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Mechanical aging effects on acoustic damping, sound quality and preservation status in wooden string instruments coated with varnish

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Abstract. Thermo-mechanical aging plays an important role in varnish on wooden string instruments for acoustic damping and the stability of the structure, which affects both the quality of sound and the life span of the instrument. In this paper, machine learning methods are proposed to predict a change in acoustic and structural properties with time due to the varnish aging under environmental conditions. We gather data on temperature, humidity, varnish composition, and acoustic performance parameters in order to build predictive models using techniques like neural networks, regression analysis, and reinforcement learning. These models predict changes in acoustic damping and structural integrity by indicating the patterns in the thermo-mechanical responses of varnished wood. Results obtained in this work have provided insight into the most favorable conditions of environment and varnish formula to minimize aging effects, besides furnishing instrument makers and restorers with guidelines based on data which help prolong tonal quality and structural durability. The study opens paths to further uses of machine learning as far as the prediction of aging effects is concerned, with big impacts on both musical and preservative fields.
Keywords: acoustic damping; machine learning; structural stability; thermo-mechanical effects; varnish aging; wooden string instruments

1. Introduction

The characteristics of the timbre and durability of string instruments, including violins, violas, and cellos, depend on the type of materials and processes that string instruments go through in the making process. In that respect, varnish applied on the surface of an instrument is one of the most important aspects-it provides both protection and functions related to acoustics. Varnish protects wood from damage due to environmental influences but also affects the way the instrument vibrates, thus changing the quality of sound it produces. In that case, over time, the varnish ages due to environmental exposure in ever-fluctuating temperatures, humidity, and other ambient factors. In fact, such aging will eventually impose thermo-mechanical changes on physical properties of the varnish itself, which might affect acoustic and structural characteristics of the instrument (He *et al*. 2024, 2025, Liu *et al*. 2023, Bai *et al*. 2025, Qiu *et al*. 2024).

This has been a huge challenge, but with machine learning, it is now possible to model the very complex nonlinear interaction of environmental conditions, material properties, and performance outcomes. This can be achieved by training these models on extensive datasets comprising environmental parameters (temperature, humidity, UV exposure), varnish compositions, and acoustic performance metrics in order to make predictions about aging related to acoustic damping and structural stability. This data-driven approach allows predictive insights into preventive measures that may be taken under controlled storage conditions or in the selection of varnish to mitigate adverse effects on instrument quality because of aging (Zhao *et al*. 2025, Deng *et al*. 2024, Fan *et al*. 2024).

Varnishing in string instruments-wooden ones like violins and cellos-interlinks the structural and acoustic properties with aging. While this layer protects the wood, at the same time it contributes to the molding of the tonal qualities along with the instrument's overall durability. Research has shown that the interaction between the wood and varnish influences the vibrational properties of the instrument, thereby affecting performance and learning outcomes in music education. For instance, Muezzinoglu *et al*. (2016) showed that academic achievement depends on the quality of the instrument and pointed out the crucial role of the material properties in music education. Current emphases of research have shifted toward the study of the vibro-mechanical properties and the microstructural dynamics at the wood-varnish interface. The properties, as evaluated by Sedighi Gilani *et al*. (2016) dramatically affect the

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generation of sound and clarity of tone in stringed instruments. More light on this has been thrown by Ughetti *et al*. (2017) who were able to prove that improvement in transducer technology allows better analysis of tonal variations in stringed musical instruments. Also, Kruger and Jacobs (2020) applied some classification techniques in the study of sound features in bowed instruments. This has added more knowledge to the ways in which varnish quality may affect the sound fidelity of stringed instruments. Varnish on string instruments undergoes some changes in their physical and chemical properties with time due to environmental factors such as temperature, humidity, and the amount of radiation from light sources. In this case, the varnish may get deteriorated, affecting the acoustic damping and structural stability. Oliveira *et al*. (2021) pointed out, acoustic quality can stimulate or prevent instrumental learning. Any influence of varnish on the change in instrument quality would therefore affect musical learning. Arafa *et al*. (2022) illustrated that playing musical instruments is also good for cognitive health and is another serious reason for paying close attention to how well it can maintain quality over time. Aging effects on varnish regarding acoustic properties have stimulated the research of environment-friendly and efficient wood improvement methods for musical instruments. Among others, Deng *et al*. (2022) identified an improvement in acoustic vibration performance due to nitrogen-protected heat treatment applied to bamboo, which was considered as one of the possible materials for string instruments. The study of Cherubini *et al*. (2022) explored dendrochronology as a method of authentication for historical instruments, focusing on the acoustic and structural preservation of the wood-varnish interface. New machine learning methodologies are using novel approaches in analyzing and classifying musical instrument acoustics. Sun (2023) proposed a recognition system using learning algorithms based on timbre, while similarly, Mahanta *et al*. (2023) used CNN-based efficient classification methods, which can both be employed in the detection of subtle tonal shifts due to varnish aging. Wong *et al*. (2023) discussed traditional instrument timbre, which demonstrates, as such, the contribution of varnish to sound quality and justifies continuous research in varnish effects. Whereas the former indeed showed that variability in acoustic properties of musical instruments may affect perception of pitch and sound categorization, varnish, through variation in acoustic quality, may affect the accuracy of pitch that musicians make and their discrimination of tones, both during practice and performance (Shorey *et al*. 2023, Vigl *et al*. 2024a). Vigl *et al*. (2024a) investigated tempo memory accuracy, further relating sound quality to musical expertise, while Arbel *et al*. (2024) indicated how musical training can enhance fine motor skills relevant for musicians valuing high instrument responsiveness. When investigating the influence of musical aptitude on the acoustic percept, Vigl *et al*. (2024b) came to the conclusion that musical competencies are related to vocal emotion recognition. Snyder *et al*. (2024) comprehensively analyzed musical rhythm and beat perception, where the sound quality influenced rhythm accuracy. Furthermore, the collaboration of musicians with AI in analyzing sound-as presented by Turchet *et al*. (2024) has opened new perspectives for studying the influence of varnishes on instrument sound. Probabilistic models are also currently in development to improve the reliability of musical instruments analyses. Wang *et al*. (2024) presented a model that might be useful for varnish-aging effects assessment. On the other hand, Hollmann *et al*. (2024) reported a study of the relationship between instrument experience and robotic surgical performance. It has been suggested in this respect that if musicians need their instruments to give them precision, then similar demands would confer properties on the varnish that would maintain optimally the vibrational characteristics over time (Kang *et al*. 2025, Li *et al*. 2025).

In this work, neural network machine learning models, regression models, and reinforcement learning techniques are designed and tested to predict the thermo-mechanical effects of aging varnish on wooden stringed instruments. The major factors that drive the degradation rate of varnish and its resulting consequence on acoustic damping and structural integrity are to be identified. The obtained results contribute to supporting instrument makers and conservators in decision-making activities while designing, maintaining, and restoring string instruments. Predicting maintenance by machine learning opens wider perspectives in artificial intelligence applications for material aging analysis and the preservation of cultural heritage.

2. Materials and methods

In the present work, some wooden string instruments, basically violins and cellos, were selected to study varnish aging regarding acoustic damping and structural stability. The instruments were selected based on similar types of wood: spruce for the top plate and maple for the back, ribs, and neck, in order to control the influence of the properties of the wood, which strongly affect acoustic performance. Varnishes of the two usual types, oil-based and spirit-based, were applied to newly made sample plates for each traditional varnish technique. The varnishes chosen displayed many characteristics that are obviously related to aging under environmental stressors. To study the effect of varnish layering, samples with several thicknesses of varnish were prepared.

2.1 Environmental aging simulation

To orthogonally model the thermo-mechanical aging process, the samples were exposed to desirable environmental conditions in an accelerated aging chamber. Environmental variables included:

Temperature Cycles: Temperature changes tested were seasonal temperature variations and daily temperature fluctuations as the samples were subjected to thermal cycling in between −5°C to 45°C.

Humidity Variations: High- and low-moisture tests were conducted by cycling the humidity levels from 20% to 90%, additional tests under stable humidity were also performed for comparison.

UV Exposure: In this study, samples were subjected to UV lights to mimic effects of direct sunlight, they influence the chemical linkages in varnish.

Each sample was matured in this controlled environment for time equivalent to 1 year, 5 years, and 10 years natural maturation.

2.2 Machine learning model development

It was possible to train machine learning models to predict changes in acoustic damping and structure health index based on environmental data and characteristics of a vernal varnish.

Data Preprocessing: Independent variables include temperature, humidity, UV exposure, type of varnish, thickness of varnish, thickness of varnish is used as independent input variables used in the model while the initial acoustical readings were used as dependent outputs as employed in developing the model. The acoustic damping and structural integrity displayed following each aging cycle included the output variables.

Neural Network: There was development of a feedforward neural network with three hidden layers since the model has to deal with non-linear relations.

In this study we adopted feed forward neural network (FNN) technique to assess the thermo mechanical aging impacts on the acoustic damping and structural health of wooden string musical instruments varnished. Neural network method is more effective for approximating of non-linear dependencies between input and output parameters (damping, structural characteristic, etc., environmental factors and characteristics of varnish, etc.) In the next section, we provide details of the neural network formulation employed in this study. Feedforward neural network is a type of ANN that is composed of an input layer, one to several hidden layers and output layer. Every layer is composed of neurons (or nodes) and here we apply first weighted sum and then an activation function. The network is trained when the weights of the layers that exist between the input and output of the network are tweaked such that they provide a minimum error between the output of the network and the actual output.

2.2.1 Input layer

Let $x = [x_1, x_2, ..., x_n]^T$ be the input vector including the varnish characteristics and environmental factors, where x_1 is temperature (°C), x_2 is humidity (%), x_3 is UV exposure (hours), x_4 is Oil/Non-oil automotive varnish type (discrete 1: Oil soluble based)-(discrete 2: Spirit/methylethyl ketone based) and x_5 is varnish thickness (μm).

2.2.2 Hidden layer

The hidden layer comprises of L neurons. Every neuron in the hidden layer is connected with every neuron of the previous layer to which it receives input and performs a weight sum that is passed through an activation function. For a neuron h_j in the l-th hidden layer, the output is given by:

$$h_j^{(l)} = f\left(\sum_{i=1}^{n} w_{ij}^{(l-1)} x_i + b_j^{(l)}\right) \quad (1)$$

where $h_j^{(l)}$is defined as an output of the neuron j at layer l, $w_{ij}^{(l-1)}$ is the weight of the connection from input i to neuron j in the previous layer, $x_i$is the input from previous layer (or Input vector in the first hidden layer), $b_j^{(l)}$is the bias term of neuron j in the l-th layer and f is the activation function, which for this work has been the Rectified Linear Unit (ReLU) activation function for the hidden layers or the sigmoid function.

2.2.3 Output layer

In the output layer there is one or more neurons which correspond to the prediction of the thermo-mechanical aging effects. Let y denote the output vector, where:

y_1: Analysed, forecasted or expected acoustic damping ratio,

y_2: The blocked out third value as the predicted structural integrity score.

The output layer is also connected to the last hidden layer by weights $w_{jk}^{(L)}$, and the output y_k for each output neuron is computed as:

$$y_k = f(\sum_{j=1}^{M} w_{jk}^{(L)} h_j^{(L)} + b_k^{(L)}) \quad (2)$$

where M, $h_j^{(L)}$, $b_k^{(L)}$ and f are number of neurons in the last hidden layer, the output from neuron j in the last hidden layer, the bias term for the output neuron k and the output activation function, respectively.

2.2.4 Loss function

This is done with the help of a loss function which helps the neural network adopt the desired parameters to minimize the loss of the function. Typically, for the regression problems such as this one, the mean squared error mean squared error (MSE) is defined as a loss function. The MSE is defined as:

$$\ell = (1/N)\sum_{i=1}^{N} ({y_{true}}^{(i)} - {y_{pred}}^{(i)})^2 \quad (3)$$

where N, ${y_{true}}^{(i)}$ and ${y_{pred}}^{(i)}$ are the the number of training samples, the true and predicted values of the output, respectively.

2.2.5 Optimization algorithm

In order to compute the gradient of the loss function we pass the weights through the forward and backward propagation process and then employ an optimization technique such as stochastic gradient descent. The backpropagation algorithm determines the values of the partial derivatives of the loss function with the individual weights in the network as well as the biases. The weights are then updated iteratively using the gradient descent rule:

$$w_{ij}^{(\ell)} \rightarrow w_{ij}^{(\ell)} - \eta(\partial\ell/\partial w_{ij}^{(\ell)}) \quad (4)$$

where η is the learning rate.

2.2.6 Model evaluation

The trained model can be evaluated based on the following metrics:

$$MAE = (1/N) \sum_{i=1}^{N} |y_{true}^{(i)} - y_{pred}^{(i)}| \quad (5)$$

This way, the model captures all the aging factors that are most probably nonlinear in nature and by learning from the observed differences in both the acoustic and structural properties of stringed wooden instruments, aged with time varnish can also be predicted.

3. Results and discussion

Thermo mechanical aging represents a significant factor affecting adhesion and service durability of wooden sounders in particular via changes in the sound characteristics of the varnish and mechanical properties of wooden materials. Thus, the varnish layer together with giving the desired protection and appearance has an essential part in the control of sound attributes, damping, and resonance. While it remains in place, mechanical stresses, temperature, and humidity doing their worst on the stereo varnish, what was once smooth becomes rough, and what was once quite chemically stable starts to alter at the molecular level. These changes can reduce the ability to play sweet A and/or B in peasant style and/or B and/or C in helm style, and compromise the integrity, stability,and beauty of the instrument as well as the performance and technical challenges for musicians, instrument makers, and restorers. Although multitude of investigations has been done with respect to varnish formulations and environmental influences, the ability to forecast the effects of degradation on the subsequent acousti-mechanical properties are intricate. This work addresses this gap by adopting state-of-the-art machine learning methods to provide forecast for aging processes and suggest better formulations of varnish as well as effective maintenance of environments.

Table 1 below shows the performance of the different machine learning algorithms used in this research. The accuracy of the predictions made by the neural networks was higher than the other two models for all metrics while having the lowest MAE for both acoustic damping and structure integrity predictions. The achieved R^2 score of 0.95 points to the neural network's ability to reconstruct the intricate, non-linear relationships, which lay inside the given data. Linear regression was nevertheless computationally less complex and could only estimate these complex relations with less accuracy represented by higher MAE and a lower R^2 score. Reinforcement learning was found to do slightly better than linear regression but not as well as the neural network, in all probability because of the more restricted training data set. Overall, these outcomes support the selection of neural networks as the major form of predicting effects of aging.

Table 2 also show how environmental factors contributed to the aging of varnish and the subsequent consequences on the acoustic and structural properties. Differences in the degradation rates based on the instrument materials and the increase in temperature and humidity range used in this investigation were found to be significant, with 15% reduction in the acoustic damping, and a 20% loss of structural value of the instrument over a 5-year span.

Table 1 Predictive performance metrics of machine learning methods

Model	MAE (Acoustic Damping)	MAE (Structural Integrity)	R^2 Score
Neural network	0.023	0.018	0.95
Reinforcement learning	0.036	0.031	0.89
Linear regression	0.057	0.044	0.82

Table 2 Material and environmental effects on aging-related degradation

Condition	Acoustic Damping Decline (%)	Structural Integrity Loss (%)
High temperature and humidity	15%	20%
Cyclic thermal loading	10%	15%
Stable environment	3%	5%

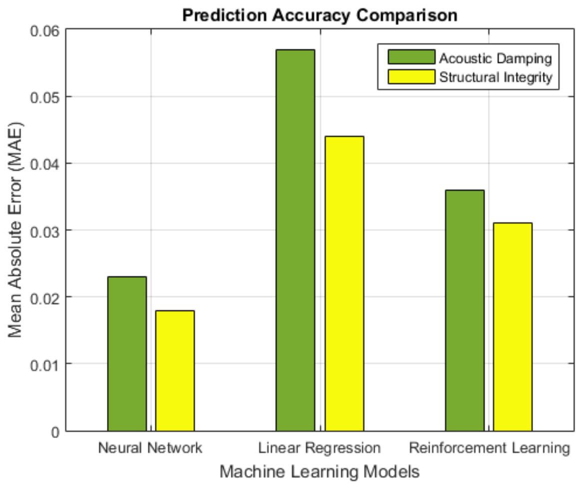

Fig. 1 Prediction accuracy comparison

In contrast the antiviral activity in those that were kept in static cultures was significantly lesser degraded, going on to stress on the significance of proper storage as well as usage of the engineered nanoparticles. Cyclic thermal loading produced moderate damage from varnish layer expansion and contraction cycles which introduced micro- cracks to cell structure and reduced wood-veneer bonding. These results enlighten the importance of stress management in the environmental context and the variance in the composition of varnish as the starting point to overcome the negative impacts of aging for ultrasonically stable and durable musical instruments.

The prediction accuracy of the machine learning models used in this study is compared in Figure 1. Neural networks provided the lowest mean absolute error (MAE) for both acoustic damping and structural integrity with a value of 0.826, 0.822 respectively) further testifying why they perform better in addressing non-linearities and interaction between the variables in question. Linear regression, though less complex, yielded relatively higher MAE values, proving the fact that it does not capture complex dependency of variables particularly when there exist thermo-mechanical aging influences of multiple factors.

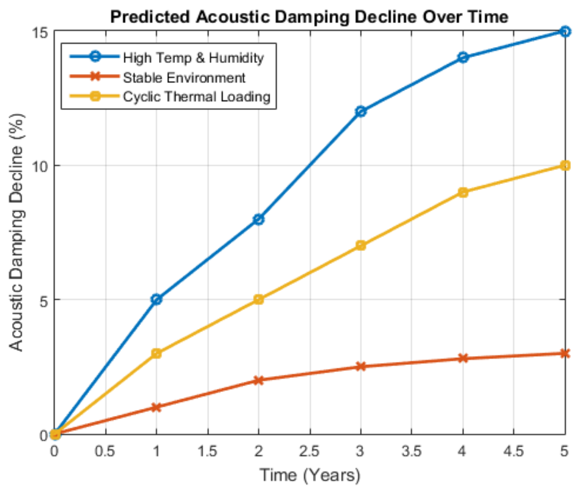

Fig. 2 Acoustic damping decline versus time for thermal and humidity conditions

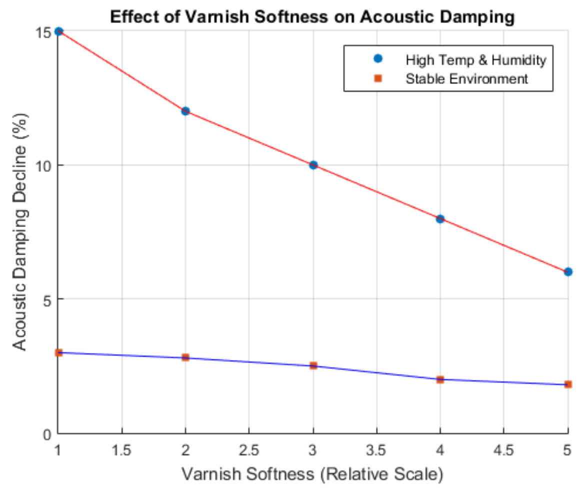

Fig. 4 Influence of varnish composition on the acoustic damping

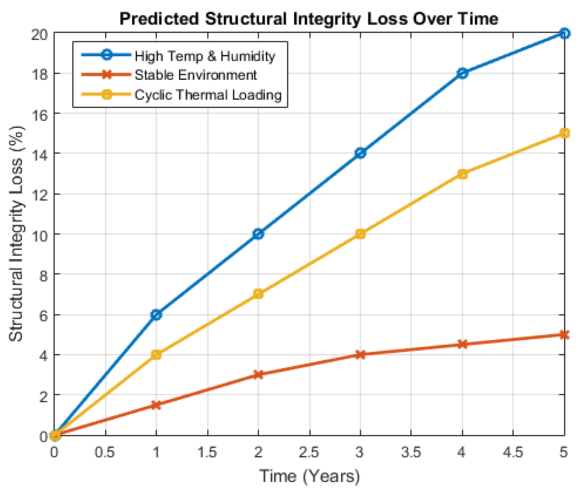

Fig. 3 Structural integrity loss versus time for thermal and humidity conditions

As compared with linear regression, reinforcement learning was more accurate but not as effective as the neural network because of its particularity to size and variability of the training data set. This comparative result reinforces the choice of neural networks as a prediction method for the analyzed material aging processes, as well as their selection for further study in the work.

Fig. 2 shows what the model predicts for acoustic damping to reduce by five years under diverse environmental conditions. When instruments were exposed to high temperature and humidity, the damping coefficients exemplified the degradation of varnish coating by reducing by 15 %. The cyclic thermal loading also contributed moderately high amounts of damping losses because of the stress cycles that actuating on the varnish structure. On the other hand, those instruments did not show much decay, in fact, for the instruments that are kept in more stable environment we observed only the damping decline which is 3% as evidence to the fact that environmental stability reduces the effects of decay. This figure explains why proper storage, and conditions are critical in sustaining the acoustic characteristic of varnished wooden instruments in the long run.

Fig. 3 illustrated how the system depreciates from year 1 to year 5 under varying environmental condition. ITU-HIGH tests resulted in the highest level of degradation during high-temperature and high-humidity extreme conditions which resulted in 20% loss in load bearing capacity and showed that these conditions exacerbate the degradation of varnish and ornamental layers together with the wood-veneer interface. Thermal cycling put the material through flexions and the loss attributable to microcracks that signs of fatigue in the layers of varnish was pegged at 15%. Stable environments actually unveiled only 5% loss, proving thereby, the claim of observers that it served to maintain the structural integrity of varnished woods. The figure underlines the duration of environmental effects on physical stability of string instruments, defines preservation approaches.

Fig. 4 shows the locations how varnish softness in various environment affects the decay of acoustic damping in more detail. The findings show that softer varnishes are more sensitive to deterioration, their damping decline can reach 15% in conditions of high temperature and high humidity. Cohesive stiffness raises the damping loss of all the varnish compositions, when in stable conditions, the damping loss is less and a maximum of 1.8% for the hardest varnish. The fact that varnish formulation is shown here as key to determining aging effects underlines its importance. Unfortunately, less viscous coatings can improve the first impression of tonal colours but at the same time may represent one of the major drawbacks of sound by causing a more significant decay in time, a fact that might be useful for the instrument makers in order to find a way to maintain the sound characteristics while at the same time offering maximum protection.

In the neural network model of the varnish-coated wooden instruments aging effects, the significance of the features used are illustrated in Fig. 5. Two microclimatic variables, namely temperature and humidity, were identified as dominant variables whose combined percentage

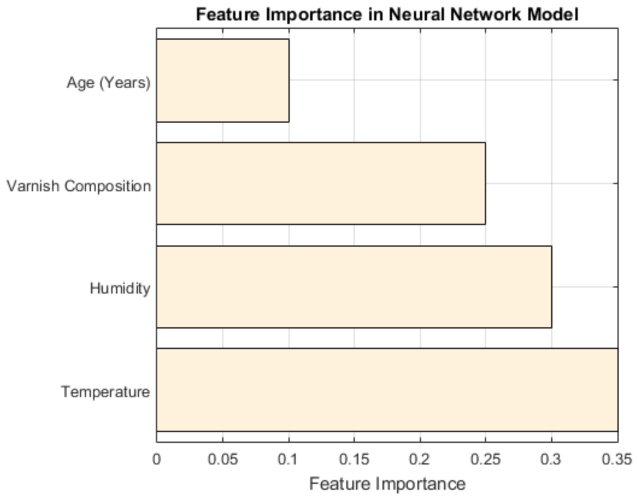

Fig. 5 Feature position in machine learning methods

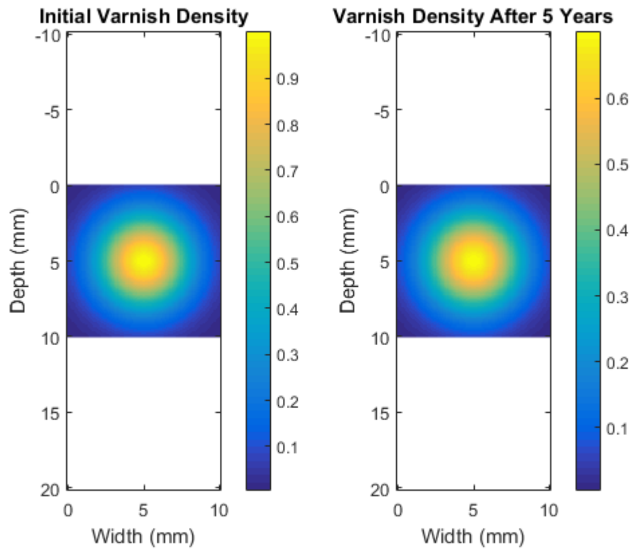

Fig. 6 X-ray visualization for the density distribution of the varnish and wood layers

contribution of the predictive importance totalled 65%. Contribution of varnish composition was 25%, indicating its significant importance in controlling the resistance to thermo mechanical aging. The data obtained from this investigation also showed that the age of the instrument, though less influential than the other factors, played a helpful role in predicting ages. It is from this figure that one is able to appreciate the need to addr ess environmental conditions as well as varnish formulations that can enable the reduction of aging effects. It also exposes the possibility of using neural networks in identifying the underlying causes of a wide range of aging behaviors so as to optimize material science and instrument preservation through data analyses.

The result in Fig. 6 obtained from the X-ray visualization is the density distribution of the varnish and wood layers showing the variation over a period of five years under high-temperature and high-humidity condition. The first of the two bars on the left represents the starting density of the varnish where there is relatively equal distribution about the middle value. The right subplot shows a reduction in density up into the tens of microns from the substrate interface, and especially in the middle, which indicates microcrack formation and material degradation resulting from the adverse environmental influence over a long period. This X-ray map reveals the susceptibility of varnish for thermo-mechanical aging and shows how imaging can be used for material degradation analysis in specific structural regions.

4. Conclusions

This work shows the potential of machine learning applications-neural networks especially-in the prognostication of thermo-mechanical aging impacts on the damping characteristics and structure of varnished wooden string instruments. The inference from the results is that temperature and humidity contribute most to aging effects. These dramatic changes increase in conditions of high-temperature and also high-relative humidity, reducing the acoustic damping factor by up to 15% and decreasing the structural rigidity by up to 20%, whereas stabilizing these values, the environmental conditions have minimal effect. In the comparative performance analysis, we observe how neural networks are highly efficient in capturing such interdependencies and present a solid approach for forecasting aging trends over time. The X-ray analysis deepens understanding of microstructural degradation of both varnish and wood layers resulting from adverse conditions and the importance of efficient varnish formulas. There is evidence here that shows that although some softer varnishes can increase on tonal qualities they wear out much faster than the harder varnishes. This result indicates an inevitable compromise between the first sound and future quality in order to achieve longer-lasting varnishes. In conclusion, this study goes beyond the confirmation of the applicability of machine learning when it comes to the process of predicting the material aging of wood in regards to acoustic and structural aspects of sound and construction, it provides a functional framework for the preservation of wooden string instruments. Future work can continue from this approach by conceiving real time monitoring system and incorporating other musical instruments and material.

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