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Original article

Classifying xylophone bar materials by perceptual, signal processing and wood anatomy analysis

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Abstract – Several different areas of expertise are required to analyse the acoustic qualities of wood. The practical experience of musical instrument makers is extremely valuable, especially with respect to selecting the most suitable wood species for different applications. Knowledge on the mechanics and anatomy of wood is also essential to determine the factors underlying the acoustic qualities of woods. In addition, music synthesis research on psychoacoustic issues can highlight perceptual attributes that account for the acoustic qualities of different woods. The present study was focused on 58 tropical wood species used in xylophone-type percussion instruments. Each wood was classified by an xylophone maker and on the basis of an analysis of radiated sound signals and these separate classifications were compared with the aim of determining key signal parameters that have an impact on the acoustic quality of wood. Relationships between perceptual classifications, signal parameters and wood anatomical characteristics were analyzed.

wood musical quality / acoustic properties / vibration / wood anatomy

Résumé – Classifications de lames de xylophone par analyse perceptive, traitement du signal et anatomie des bois. Le bois est un matériau essentiel pour la fabrication de nombreux instruments de musique. En évaluer les qualités acoustiques relève de la mise en commun de plusieurs domaines de compétence. D'une part, les luthiers apportent un savoir empirique très précieux qui permet le choix des meilleures essences. D'autre part, les connaissances en mécanique et en anatomie du bois permettent une meilleure compréhension de l'origine de ces qualités. Parallèlement, les recherches en synthèse musicale associées aux problématiques de la psychoacoustique donnent un éclairage sur les attributs perceptifs à l'origine de la qualité acoustique d'une essence. L'étude porte sur une soixantaine d'essences tropicales et se limite aux instruments percussifs de type xylophone. Deux classifications sont réalisées et mises en parallèle, celle du luthier et celle donnée par l'analyse des signaux sonores rayonnés, dans le but d'identifier les paramètres déterminants du signal du point de vue de la qualité acoustique du matériau. Les relations entre une classification perceptive, les paramètres du signal, et des caractéristiques anatomiques sont analysées. Elles permettent de mettre en évidence des critères objectifs et pertinents utilisables pour évaluer la qualité des bois de lutherie.

qualité musicale du bois / propriété acoustique / vibration / anatomie du bois

1. INTRODUCTION

Wood is used in making many musical instruments because of the indispensable physical and mechanical properties of this material. The sound quality of wood is perceptually assessed by musical instrument makers and musicians. Analyzing the acoustic qualities of wood is highly complex, and this issue has only been partially dealt with to date. Holz [7] focused on key qualities of wood used for making xylophone bars and proposed a map of around 20 species classified on the basis of their modulus of elasticity, density and damping features. Ono and Norimoto [15] demonstrated that samples of spruce wood (*Picea excelsa, P. glehnii, P. sitchensis*) – which is considered to be a suitable material for soundboards – all had a high sound velocity and low longitudinal damping coefficient as compared to other softwoods. The cell-wall structure could account for this phenomenon. Internal friction and the longitudinal modulus of elasticity are markedly affected by the microfibril angle in the S2 tracheid cell layer, but this general trend does not apply to all species. For instance, pernambuco (*Guilandina echinata* Spreng.), which is traditionally used for making violin bows, has an exceptionally low damping coefficient relative to other hardwoods and softwoods with the same specific modulus [10, 21]. This feature has been explained by the abundance of extractives in this species [11]. Obataya et al. [14] confirmed the importance of extractives for the rigidity and damping qualities of reed materials. Matsunaga et al. [12] reduced the damping coefficient of spruce wood by impregnating samples with extractives of pernambuco (*Guilandina echinata* Spreng.).

It is essential to know what musical instrument or component is involved when assessing the "acoustic quality" of a

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wood specimen. Our scientific study was thus designed to gain further insight into the relationship between the physical properties, anatomical characteristics and the perceptual classification of woods to be used in xylophone and marimba type percussion instruments. Hence, a xylophone maker perceptually classified 58 tropical wood species and, based on this classification, key signal parameters pertaining to the acoustic quality of the material were identified. These parameters were then correlated with the physical and anatomical properties of each wood. Finally, we propose a nondestructive method for assessing the quality of woods earmarked for making musical instruments.

2. MATERIALS AND METHODS

The study focused on 58 tropical wood species belonging to the tropical wood collection of CIRAD (Tab. I). They were selected in order to cover a wide range of density going from 206 to 1277 kg/m^3. The xylophone maker recommended the following test sample dimensions: 350 mm long, 45 mm wide, 20 mm thick, which was in line with the rough size of the samples and sawing constraints. When possible, the specimens were prismatic, straight grained, knot-free, and without defects. The specimens were cut to minimize the curve of the growth rings, with the ring parallel to the tangential grain of the wood. The longitudinal direction was colinear to the longitudinal axis of the specimens. The specimens were stabilized in a climatic chamber at 65% ambient humidity and 20 °C ambient temperature, with a theoretical wood moisture content of 12% at equilibrium.

2.1. Classification test of the xylophone maker

The acoustic space, minus the pitch (mainly linked to frequency), loudness (intensity) and duration, is called the "timbre". Any dimension can be assessed on the basis of perceptual features (as in the present case), described on the basis of semantic attributes, or acoustic features and thus quantified according to signal parameters or "descriptors", or physical features whereby sound source properties are used to describe sound. The differential semantic approach was described by Bismarck [1], a method that involves assessing a set of sounds on digital scales. Grey contributed to the analysis of timbre by using multidimensional statistical analysis methods [6]. In most multidimensional analyses of timbre, the spectral center of gravity and acoustic "assault" (rise time) are the main dimensions of the perceptual space [13]. The third dimension seems to be less stable and varies between studies. Note that these studies were conducted on a broad range of instruments with resonating structures (tubes, balls, strings, etc.) and different excitation modes (rubbing, plucking and percussion).

A xylophone maker conducted a first classification with the wood specimens at hand (multisensory classification) and then, secondly, indirectly on the basis of recorded sounds (acoustic classification). The xylophone maker had access to the wood specimens for 1 week for the multisensory classification. A computer interface was designed for the acoustic classification. All sounds, represented by identical icons, were randomly distributed on the computer screen. The xylophone maker could click on an icon to listen to a sound as many times as he wished, and then he classified the sounds by sorting the icons in order of acoustic quality on the screen. The classification method was described by Bismarck [1], with the wood specimens classified in terms of their "musical suitability" for xylophone bar material.

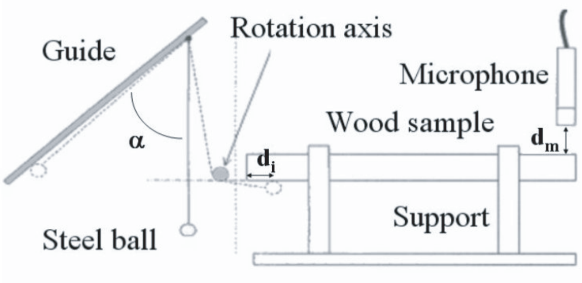

Figure 1. Experimental set up for acoustic radiation measurements (α = 30°, d_i = 1.5 cm, d_m = 2.5 cm).

2.2. Dynamic test

2.2.1. Test procedure

The system for measuring the acoustic signal radiated via the wood specimens was designed to obtain an accurate analysis of the mechanical and acoustic properties of the material, while also enabling the xylophone maker to classify the species (Fig. 1). It was thus important to conduct the analyses in conditions resembling those in which a musician would play a xylophone. The prismatic-shaped wood samples were set on two elastic supports with a very low vibration frequency (< 10 Hz). A pendulum, consisting of a nylon cord (30 cm long) and a metal ball (14 mm diameter, 12 g weight), was set in motion to trigger a vibration in the wood specimen by hitting the end with the metal ball. An omnidirectional microphone was placed at the other end to measure the acoustic pressure radiated at impact.

The data acquisition system included a NEUMAN KM183 MT microphone, a DIGIDESIGN 001 converter (48 kHz sampling frequency, 16 bit resolution) and the PROTOOLS software package. The sounds were produced and recorded in an anechoic room (70 Hz cutoff frequency). The test table was covered entirely with an absorbent material (melamine).

2.2.2. Signal processing

Sound signal "descriptor" parameters were used within the frequency space in the first approach which was designed to accurately analyze the timbre of the tested wood samples. The Spectral Center of Gravity (*SCG*) was thus determined (1), along with the Spectral Range (*SR*) (2) and the harmonicity factor (*HF*) (3).

$$SCG = \frac{\sum_{i=1}^{N} A_i f_i}{\sum_{i=1}^{N} A_i} \tag{1}$$

where A_i is the modulus of the discrete Fourier transform at frequency f_i.

$$SR = \sqrt{\frac{\sum_{i=1}^{N} A_i \, (f_i - SCG)^2}{\sum_{i=1}^{N} A_i}} \tag{2}$$

$$HF(i) = \frac{\text{resonance frequency of rank } i}{\text{fundamental frequency}} - i \,. \tag{3}$$

Table I. List of wood species.

Database No.	Botanical name	Country	Density (kg/m^3)
4271	*Scottellia klaineana* Pierre	Côte d'Ivoire	629
5329	*Ongokea gore* Pierre	Congo	842
6704	*Humbertia madagascariensis* Lamk.	Madagascar	1234
6779	*Ocotea rubra* Mez	French Guiana	623
6966	*Khaya grandifoliola* C.DC.	Côte d'Ivoire	646
7021	*Khaya senegalensis* A.Juss.	Burkina Faso	792
7299	*Coula edulis* Baill.	Cameroon	1048
11136	*Tarrietia javanica* Bl.	Cambodia	780
13293	*Entandrophragma cylindricum* Sprague	Côte d'Ivoire	734
14233	*Afzelia pachyloba* Harms	Cameroon	742
14440	*Swietenia macrophylla* King	Martinique	571
14814	*Aucoumea klaineana* Pierre	Congo	399
15366	*Humbertia madagascariensis* Lamk.	Madagascar	1277
15377	*Faucherea thouvenotii* H.Lec.	Madagascar	1061
15717	*Ceiba pentandra* Gaertn.	Côte d'Ivoire	299
16001	*Letestua durissima* H.Lec.	Congo	1046
16084	*Monopetalanthus heitzii* Pellegr.	Gabon	466
16136	*Commiphora* sp.	Madagascar	390
16211	*Dalbergia* sp.	Madagascar	916
16624	*Hymenolobium* sp.	French Guiana	600
16627	*Pseudopiptadenia suaveolens* Brenan	French Guiana	875
16641	*Parkia nitida* Miq.	French Guiana	232
16664	*Bagassa guianensis* Aubl.	French Guiana	1076
16725	*Discoglypremna caloneura* Prain	Gabon	406
16790	*Faucherea parvifolia* H.Lec.	Madagascar	853
16796	*Brachylaena ramiflora* Humbert	Madagascar	866
17431	*Simarouba amara* Aubl.	French Guiana	455
18077	*Gossweilerodendron balsamiferum* Harms	Gabon	460
18127	*Manilkara mabokeensis* Aubrev.	Central African R.	944
18283	*Shorea-rubro squamata* Dyer	Philippine	569
18284	*Autranella congolensis* A.Chev.	Central African R.	956
18412	*Entandrophragma angolense* C.DC.	Congo	473
18752	*Distemonanthus benthamianus* Baill.	Cameroon	779
19041	*Terminalia superba* Engl. & Diels	Cameroon	583
20030	*Nesogordonia papaverifera* R.Cap.	Côte d'Ivoire	768
20049	*Albizia ferruginea* Benth.	Côte d'Ivoire	646
20982	*Gymnostemon zaizou* Aubrev. & Pellegr.	Côte d'Ivoire	380
21057	*Anthonotha fragrans* Exell & Hillcoat	Côte d'Ivoire	777
24440	*Piptadeniastrum africanum* Brenan	Côte d'Ivoire	975
25971	*Guibourtia ehie* J.Leon.	Côte d'Ivoire	783
26439	*Manilkara huberi* Standl.	Brazil	1096
27319	*Pometia pinnata* Forst.	Salomon Islands	713
27588	*Glycydendron amazonicum* Ducke	French Guiana	627
28071	*Cunonia austrocaledonica* Brong. & Gris.	New Caledonia	621
28082	*Nothofagus aequilateralis* Steen.	New Caledonia	1100
28086	*Schefflera gabriellae* Baill.	New Caledonia	570
28089	*Gymnostoma nodiflorum* Johnst.	New Caledonia	1189
28099	*Dysoxylum* sp.	New Caledonia	977
28100	*Calophyllum caledonicum* Vieill.	New Caledonia	789
28102	*Gyrocarpus americanus* Jacq.	New Caledonia	206
28103	*Pyriluma sphaerocarpum* Aubrev.	New Caledonia	793
28163	*Cedrela odorata* L.	Guadeloupe	512
29468	*Moronobea coccinea* Aubl.	French Guiana	953
29503	*Goupia glabra* Aubl.	Brazil	885
29509	*Manilkara huberi* Standl.	Brazil	1187
30231	*Micropholis venulosa* Pierre	French Guiana	665
30258	*Cedrelinga catenaeformis* Ducke	Brazil	490
30679	*Vouacapoua americana* Aubl.	French Guiana	882

Table II. Xylophone maker's acoustic classification (best quality: 16211, worst quality: 16790).

	Good	Medium				Poor			
Quality	1	2	3	4	5	6	7	8	9
1	16211 Dalb. sp.	15366 *Humb. m.*L.	16084 *Mono. h.*P.	30231 *Micr. v.*P.	15377 *Fauc. t.*H.L.	14814 *Auco. k.*P.	5329 *Ongo. g.*P.	7299 *Coul. e.*B.	29503 *Goup. g.*A.
2	16624 *Hyme.* sp.	30258 *Cedr. c.*D.	24440 *Pipt. a.*B.	28163 *Cedr. o.*L.	6779 *Ocot. r.*M.	20982 *Gymn. z.*A.P.	18127 *Mani. m.*A.	15717 *Ceib. p.*G.	18284 *Autr. c.*A.C.
3	16136 *Comm.* sp.	27588 *Glyc. a.*D.	6704 *Humb. m.*L.	18412 *Enta. a.*C.	7021 *Khay. s.*A.J.	13293 *Enta. c.*S.	28102 *Gyro. a.*J.	18077 *Goss. b.*H.	16725 *Disc. c.*P.
4	28100 *Calo. c.*V.	28099 *Dyso.* sp.	6966 *Khay. g.*C.	20049 *Albi. f.*B.	30679 *Voua. a.*A.	28071 *Cuno. a.*B.G.	28086 *Sche. g.*B.	26439 *Mani. h.*S.	16790 *Fauc. p.*H.L.
5	14440 *Swie. m.*K.	29468 *Moro. c.*A.	16664 *Baga. g.*A.	16641 *Park. n.*M.	27319 *Pome. p.*F.	29509 *Mani. h.*S.	20030 *Neso. p.*R.C.	28082 *Noth. a.*S.	
6	16627 *Pseu. s.* B.	14233 *Afze. p.*H.	18283 *Shor. s.*D.	19041 *Term. s.*E.D		4271 *Scot. k.*P.	25971 *Guib. e.*J.L.	28103 *Pyri. s.*A.	
7	17431 *Sima. a.* A.	11136 *Tarr. j.*Bl.	18752 *Dist. b.*B.	16796 *Brac. r.*H.		21057 *Anth. f.*E.H.	16001 *Lete. d.*H.L.	28089 *Gymn. n.*J.	

In the second approach, the sound signal "descriptor" parameters were used in the temporal space. The parametric method of Steiglitz-McBride [20] was used to simultaneously determine the amplitude β_i and the temporal damping α_i associated with the resonance frequency (4). In the equation (4), the summation was limited to the first three resonance frequencies because of the frequency contents of measured signals (excitation of specimens by a finite impulse which acts as a low pass filter in addition with the damping properties of wood material).

$$s(t) \approx \sum_{i=1}^{3} \beta_i \exp(-\alpha_i t)\sin(2\pi f_i t + \varphi_i) \tag{4}$$

where s is the radiated signal as a function of time t, f_i is the resonance frequency of the order i and φ_i is the phase shift. Amongst the temporal descriptors, dissipation in wood material under longitudinal or transverse vibration conditions is usually characterized by a logarithmic decrement calculation [2, 16, 19]. This value, relative to a free-free vibration frequency of the material, can be used through a generalization of the vibrational response of a dissipative system at one degree of freedom (5) and via complex dissipative systems [17].

$$s(t) \approx \sum_{i=1}^{3} \beta_i \exp(-\lambda_i 2\pi f_i t)\sin\left(\left(2\pi f_i\sqrt{1-\lambda_i^2}\right)t + \varphi_i\right) \tag{5}$$

when the damping rate λ_i is much lower than 1, the logarithmic decrement $\delta_{\mathrm{Log}(i)}$ is proportional to the damping rate [2]. The damping rate and logarithmic decrement are thus linked by the following relation (6):

$$\delta_{\mathrm{Log}(i)} \approx 2\pi\lambda_i\,. \tag{6}$$

Logarithmic decrement studies have been carried out notably by Kollmann [8], Bordonné [2] and Holz [7] among others. A lack of relationship between the density and the logarithmic decrement $\delta_{\mathrm{Log}(i)}$ was experimentally noted by Kollmann [8] in oak and spruce, and by Bordonné [2] in tropical species. However, Bordonné [2] observed a regular increase in the logarithmic decrement with the associated frequency in kaori, which is a softwood. This trend was also noted by Holz [7] in spruce.

Temporal descriptors, along with associated vibrational frequencies, of a dynamic dissipation phenomenon in a material are all equivalent, but it is important to specify the equations that link these different parameters. Equation (6) establishes the first linkage. For additive synthesis of a real signal, the signal must be composed of a sum of exponentially damped sinusoids (4). The combined use of additive synthesis models and waveguide synthesis can highlight relationships between different signal damping, damping rate λ_i, temporal damping α_i, and internal friction tan δ_i quantitative values associated with the complex modulus concept [18] with respect to transverse vibrations [3]:

$$\alpha_i = 2\pi\lambda_i f_i \tag{7}$$

$$\alpha_i = \frac{\pi}{2} f_i \tan\delta_i\,. \tag{8}$$

In the third approach, the signal was used to determine the mechanical parameters of the material [5, 9]. The longitudinal modulus of elasticity and the transverse shear modulus can be calculated when the geometry and mass of the test samples are known [4].

3. RESULTS AND DISCUSSION

3.1. Acoustic and multisensory classifications of the xylophone maker

The acoustic and multisensory classification results are given in Tables II and III. The classifications are linear – graded from best to worst – with the results separated in three separate groups, i.e. good, medium and poor. The xylophone maker detected eight odd samples due to defects or cutting problems (Tab. III). These odd samples were excluded from the analyses.

During the multisensory classification, the xylophone maker separated the low and high density woods (Tab. III). The light woods had some defects that would hamper their professional use, i.e. fragility, instability and lack of acoustic power. However, these two categories were not differentiated in the acoustic classification (Tab. II). The density was not reflected in the acoustic information. The two classifications were still coherent since the very good and very poor acoustic quality samples were properly positioned at the extremes in the two tables (Tabs. II and III). In the qualitative classification, the acoustic information thus took precedence over the esthetic and textural features.

Table III. Xylophone maker's multisensory classification (best quality: 16211, worst quality: 7299). Odd samples were not taken into account in further analyses.

Quality	Medium or high density (from 600 to 1277 kg/m^3)					
	Good		Medium		Poor	
	1	2	3	4	5	6
1	16211 Dalb. sp.	15366 *Humb. m.*L.	18752 *Dist. b.*B.	25971 *Guib. e.*J.L.	7021 *Khay. s.*A.J.	29509 *Mani. h.*S.
2	16624 *Hyme.* sp.	24440 *Pipt. a.*B.	27588 *Glyc. a.*D.	6966 *Khay. g.*C.	28071 *Cuno. a.*B.G.	30679 *Voua. a.*A.
3	28100 *Calo. c.*V.		11136 *Tarr. j.*Bl.	6704 *Humb. m.*L.	6779 *Ocot. r.*M.	5329 *Ongo. g.*P.
4	14233 *Afze. p.*H.		16796 *Brac. r.*H.	18283 *Shor. s.*D.	15377 *Fauc. t.*H.L.	7299 *Coul. e.*B.
5	28099 Dyso. sp.		16664 *Baga. g.*A.	20049 *Albi. f.*B.	18127 *Mani. m.*A.	
6	16627 *Pseu. s.* B.		4271 *Scot. k.*P.	20030 *Neso. p.*R.C	16001 *Lete. d.*H.L.	
7	29468 *Moro. c.*A.		21057 *Anth. f.*E.H.	27319 *Pome. p.*F.	28103 *Pyri. s.*A.	

Quality	Low density (from 206 to 600 kg/m^3)				Odd samples	
	Good		Medium			
	1	2	3	4		
1	16136 *Comm.* sp.	28163 *Cedr. o.*L.	18077 *Goss. b.*H.		14814 *Auco. k.*P.	28089 *Gymn. n.*J.
2	30231 *Micr. v.*P.	16084 *Mono. h.*P.	28102 *Gyro. a.*J.		28082 *Noth. a.*S.	
3	14440 *Swie. m.*K.	28086 *Sche. g.*B.	20982 *Gymn. z.*A.P.		13293 *Enta. c.*S.	
4	18412 *Enta. a.*C.		15717 *Ceib. p.*G.		26439 *Mani. h.*S.	
5	30258 *Cedr. c.*D.		16725 *Disc. c.*P.		16790 *Fauc. p.*H.L.	
6	19041 *Term. s.*E.D.		16641 *Park. n.*M.		18284 *Autr. c.*A.C.	
7	17431 *Sima. a.* A.				29503 *Goup. g.*A.	

3.2. Comparison of the acoustic classification and the signal processing analysis results

The number of samples analysed was reduced to 50 after the 8 odd samples were eliminated from the initial batch. The 14 parameters derived from the sound signal analysis are presented in Table IV. The aim here was to identify parameters that would best account for the xylophone maker's acoustic classification.

The bivariate correlation matrix (Fig. 2) calculated on the basis of the 14 characteristic parameters revealed close colinearity between these parameters. A principal component analysis was thus conducted. This analysis generated a new set of parameters derived from the original set in which the new parameters (principal components) were not correlated and closely represented the variability of the original set. Table V shows that five principal components accounted for 94% of all information contained in the 14 original parameters.

A hierarchical cluster analysis was performed on the basis of the principal components, such that: (a) the measurement of similarities between studied individuals is a distance measurement, (b) the distance measurement is the Euclidian distance calculated in the orthogonal space formed by the five standard principal components, and (c) the agglomeration method uses the mean distance between groups.

The resulting tree diagram highlighted three groups, called G1, G2 and G3. The composition of these groups was compared to that of the three groups derived from the xylophone maker's acoustic classification on the basis of the contingency table (Tab. VI). This table indicates differences between the acoustic and hierarchical classifications. Two different hypotheses

Table IV. Characteristic parameters computed from dynamic test results.

No.	Characteristic parameters
1	Density
2	Longitudinal modulus of elasticity (E_L)
3	Shear modulus (G_{TL})
4	Ratio: modulus of elasticity/density
5	Ratio: shear modulus/density
6	Rank 1 vibration frequency (fundamental)
7	Rank 2 vibration frequency (1st harmonic)
8	Harmonicity factor (*HF*)
9	Spectral center of gravity (*SCG*)
10	Spectral range (*SR*)
11	Fundamental amplitude (β_1)
12	1st harmonic amplitude (β_2)
13	Fundamental damping coefficient (α_1)
14	1st harmonic damping coefficient (α_2)

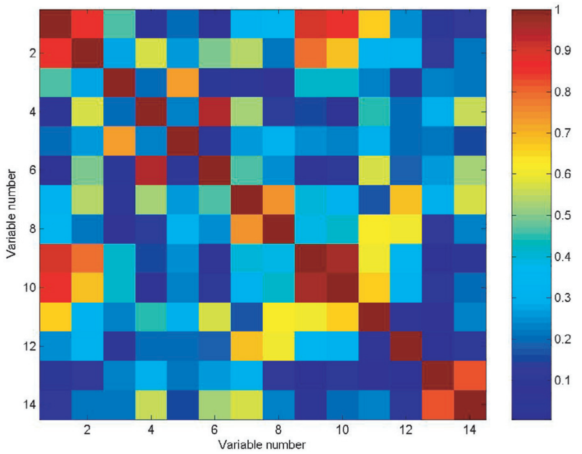

Figure 2. Absolute bivariate correlation coefficients for characteristic parameters[1].

might explain this lack of fit, i.e. either (1) the xylophone maker based his classification on information other than that contained in the parameters used, or (2) he only used part of the information of parameters derived from the sound signal analysis.

A partial least-squares regression model was used to determine whether either of these hypotheses applied. By this regression method, a multiple linear regression is performed on a new set of variables (latent variables) assembled by taking the variability in the original set as well as the variability in the target set (here the xylophone maker's acoustic classification) into account [22]. A unitary distance between two samples in the acoustic classification was arbitrarily attributed in order to make the acoustic classification variable quantitative.

The partial least squares regression obtained was highly significant ($R^2 = 0.74$, Tab. VII). The two latent variables that best accounted for the xylophone maker's classification pooled an equal share of the experimental information (around 20% per variable). However, the first latent variable accounted for a major part (58%, Tab. VII) of the variability noted in the xylophone maker's acoustic classification.

Table V. Total variance explained by principal components.

No. PC	% of variance	% Cumulative
1	35	35
2	26	61
3	15	76
4	10	86
5	8	94

Table VI. Comparison of acoustic classification and hierarchical clustering performed on principal components (contingency table).

Size of group	G1	G2	G3
Good	3	4	0
Medium	7	16	3
Poor	4	7	6

Table VII. Total variance explained by latent variables (NIPALS algorithm).

Latent variable	Characteristics parameters		Acoustic classification	
	% of variance	% cumulative	% of variance	% cumulative
1	20	20	58	58
2	19	39	16	74

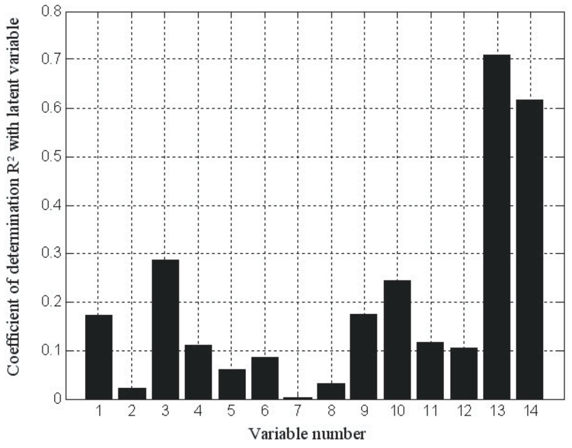

Figure 3. Bilateral regression coefficients for variables and latent variable 1.

Figure 3 shows that the first latent variable pooled information contained in the temporal damping variables (Nos. 13 and 14, Tab. IV), which were closely correlated (Fig. 2). The second

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[1] Figure available in colour at www.edpsciences.org/forest

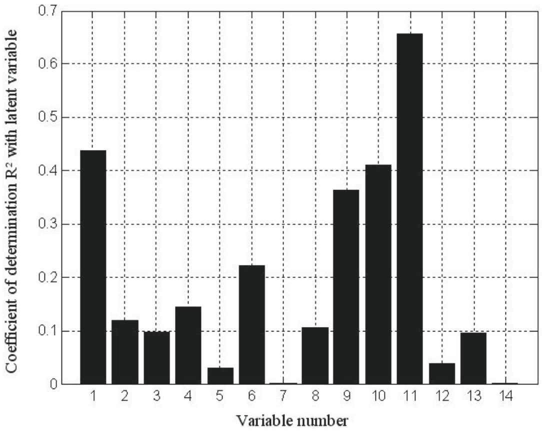

Figure 4. Bilateral regression coefficients for variables and latent variable 2.

latent variable pooled information of variables No. 1, 9, 10 and 11 (Fig. 4). The fundamental frequency amplitude was the original variable best represented by this latent variable (No. 11, Tab. IV). The other original variables (Nos. 1, 9 and 10) were represented by this latent variable because of their close correlation with variable No. 11 (Fig. 4). The xylophone maker's choices were thus mainly influenced by temporal damping of the fundamental frequency, and to a lesser extent by the amplitude of this frequency.

Note that the classified samples were not musically tuned. Between-specimen differences in pitch hampered clear comparisons between species. This could account for the absence of frequency descriptor in the explanation of the xylophone maker's choices.

3.3. Acoustic classification and wood anatomy

The study of the relationship between the qualitative classification and anatomical structure of the wood specimens was focused on species ranked at both extremes of the classification. The discussion is thus mainly hinged on the seven species classified as "good" and the seven species classified as "poor" in both the acoustic and multisensory classifications (Tab. VIII).

Table VIII. Species with the best and worst acoustic qualities which were classified identically in the acoustic and multisensory tests.

Good acoustic quality	Poor acoustic quality
Dalbergia sp.	*Coula edulis* Baill.
Hymenolobium sp.	*Ongokea gore* Pierre
Commiphora sp.	*Manilkara huberi* Standl.
Calophyllum caledonicum Vieill.	*Pyriluma sphaerocarpum* Aubrev.
Swietenia macrophylla King	*Letestua durissima* H.Lec.
Pseudopiptadenia suaveolens Brenan	*Manilkara mabokeensis* Aubrev.
Simarouba amara Aubl.	*Cunonia austrocaledonica* Brong. & Gris.

3.3.1. Vessel elements

All tested specimens were tropical woods, so there was very little variation in the vessel diameters within each annual growth ring, except for the *Dalbergia* from Madagascar which showed clear semi-ring-porous areas. The mean tangential diameter ranged from 140 to 280 µm in all of the good acoustic woods and from 60 to 160 µm in the poor acoustic woods. The vessel frequency/mm^2 ranged from 2 to 8 (up to 18 in *Commiphora*) in the "good" specimens, and from 7 (4 in *Letestua*) to 20 (50 in *Cunonia*) in the "poor" specimens. The vessels were solitary and in radial multiples of 2 to 4 in most of the woods, but they were exclusively solitary in *Cunonia* and *Ongokea* (poor acoustics) and in *Calophyllum* (good acoustics), whereas they were commonly in radial multiples of 4 and more in *Letestua* and *Pyriluma* (poor acoustics) and *Hymenolobium* (good acoustics). They were generally diffuse but with a tendency to be arranged radially in *Letestua*, *Manilkara* and *Pyriluma* (typical feature of woods belonging to the Sapotaceae family).

3.3.2. Axial parenchyma

The axial parenchyma was found to be mainly paratracheal in the good acoustic woods, ranging from scanty paratracheal (*Calophyllum*, *Commiphora* and *Swietenia*) or lozenge-aliform – (*Dalbergia*, *Pseudopiptadenia* and *Simarouba*) to highly abundant and very confluent, forming wide bands linking vessels (*Hymenolobium*). Only *Calophyllum* and *Swietenia* had an apotracheal parenchyma, i.e. the first in the form of a few short to long bands, and the latter in marginal bands. All wood specimens with poor acoustics had an apotracheal parenchyma, i.e. abundant diffuse-in-aggregates parenchyma (*Coula*, *Cunonia*, *Ongokea* and *Pyriluma*) or with many tangential narrow bands (*Letestua* and *Manilkara*).

3.3.3. Rays

In the good acoustic woods the rays frequency ranged from 4 to 9/mm. The rays were 1-3- to 4-seriate (15–55 µm wide) and 180–500 µm high. Their structure was homogeneous or subhomogeneous, i.e. composed only of procumbent cells or procumbent cells with one row of square marginal cells. In the poor acoustic woods the rays frequency ranged from 9 to 16/mm. The rays were 2-4- to 5-seriate (20–50 µm wide) and 400–1000 µm high. Their structure was heterogeneous, i.e. procumbent cells in the body with several rows of square and/or upright marginal cells.

3.3.4. Fibres

The wood fibres in specimens with good acoustics were relatively short, i.e. from 900 µm (*Dalbergia*) to 1300 µm (*Swietenia*) long, and up to 2000 µm in *Hymenolobium*, wide from 19 µm (*Pseudopiptadenia*) to 36 µm (*Commiphora*), with a lumen diameter ranging from 9 µm (*Pseudopiptadenia*) to 28 µm (*Commiphora*). Fibres in the poor acoustic woods were 1300 µm (*Ongokea*) to 2000 µm (*Coula*) long, and 20 µm (*Manilkara*) to 34 µm (*Ongokea*) wide, with a lumen diameter of less than 10 µm. All woods with good acoustics had libriform fibres (simple pits), whereas those with poor acoustics had either libriform fibres (*Letestua*, *Manilkara* and *Pyriluma*) or fibre-tracheids (bordered pits), e.g. *Coula*, *Cunonia* and *Ongokea*.

3.3.5. Storied structure

All poor acoustic woods as well as three with good acoustics (*Calophyllum*, *Commiphora* and *Pseudopiptadenia*) did not show a storied structure. However, all the axial elements and the rays have a clearly defined horizontal storied pattern in *Dalbergia* and *Hymenolobium*, with a relatively storied pattern in *Simarouba* and *Swietenia*.

3.3.6. Relationship between the acoustic classification and the wood anatomy

The acoustic quality of the woods could not be explained by any vessel characteristics. The present findings do not comply with the theory that the narrow diameter and high frequency of vessels in wood is detrimental to acoustic quality since *Ceiba* and *Discoglypremna*, which only have a few (1–2/mm^2) large vessels (around 200 µm diameter), had very poor acoustics.

However, the parenchyma tissue, depending on their distribution patterns and abundance, seemed to have an impact on the acoustic quality. Woods with the best acoustics had axial parenchyma, which was mainly paratracheal and not very abundant (but this latter condition did not seem critical), with only a few short rays, and definitely with a homogeneous structure.

Characterization of the organization of wood components could be enhanced by approaching it from a different perspective, i.e. assuming that woods with the best acoustic qualities have wood structure not regularly disrupted by parenchyma. There are always tangential disruptions due to the presence of rays (a few wood rayless species exist, but these are rare scientific curiosities). These disruptions are minimized when only a few small rays are present. Radial disruptions in the wood structure consistency are primarily due to the presence of vessels (this applies to all woods tested in the present study, but woods of gymnosperm species and of a few rare small dicot families do not have vessels). Hence, woods with few vessels should theoretically have better acoustics than very porous woods. The presence of paratracheal parenchyma does not increase the number of disruptions in the fibrous tissues but it slightly increases disruptions induced by the vessels. However, apotracheal parenchyma, diffuse-in-aggregates or in tangential bands, regularly and frequently disrupts the radial cohesion between fibres. For instance, in the woods with good acoustics, the fibrous tissue was radially disrupted about twice/cm by marginal parenchyma bands in *Swietenia*, 15 times by bands in *Hymenolobium*, while in the woods with poor acoustics the tissues were disrupted 35–50 times/cm by parenchyma bands in *Manilkara* and up to 120 times/cm by diffuse-in-aggregates parenchyma in *Pyriluma*.

The fibre morphology did not seem to have a major impact on the acoustic quality of the woods as long as the lumen diameter was 10 µm or more, i.e. the fibre flexibility coefficient (lumen diameter/fibre width × 100) had to be above 40 or so.

A storied wood structure does not always ensure good acoustics but it likely does enhance the sound quality.

We did not experimentally assess the impact of some anatomic features of the wood specimens on acoustic quality. However, a few structural characteristics of the specimens that were classified (in terms of acoustic quality) as slightly less good than the top seven woods and not quite as bad as the poorest woods could be briefly considered.

Of the specimens ranked just under the seven best woods in the acoustic classification, *Humbertia*, *Cedrelinga* and *Afzelia* had a scanty paratracheal or lozenge-aliform parenchyma (*Afzelia*) as well as a few diffuse parenchyma in the top two species or narrow marginal bands (*Afzelia*). They had many rays (5–8/mm), that were short (less than 300 µm high) with a homogeneous structure. The vessel frequency was 1–5/mm^2. The fibre lumen diameter was very narrow in *Humbertia* and *Afzelia*, but very wide in *Cedrelinga*. Finally, none of these three woods had a storied structure.

The three species that were ranked just above the seven poorest woods in the acoustic classification were *Discoglypremna*, *Nesogordonia* and *Ceiba*. All three had a diffuse-in-aggregate parenchyma. Their rays were either relatively low (250–650 µm high) and numerous (10–15/mm) in the first two species, or few in number (5/mm) but very high (more than 1200 µm) in *Ceiba*, with a heterogeneous (*Discoglypremna* and *Ceiba*) or subhomogeneous (*Nesogordonia*) structure. The vessel frequency was 1–3/mm^2 in *Discoglypremna* and *Ceiba*, and around 20/mm^2 in *Nesogordonia*. The fibre lumen diameter was relatively narrow in this species, but wide to very wide in the other two. The wood structure was regularly storied including the rays in *Nesogordonia*, but with most of the rays nonstoried in *Ceiba*.

4. CONCLUSION

When analyzing materials it is essential to determine the relationships between the manufacturing process (in our case the wood development), the microstructure and properties, while also correlating the properties with performance. This is useful for designing methods to help users make optimal choices on materials and implementation conditions, and to determine cost-effective ways of achieving the best performance, increasing the reliability of the materials and controlling assembly processes. The properties of cellular solids depend on two sets of parameters; those which describe the geometric internal structure and those which describe the intrinsic properties of the material of which the cell walls are made. When the material is wood, each species could be considered as a "wood factory" that produces a unique wood, always having the same basic composition: a cellular composite consisting of cellulose, lignin and hemicelluloses containing various quantities of extractives. The most marked variations between species are noted in the cellular organization pattern, i.e. the distinctive "fingerprint" of each species. It is thus of interest to assess the relationship between these patterns and the acoustic or vibratory properties of the wood and to compare them with the acoustic performances responsible for the acoustic quality.

The percussive acoustic quality of a wood, as determined empirically by the xylophone maker, can first be related to the two sound signal parameters, i.e. temporal damping of the fundamental frequency and to a lesser extent the amplitude of this frequency. The wood density doesn't impact this acoustic quality, but the light woods have some technological drawbacks.

Our analysis of the organization of wood components in the tested species relative to the acoustic quality classification highlighted the importance of the regularity and homogeneity of the anatomical structures.

A draft anatomical portrait of a good acoustic wood could be drawn up on the basis of our analysis of wood structures in the seven acoustically best and seven poorest woods. This portrait should include a compulsory characteristic, an important characteristic and two or three others of lesser importance.

The axial parenchyma is the key trait. It should be paratracheal, and not very abundant if possible. If abundant (thus highly confluent), the bands should not be numerous. Apotracheal parenchyma can be present, but only in the form of well spaced bands (e.g. narrow marginal bands).

The rays (horizontal parenchyma) are another important feature. They should be short, structurally homogeneous but not very numerous.

The other characteristics are not essential, but they could enhance the acoustic quality. These include:

- Small numbers of vessels (thus large);
- A storied structure;
- Fibres with a wide lumen (or a high flexibility coefficient).

The samples tested in this study were not musically confirmed, so the analysis was biased since no frequency descriptor could be identified. This parameter should be taken into consideration in future studies in order to come up with a more exhaustive list of parameter descriptors of acoustic quality for wood specimens and to identify other subtle features associated with acoustic quality.

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