Using Artificial Neural Networks (ANN) for Modeling Predicting Hardness Change of Wood during Heat Treatment

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Abstract. In this study, an artificial neural network (ANN) model was built to study the relationship between the process parameters of heat treatment and the hardness of wood. Three important parameters: temperature (170, 180, 190, 200 and 210°C), treatment time (2, 4, 6 and 8h), and wood species (Larch and Poplar) were considered as the inputs to the neural network. There were four neurons in the hidden layer that were used, and an output layer as wood hardness. According to the results, the mean absolute percentage errors (MAPE) were determined as 0.1167%, 0.355% and 1.34% in the prediction of wood hardness values for training, validation, and testing data sets. Determination coefficients (R2) greater than 0.99 were obtained for all data sets with the proposed ANN models. These results show that ANN models can be used successfully for predicting hardness changes hardness of wood during heat treatment.

1. Introduction

For many years, wood has been a favorite material for human use. There is a natural abundance, can be sustainable, environmentally friendly, lightweight, and strong [1]. Moreover, wood can exhibit beauty in color and grain and provide higher aesthetic value over other materials. In recent years, there has been a growing need for timber due to depletion of global forest resources [2]. Therefore, application of wood resources from plantation forests has become intensively studied. Larch and Poplar are fast-growing tree species that are dominant in the planted forests of northeast China [3-4]. Every year a large quantity of Larch and Poplar wood is harvested but the light color ranges from nearly white to grayish-white limits its application in luxury markets. Further, special applications can require higher biological durability and better dimensional stability.

In recent years, due to increased demand for solutions to the problems common in fast-growing wood, several novel wood treatments such as acetylation, furfurylation, and heat treatment have been commercialized. In comparison with the previously reported methods, heat treatment of wood is an environmentally friendly wood protection method, which results in value added wood products.

According to experimental studies the heat treatment conditions such as temperature and time are important factors that directly influence wood hardness. Thus, the choice of right parameters assists in acquisition of the desired hardness values and is also the basis for industrial production. However, for this purpose, many experiments need to be performed to determine optimum values, which are time
consuming, expensive, and labor intensive. Thus, the building of a model that predicts the relationship between the process parameters of thermal treatment and the hardness properties of wood is necessary. An artificial neural network (ANN) has been used in the field of wood to solve the saving wood materials problem, reduce the number of experiments, and optimize the process.

This study aims to use an ANN model to predict the hardness change of Larch and Poplar wood during heat treatment with different treatment temperature variables and different treatment time variables.

2. Materials and methods

2.1. Materials
In this study, Larch (Larix gmelinii) a softwood species with a density of 0.55 g/cm³ and Poplar (Populus alba) a hardwood species with a density of 0.35 g/cm³ were used. Larch and Poplar was provided by the Material Science and Engineering College of the Northeast Forestry University. 120 Larch and 120 Poplar wood blocks measuring 100 × 100 × 20 mm³ (l x t x r) for hardness experiments were cut and oven-dried at 103°C for 48 h to be dry before heat treatment.

2.2. Experimental procedures

2.2.1. Heat treatment. In the early stage of heat treatment, the temperature rose gradually from room temperature to 100°C at a ramp rate of 18°C/h; from 100°C to 120°C at a ramp rate of 10°C/h, at 120°C the temperature was held for 5 hours and nitrogen input was started in the heat treatment equipment. From 120°C to 150°C a ramp rate of 2°C/h was used and at 150°C the temperature was held for 5 hours. The temperature was ramped at 2°C/h set values of 170, 180, 190, 200, and 210 and held at the respective temperatures for 2, 4, 6, and 8 h. In the heat treatment process, nitrogen was introduced into the tank at 120°C as the protective gas to ensure that the mass fraction of oxygen in the heat treatment equipment was lower than 2%. After the heat treatment was finished, the heat-treated wood was cooled to room temperature under ambient conditions.

2.2.2. Hardness Measurement. The hardness properties of heat-treated wood were determined after the equilibrium moisture content was reached (hardness of transverse section; and hardness of longitudinal section) and hardness properties determinations were carried out according to the Method of testing in hardness of Wood (GB/T1941-2009).

2.2.3. Artificial neural network. In this study, a proposed ANN model was designed by software developed using the MATLAB Neural Network Toolbox and using a multi-layer perception (MLP) model for prediction [5]. The MLP architecture consisted of an input layer, one or more hidden layers, and an output layer as a result of the network [6] (Figure 1). The ANN structure chosen as the prediction model included the input layer that consisted of three input nodes: wood species, treatment temperature, and treatment time. The hidden layer utilized four neurons, and the output layer consisted of one output node: wood hardness (Figure 2). The hidden layer used a hyperbolic tangent sigmoid transfer function and the training algorithm was the Levenberg-Marquardt backpropagation.
To examine the effects of treatment temperature and treatment time on the hardness change of wood, the existing data are generally divided into training, validation, and testing sets [7]. The average values of the wood hardness were used in the ANN model with a total of data points. The data generated by these experiments was randomly divided into three groups without repetition, including the 28 data points (70% of the total data) used for the ANN training process group, 6 data points (15% of the total data) for validation group, and 6 data points (15% of all data) for the testing processes group (Table 1).

![Figure 1. A typical MLP structure](image1)

![Figure 2. ANN architectures selected as the prediction models for hardness change of wood](image2)

Table 1. The experimental measured change of wood hardness

| Treatment temperature (°C) | Treatment time (h) | N | Average of sample data |  |  |
|---------------------------|-------------------|---|-----------------------|--|--|
|                           |                   |   | Larch (N/mm²)         | Poplar (N/mm²) | Average value of Poplar wood hardness |
|                           |                   |   | Hardness of Transverse Section | Hardness of Longitudinal Section | Average value of Larch wood hardness | Hardness of Transverse Section | Hardness of Longitudinal Section |
| Untreated wood            |                   |   | 12.10                  | 12.97               | 12.54                  | 10.56               | 11.76               | 11.16               |
| 170                       | 2 6               |   | 15.21                  | 14.03               | 14.62                  | 13.33               | 12.79               | 13.06               |
|                           | 4 6               |   | 15.09                  | 13.79               | 14.44                  | 13.15               | 11.88               | 12.52               |
|                           | 6 6               |   | 14.65                  | 13.69               | 14.17                  | 12.15               | 11.46               | 11.81               |
|                           | 8 6               |   | 14.21                  | 13.06               | 13.64                  | 12.09               | 12.17               | 12.13               |
| 180                       | 2 6               |   | 14.55                  | 14.99               | 14.77                  | 12.34               | 12.65               | 12.50               |
|                           | 4 6               |   | 14.36                  | 14.46               | 14.41                  | 11.90               | 12.43               | 12.17               |
|                           | 6 6               |   | 13.59                  | 13.79               | 13.69                  | 12.04               | 12.55               | 12.30               |
|                           | 8 6               |   | 13.12                  | 13.44               | 13.28                  | 11.95               | 12.13               | 12.04               |
| 190                       | 2 6               |   | 13.56                  | 12.67               | 13.12                  | 11.77               | 10.89               | 11.33               |
|                           | 4 6               |   | 13.43                  | 13.54               | 13.49                  | 11.56               | 11.76               | 11.66               |
|                           | 6 6               |   | 12.35                  | 12.44               | 12.40                  | 10.24               | 10.62               | 10.43               |
|                           | 8 6               |   | 12.29                  | 12.34               | 12.32                  | 10.36               | 10.24               | 10.30               |
| 200                       | 2 6               |   | 11.88                  | 12.97               | 12.43                  | 9.91                | 10.84               | 10.38               |
|                           | 4 6               |   | 11.35                  | 12.53               | 11.94                  | 9.47                | 10.72               | 10.10               |
|                           | 6 6               |   | 11.11                  | 12.66               | 11.89                  | 9.37                | 10.57               | 9.97                |
|                           | 8 6               |   | 11.00                  | 12.50               | 11.75                  | 9.34                | 10.71               | 10.03               |
| 210                       | 2 6               |   | 10.58                  | 9.74                | 10.16                  | 8.99                | 8.65                | 8.82                |
|                           | 4 6               |   | 9.87                   | 10.34               | 10.11                  | 7.69                | 8.44                | 8.07                |
|                           | 6 6               |   | 9.55                   | 9.67                | 9.61                   | 7.34                | 7.84                | 7.59                |
|                           | 8 6               |   | 9.18                   | 8.33                | 8.76                   | 7.26                | 6.77                | 7.02                |

The mean absolute percentage error (MAPE), the root mean square error (RMSE), and determination coefficient (R²) were utilized to evaluate the performance of the ANN. The values were mathematically calculated with Eq. (1), (2), (3).

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (t_i - t\hat{d}_i)^2}
\]  (1)
3. Results and discussion

3.1. Effects of heat treatment on change wood hardness

The results of the change value of wood hardness for Larch and Poplar are shown in Table 1. The spectrophotometrical hardness measurements in Table 1 show that the hardness values of Larch and Poplar include hardness of transverse section and hardness of longitudinal section both increased when the temperature treatment increases from 170°C to 180°C decreased when temperature treatment increases from 190°C to 210°C compared to that of unmodified wood.

The wood hardness became decreased with increasing treatment time and temperature of heat treatment which agreed with earlier findings [8]. The wood hardness change due to thermal treatment can be degradation products from extractives, hemicelluloses, and lignin.

![Figure 3. Mean values of ΔE of experimental samples and the results of Duncan’s multiple mean comparison test](image)

The evaluation effects of treatment temperature, treatment time and wood species on the change in wood hardness was carried by means of variance analysis. To establish homogenous groups the Duncan test (Duncan's Multiple Range Test) was applied with the results shown in Figure 3. The averages for all parameters generally decreased with increasing treatment temperature and treatment time. According to the test results, the effects of the parameters on wood hardness were statistically significant with a 1% error margin.
3.2. Predicting change wood hardness by ANN

Table 2. The predicted outputs from the ANN and their percentage errors

| Treatment temperature (°C) | Treatment time (h) | N   | Hardness Wood Average of sample data | Larch | Error (%) | Poplar | Error (%) |
|---------------------------|--------------------|-----|-------------------------------------|-------|-----------|--------|-----------|
|                           |                    |     |                                     |       |           |        |           |
| 170                       | 2                  | 6   | 14.608                              | 0.012 |           | 13.066 | -0.006    |
|                           | 4                  | 6   | 14.452                              | -0.012|           | 12.489 | 0.031     |
|                           | 6                  | 6   | 14.169                              | 0.001 |           | 11.900 | -0.090    |
|                           | 8                  | 6   | 13.543                              | 0.097 |           | 12.173 | -0.043    |
| 180                       | 2                  | 6   | 14.772                              | -0.002|           | 12.507 | -0.007    |
|                           | 4                  | 6   | 14.504                              | -0.094|           | 12.213 | -0.043    |
|                           | 6                  | 6   | 13.727                              | -0.037|           | 12.331 | -0.031    |
|                           | 8                  | 6   | 13.340                              | -0.060|           | 12.096 | -0.056    |
| 190                       | 2                  | 6   | 13.128                              | -0.008|           | 11.513 | -0.183    |
|                           | 4                  | 6   | 13.527                              | -0.037|           | 11.820 | -0.160    |
|                           | 6                  | 6   | 12.416                              | -0.162|           | 10.445 | -0.015    |
|                           | 8                  | 6   | 12.343                              | -0.023|           | 10.309 | -0.009    |
| 200                       | 2                  | 6   | 12.464                              | -0.034|           | 10.410 | -0.030    |
|                           | 4                  | 6   | 12.062                              | -0.122|           | 10.103 | -0.003    |
|                           | 6                  | 6   | 12.050                              | -0.160|           | 9.968  | 0.002     |
|                           | 8                  | 6   | 11.901                              | -0.151|           | 10.028 | 0.002     |
| 210                       | 2                  | 6   | 10.163                              | -0.003|           | 9.335  | -0.515    |
|                           | 4                  | 6   | 10.109                              | 0.002 |           | 8.070  | 0.000     |
|                           | 6                  | 6   | 9.613                               | -0.003|           | 7.342  | 0.248     |
|                           | 8                  | 6   | 9.286                               | -0.526|           | 7.020  | 0.001     |

Note:

Bold values: testing data,
Bold italics underline values: validation data, the other values: training data
N: Number of samples

In order to predict the hardness change of larch and poplar wood, this article used experimental data that was grouped into training, validation, and testing and are shown in Table 2. As seen in Table 2, the prediction values obtained by ANN were determined with very low percentage errors with the maximum absolute percentage error of 0.25% and the minimum absolute percentage error was 0.001% for hardness change of larch and poplar wood. This indicates that predicting the hardness change of wood with heat treatment via the ANN model is excellent.

Predictive ability of the established models was evaluated by performance indicators such as MAPE, RMSE, and R². Table 3 shows evaluation results of the criteria used in predicting hardness change values of larch and poplar wood.

Table 3. Evaluation results of the criteria used in predicting hardness change of larch and poplar wood

| Performance criteria | Training Data | Validation Data | Testing Data |
|----------------------|---------------|-----------------|--------------|
| MAPE                 | 0.1167        | 0.3550          | 1.3400       |
| RMSE                 | 0.0469        | 0.0671          | 0.2203       |
| R²                   | 0.9948        | 0.9994          | 0.9868       |

The MAPE and RMSE values were considered the most important performance criterion [9, 10]. According to research of Haghbakhsh [11] if RMSE and MAPE approach 0, and R² approach 1
then the ANN predictions are optimum. Table 3 shows that MAPE were determined as 0.1167%, 0.3350 % and 1.34% in the prediction of percentage hardness values for training, validation, and testing data sets. RMSE was found as 0.0469% for training, 0.0671% for validation and 0.2203% for testing. From these results the prediction of hardness change for wood after heat treatment was successful in terms of the MAPE and RMSE criterion.

Figure 4 shows the relationship between actual values and predicted values of wood hardness in the training, validation, and testing. The R values were found as 0.99939 for training, 0.99924 for validation and 0.99784 for testing. According to Table 3 the R² values were 0.9948, 0.9994, 0.9868 for training, validation and testing data sets, respectively. These results indicate that the ANN approach is quite accurate for the prediction of wood hardness change.

![Figure 4. Relationship between actual values and predicted values of wood hardness](image)

With results in the above, it is possible to say that the proposed model was properly trained and showed an acceptable accuracy in predicting the hardness change of wood after heat-treatment. Therefore, it can be said that well-trained ANN models can predict the hardness change of wood using different inputs.

4. Conclusion
In this article, the focus was on modeling the effects of treatment temperature and time on hardness change in larch and poplar wood samples via prediction by an artificial neural network (ANN).

The results of the study indicate that the values of MAPE and RMSE in all of the sets were less 1%. The value of the determination coefficients (R²) in all of the sets were higher than 0.99. The predicted wood hardness change in the wood represented by hardness values from the model is close to the values measured experimentally. Therefore, the ANN model has proven to be a sufficient and successful tool for accurately modeling predicted hardness change of wood during heat treatment.

This study also points to a new application for predicting hardness change of wood during heat treatment using the artificial neural network model. From there, it is possible to create a suitable heat
treatment program that corresponds to a desired hardness without needing experimental studies that need time and high experimental costs.

Acknowledgments
This work is financially supported by Applied Technology Research and Development Program of Heilongjiang Province (GX16A002).

References
[1] T.T. Nguyen, X.D. Ji, T.H. Van Nguyen, M.H. Guo, Wettability modification of heat-treated wood (HTW) via cold atmospheric-pressure nitrogen plasma jet (APPJ). Holzforschung 71 (2017) 543-680.
[2] S.F.J. Gulpen, Using country-level forest coverage to analyze the existence of an Environmental Kuznets Curve. Attribution United States (2014)
[3] P. Zhang, G. Shao, G. Zhao, China's Forest Policy for the 21st Century. Science (2000) 288: 2135.
[4] Q.Z. Mao, M. Watanabe, T. Koike, Growth characteristics of two promising tree species for afforestation, birch and larch in the northeastern part of Asia. Eurasian J Forest Res 13 (2010) 69-76.
[5] S. Tiryaki, C. Hamzaçebi, Predicting modulus of rupture (MOR) and modulus of elasticity (MOE) of heat treated woods by artificial neural networks. Measurement 49 (2014) 266-274.
[6] Hamzaçebi, C. Ebi, D. Akay, F. Kutay, Comparison of direct and iterative artificial neural network forecast approaches in multi-periodic time series forecasting. Expert Syst Appl 36 (2009) 3839-3844.
[7] G. Zhang, B.E. Patuwo, M.Y. Hu, Forecasting with artificial neural networks: The state of the art. Int J forecast 14 (1998) 35-62.
[8] H. Yang, W. Cheng, G. Han, Wood Modification at High Temperature and Pressurized Steam: a Relational Model of Mechanical Properties Based on a Neural Network. Bioresources (2015) 10
[9] A. Canakci, S. Ozsahin, T. Varol, Modeling the influence of a process control agent on the properties of metal matrix composite powders using artificial neural networks. Powder technol 228 (2012) 26-35.
[10] S. Sagioglu, E. Besdok, M. Erler, Artificial intelligence applications in engineering-1: Artificial neural networks. Ufuk Books Stationery, (2003) pp 10-20
[11] R. Haghbaksh, H. Adib, P. Keshavarz, M. Koolivand, S. Keshtkari, Development of an artificial neural network model for the prediction of hydrocarbon density at high-pressure, high-temperature conditions. Thermochim Acta 551 (2013) 124-130.