However, they were the result of repeated cutting of a rather small number of knots, grouped into whorls, which allowed the choice of crosscutting of timber in flitches.

Unexpectedly, the differences between the resonance trees in terms of knot frequency were large, from equal to double, which revealed a large variability in the case of resonance wood even within the same forest.

Table 7. The Content of Knots in the Resonance Timber Surveyed

Statistics	Frequency of Knots (pcs/m^3 Timber)		
	Knots with diameter < 10 mm	Knots with diameter ≥ 10 mm	Total number of knots
Mean	127.3	125.4	252.7
Median	134.0	119.0	240.0
Min	82.0	77.0	160.0
Max	189.0	172.0	346.0
Coefficient of variation (%)	28.6	23.0	24.1
Significance of the differences between trees (p from T test)	≤ 0.005		

Along the stem, the highest frequencies of knots were recorded at the tree base, *i.e.* in the first 4 m, after which they decreased when reaching first green branches (8 m to 10 m above the ground), as shown in Fig. 6.

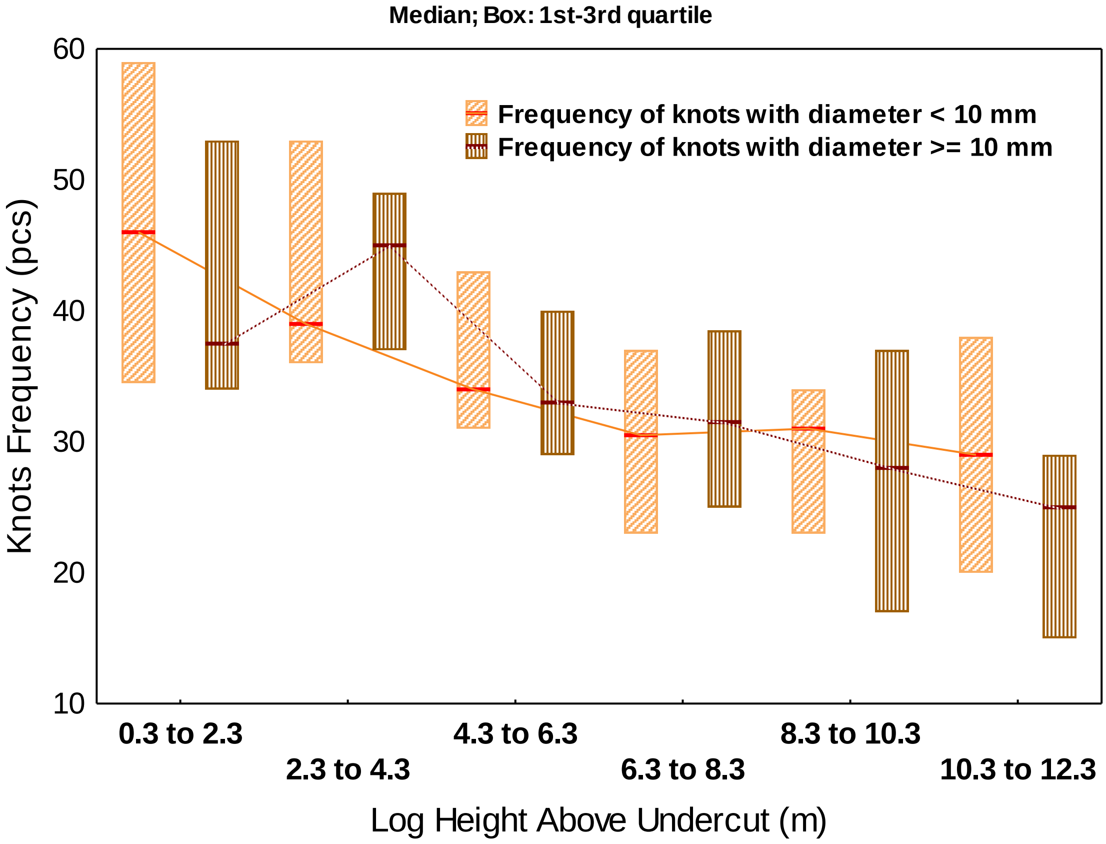

Fig. 6. Variation of the knots frequency along the resonance spruce trees

For several decades, an alternative to the traditional procedure for quantifying the presence of knots has been the use of non-destructive techniques for scanning raw wood (Benson-Cooper *et al.* 1982; Oja 2000; Bucur 2003).

The samples that made up the pairs had the same distribution of knots and geometry thereof (Table 8). Pairs of flitches differed according to the thickness of the knots, their frequency, and the angle thereof. At least half of the radial knots were round;

the others were generally oval and rarely elongated (5% of cases). With one exception, the tangential knots were round (ellipticity < 2).

The width of knot influence area on the neighbouring annual rings was 2 to 3 times greater than the diameter of the knot itself (Table 8). The area of knot influence on the shape of the rings extended in the first 4 mm to 39 mm from the edge of the knot, being often inversely proportional to the thickness of the knot (Spearman rank order correlation: -0.379, p = 0.002). Adding the influence area to the thickness of the knot, it turned out that 0.8 cm to 7.4 cm (average 2.8 cm) of wood along the fibre could no longer be used when making the musical instrument. If the knot angle was also considered as well as its length, it turned out that, on average, 60 mm of the length of the flitch was affected by the presence of the knot.

Table 8. Basic Statistic of Knots Features on Flitches for Cello

Feature	Mean	Median	Min	Max	Coefficient of Variation Between Knots (%)	Significance of the Differences* Between	
						Flitches pairs	Pairs samples
Number of knots on the radial side	1.94	2.00	0.00	7.00	99.57	0.01	0.55
Number of knots on the inner edge	1.38	1.00	0.00	7.00	94.75	0.02	0.53
Maximum diameter of the knots on the radial side (mm)	11.78	12.00	2.00	30.00	55.10	0.002	0.79
Maximum diameter of the knots on the radial side (mm)	2.07	1.63	0.67	5	50.14	0.06	0.14
Knot length (mm)	47.43	33.50	5.00	245.00	90.80	0.80	0.91
Knot angle (°)	72.72	83.00	45.00	90.00	22.40	0.006	0.43
Maximum diameter of the knots on the tangential side (mm)	11.09	11.00	2.00	27.00	53.09	0.002	0.63
Ellipticity of the knots on the tangential side	1.17	1.10	1.00	2.14	17.52	0.44	0.81
Influence of the knot area ratio	2.40	2.33	1.75	3.33	15.12	0.41	0.72

* p from Kruskall-Wallis test (0.05 is the threshold value for statistical significance); none of the variables have normal distribution

Some of the knots (59%) could be viewed in depth on the radial side of the flitches, and thus their length could be measured. They were actually cover knots, which could not be found when choosing the raw material for making musical instruments. At these knots, two adherence areas to the surrounding wood were distinguished: an inner, intergrown area, and an outer area, in which the knot was loose. The transition from one area to another meant the elongation of the branch that produced the respective knot. The observations that were made in some flitches indicated that the elongation lasted for resonance spruce trees for approximately 60 years. Given the value of resonance wood, the pruning could be artificially driven, starting from the 3 cm to 5 cm branch diameter (Nicolescu 2018). In this way, the knots would be clustered in the area without acoustic use of the tree bole. The authors propose that the artificial pruning operation be performed during the inactive season.

The knots on the radial sides that were not radially cut (*i.e.*, the remaining 41%) are actually penetrating knots. Observations showed that these knots were, in most cases, clustered in groups of two or three and were thinner than 2 cm.

The most problematic ones were the knots that appeared only on the narrow edge of the flitch and whose depth could not be assessed according to external features. Such samples were accepted if these knots were positioned closer to one of the ends of the flitch, so that they could be removed as needed.

Knots with a diameter greater than 1 cm, which represented 62% of the cases encountered on the radial side and only 4.4% of the cases on the tangential side, were declassified for flitch-making purposes.

Regardless of their size, both knots and resin pockets could be used if they were clustered so that the template for the future instrument would fit only in the “zero defects” wood category. If this was not possible, an attempt was made to use the flitch for a smaller musical instrument, up to the smallest violins (1/16 or even 1/32) in terms of size.

Resin Pockets Biometrics

A total of 23 resin pockets were found in the 25 flitches for the examined cello, of which 12 were pair resin pockets (present in both pieces in the pair). The traces of resin pockets on the radial sides had dimensions close from one flitch to another, with the differences between pairs not being statistically proven (Table 9). Observations showed that the thickness of the resin pocket often coincided with the width of the annual ring in which it was formed.

On the tangential sides of the flitches, resin pockets were found only on the wide edge and only in a small number (*i.e.*, 3 samples in total). This was probably related to the increasing frequency of resin tissues with the separation of the pith (Temnerud 1999). The tangential sections of the resin pockets were 26 mm to 33 mm long and 14 mm wide.

Moreover, the frequency of the resin pockets decreased with the distance from the ground when above the height of 4 m (Fig. 7). In some trees, the authors found that the frequency of the resin pockets increased again at heights above 6 m or 8 m. On average, the lowest content of resin pockets was located at heights between 10 m to 12 m. However, in terms of resin pockets density, the differences between the logs by height of the trees were not statistically valid (p from Kruskall-Wallis test = 0.39).

Extrapolating from the volume of resonance wood to the volume of logs resulted in an average of 17 resin pockets per cubic meter of wood (Table 10). The resin pockets measured in this study were significantly smaller than those presented in the literature, where the resin pocket length can reach 175 mm, the pocket width can reach 65 mm, and the thickness can reach 7 mm (Temnerud 1997). However, the frequency of resin pockets in the resonance trees sampled was quite high.

Table 9. Basic Statistic of Resin Pockets Features on Raw Material for Cello

Feature	Mean	Median	Min	Max	Coefficient of Variation Between Pockets (%)	Test of Significance*	
Dimensions of Sectioned Resin Pockets (in flitches)							
Pocket length on radial sides of flitches (mm)	28.82	26.00	10.00	55.00	34.72	Differences between pair flitches: p = 0.65	Differences between pair flitches: p = 0.55
Pocket width on radial sides of flitches (mm)	12.59	12.00	2.00	26.00	43.12	Differences between pair flitches: p = 0.90	Differences between pair flitches: p = 0.55
Resized (Primary) Dimensions of Resin Pockets							
Pocket length (mm)	29.00	28.50	18.00	43.00	32.79	Differences between pair flitches: p = 0.19	
Pocket width (mm)	25.67	23.00	18.00	34.00	26.27	Differences between pair flitches: p = 0.28	
Pocket thickness (mm)	1.35	1.25	0.80	2.00	41.84	Differences between pair flitches: p = 0.41	
Frequency of Resin Pockets							
Pockets frequency (pcs./log)	5.72	5.50	0.00	17.00	67.98	Differences between sampled trees: p < 0.0001	
Pockets frequency (pcs./m^3)	17.34	14.00	7.00	39.00	60.18	Differences between sampled trees: p = 0.44	

* p from Kruskall-Wallis test (0.05 is the threshold value for statistical significance); none of the variables have normal distribution

The occurrence of resin pockets was climatically explained by storm incidents and drought (Seifert *et al.* 2010). Trees were well and constantly supplied with water in the forest site through the high accumulation capacity of the soil (Table 2). Although the terrain configuration protected the vegetation from the strong influence of wind, windthrow could not be avoided at the altitude of the area surveyed. Dominant spruce trees, just like the resonance trees (Geambașu 1995), have a higher incidence of pockets of resin (Temnerud 1999).

Even if the surveyed sample did not allow firm conclusions to be drawn regarding the connection of resin pockets with other characteristics of the trees, the correlations that were found suggested some trends (Table 9). Trees with a higher frequency of resin pockets were oval in section, taller (R = +0.486, p = 0.15), and had longer crowns and softer wood (with a smaller share of late wood). Fortunately, the presence of resin pockets in resonance spruces did not restrict the length of the area that could be used acoustically because the trees with multiple resin pocket pockets had an even wider resonance area (Table 9). In fact, it was about a multicollinearity here, because trunks of trees with more resin pockets were a minimally thicker. An inverse correlation between the frequencies of resin pockets and knots was found (R = -0.388), but it was statistically uncertain (p = 0.26).

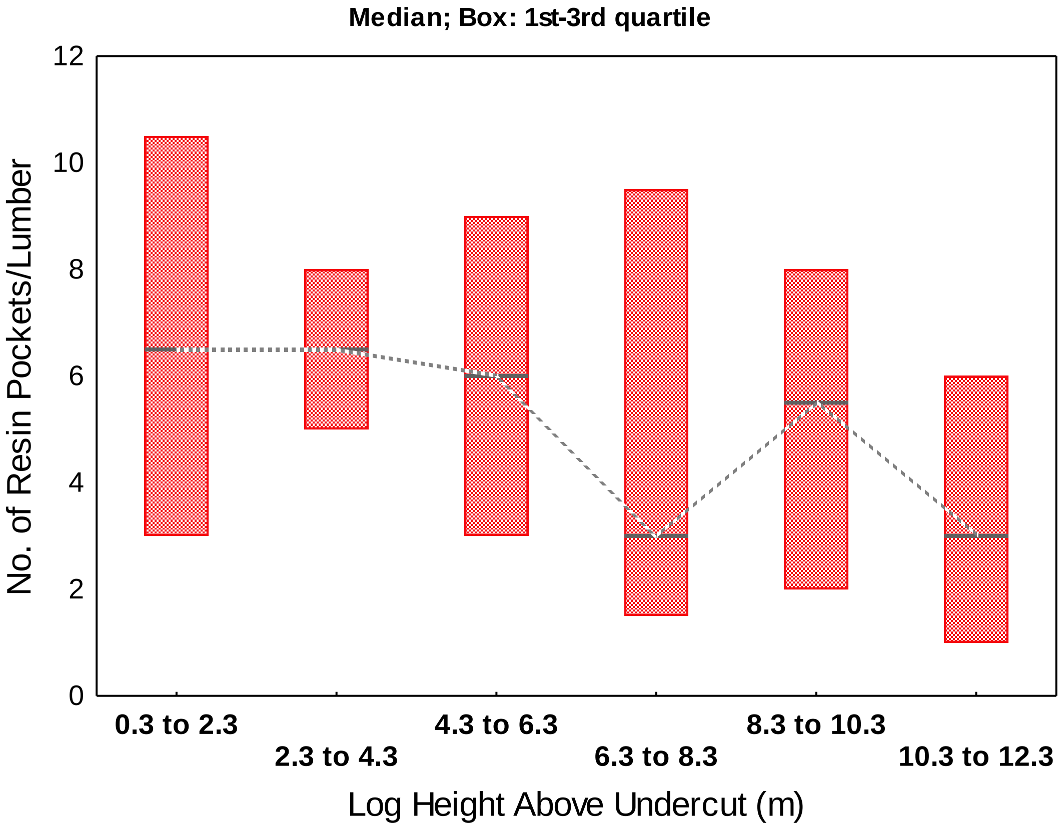

Fig. 7. Variation of the resin pockets frequency along the resonance spruce trees

Table 10. Correlations of Some Features of the Trees with the Frequency of the Resin Pockets at the Resonance Lumber

Tree Features	Spearman Rank Order Correlations with the Number of Resin Pockets/m^3 Timber (Only the Correlations with R > 0.5 are Shown) / p
Stem ovality	+0.707 / 0.02
Length of crown	+0.546 / 0.10
Share of late wood from annual rings at breast height*	-0.591 / 0.05
Length of the area suitable for resonance within the section radius from the height of 1.30 m	+0.817 / 0.004
*Measured by increment cores; the method and results of the measurements are presented by Dinulică *et al.* (2015)	

The shortcoming involved by the presence of resin pockets to the raw material used in the manufacturing of musical instruments was of an aesthetic and acoustic nature. Resin pockets are discontinuities in spruce wood structure, which could affect sound propagation by decreasing, but not compromising, the quality of the musical instrument (Albu 2010). Whatever the discontinuities, they are against the high order in the structural organization of resonance wood (Bucur 1980b). The acoustic measurements made on Scots pine wood, before and after the resin removal, showed the resin depressive effect on dynamic modulus of elasticity (Holz 1967). In Sitka spruce wood, the intense resin streaks increase internal friction (Norimoto *et al.* 1983).

To increase the output of resonance spruce wood, the raw material with small resin pockets (length < 10 mm, width < 8 mm, and thickness < 2 mm) could be replaced by a plug made of the same wood, which, cleverly glued together, could mimic the fibre design with a minimal acoustic impact. Of course, the resulting musical instruments would be of lower quality (*i.e.*, School class).

Musical Instruments Output

The resonance logs averaged between 65% and 93% of the standing trees volume. It seemed that the resonance wood had a large share of the selected trees. In fact, the wood from sampled stems at heights greater than 16 m was of poorer quality and used to make violins smaller than usual.

From the resonance-sorted wood, the resulting flitches were mainly violin flitches (Table 11), which were smaller and therefore demanded a smaller volume of wood with zero defects. The flitches for double bass were hard to obtain, because only half of the felled spruce trees could offer such material. The total volume of flitches cut from a tree varied between 0.259 m^3 and 0.880 m^3, with an average of 0.535 m^3.

The output in flitches from logs ranged between 18.91% and 32.23% from tree to tree, with an average of 25.2%. From 1 m^3 of resonance logs, one could obtain:

- ✓ 70 to 135 flitches for violin, on average 100 pcs/violin, and
- ✓ 1 to 7 flitches for cello, on average 2 to 3 pcs/cello.

For a double bass flitch, 2 m^3 of resonance wood was needed.

Table 11. An Overview of the Output in Flitches for Musical Instruments

Feature		Unit	Size
Total volume of the felled resonance trees		m^3	26.407
Total volume of resonance logs		m^3	21.24
Total number of flitches obtained	Violin	pcs	2065
	Cello	pcs	62
	Double bass	pcs	12
Average number of flitches /m^3 of logs	Violin	pcs	100.7
	Cello	pcs	2.6
	Double bass	pcs	0.5
Total volume of flitches		m^3	5.351
Volume of flitches	Violin	m^3	4.12
	Cello	m^3	0.816
	Double bass	m^3	0.415
Resonance flitches recovery factor from logs		%	25.19
Resonance flitches recovery factor from standing trees		%	20.26

Output in flitches from trees ranged between 12.64% and 29.71% from tree to tree, with an average of 20%. Trees with a right insertion angle of branch and wood with small number of knots greater than 10 mm gave higher yields in terms of flitches (Spearman rank order correlations +0.640, $p = 0.04$ and -0.600, $p = 0.05$, respectively). The yield of cello flitches best described the overall tree output ($R = +0.663$, $p = 0.04$).

The soundboards outputs showed that by a responsible sorting, with the minimization of losses due to presence and position of defects, the market of musical instruments manufacturers could still be supplied with the corresponding qualitative raw material. The results proved that the raw material could also be chosen from logs that did not meet the traditional requirements, especially from the perspective of the incidence of knots and resin pockets, provided that the defects were clustered, which allowed them to be avoided when dimension cutting the vibrating plate of the instrument.

To increase the output, the authors recommended the dimensional diversification of flitches for some stringed instruments. In this way, rejection of raw material because of insufficient dimensions of wood with zero defects could be prevented. For example, for a cello size 4/4, the flitches could be shortened from 850 mm to 780 mm, which would provide an allowance for shrinkage length of 20 mm. Additionally, the double bass flitches could be shortened from 1250 mm to 1200 mm, which would provide a sufficient allowance for shrinkage of 31 mm.

CONCLUSIONS

1. The noticeable number of flitches that were produced from the felled trees demonstrated that substantial raw material for the manufacturing of strings could be obtained through a responsible sorting even under the qualitative regression of resonance trees.
2. Buttress, understood as the difference between the tree diameters from 0.30 m and 1.30 m above the ground, was one of the defects that did not restrain the use of the raw material in the manufacturing of musical instruments and could be allowed up to 20 cm in size. For the sampled trees, the root-swelling comprised the first 70 cm above the undercut section.
3. The admissibility of knots, even those with a diameter greater than 10 mm, depended on the ability to recover enough clear wood for flitches. In principle, wood could be used where the knots were grouped in the whorls and the distance between the whorls was greater than the length of the violin flitch. One cubic meter of resonance lumber analysed contained an average of 252 knots. The knot area influence on the rings contour was 2 to 3 times wider than the diameter of the knot itself.
4. In the resonance flitches, the resin pockets could be accepted up to 10 mm long and 2 mm thick, if they remain outside the musical instrument molds. One cubic meter of resonance lumber surveyed contained an average of 17 resin pockets.
5. For eccentricity and ovality, not exceeding 10% of the diameter, no concession should be made. With regard to the ring shake, the requirements should be tightened. The authors propose that the ring shake be tolerated up to a maximum of 20%, which implies its location in the core of the tree trunk, which however has no acoustic value.
6. From the evolution of shape log defects along the tree, it follows that the first meter in the trunk should be avoided. The frequency of knots and resin pockets had similar tendencies once observation moved away from the undercut section of the trees. The highest frequency of knots and resin pockets was recorded at the timber collected from the first 4 m.
7. The studied tree sample was not homogeneous in terms of the qualitative characteristics of the defects. The eccentricity, the frequency of the knots, and especially the frequency of the resin pockets distinguished the resonance spruce trees between them. The geometry of the knots differed from one flitch to another. In contrast, the dimensions of the resin pockets were stable.

8. The output in terms of flitches for musical instruments was 25% of the volume of the cut resonance logs and 20% of the volume of the standing trees and was accomplished mainly based on the violin flitches. The material suitable for making a double bass involves the sorting of at least 2 m^3 of raw wood.

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