Determining the Age of Streetside Trees with Diameter at Breast Height-based Multifactorial Model

Jan Łukaszkiewicz and Marek Kosmala

Abstract. This article evaluates the possibility of determining tree age based simultaneously on diameter at breast height (dbh) (1.3 m [4.3 ft]) and total tree height using common lime, common ash, and horse chestnut species. The first step was the identification and measuring groups of trees growing in similar conditions (streetside trees in Warsaw area, Poland) in which planting ages were known (mainly from archives). Next, multifactorial regression model was developed describing the growth of both tree parameters (dbh and height) over time. In the majority of cases, plotting tree age against diameter and height yielded a regression coefficient r value and determination coefficient r² value above 0.9. For graphic interpretation of elaborated multifactorial models, nomograms were applied. This kind of graph allows explaining tree age based on both dbh and height of trees. Another step was verification. The resulting model was applied to unrelated groups of trees of known age. Mean bias values were established for each model. The difference between the actual age and mean age calculated with the model was less than ±15%. Presented model, although not meant for application to individual trees, might be useful to determine the age of groups of trees growing along streets and roads.

Key Words. Common ash; common lime; dbh–height regression model; horse chestnut; streetside trees; tree age nomograms.

The knowledge of tree age is necessary for examining growth stage and age structure in urban tree stands to ensure their proper maintenance and preservation. The tree age data find a significant potential of application in tree maintenance, especially in preparation of management plans for urban stands. These kinds of plans provide directions about frequency and benefits of maintenance aspects such as fertilizer requirements, different ways of pruning, removing trees causing threats, and planning new planting. Tree age data should be also taken into account among factors like plant species, damage rate, and location for assessment threats caused by old trees old with weakened static.

In addition to that, data concerning the relationship of tree age and dendrometric parameters is very important for determining monetary value of trees and costs of tree replacement (McPherson 2007). Tree growth formulae make possible forecasting the effect of urban trees on energy savings, atmosphere CO₂ reductions, air quality benefits, storm water runoff, and the cost of tree maintenance. Research on the correlation of tree age and the growth of dendrometric parameters serves as a starting point for developing various computer programs (e.g., DISMUT [Australian National University, Canberra, Australia], eco-Smart [USDA Forest Service, Davis, CA], or Stratum [i-Tree, Kent, OH]) enabling one to calculate the economic effect of trees on forestry and in arboriculture. Mathematical models of exponential tree growth over time such as the increase of diameter at breast height (dbh), total tree height, crown radius, and leaf area. This equally concerns the research on forestry and in arboriculture. Mathematical models of exponential tree growth over time are chiefly based on the regression principle (see Pigott 1989; Brack and Wood 1998; Brzeziecki 1999; Greenberg and Simons 1999; Bolibok and Brzeziecki 2000; Peper et al. 2001b; Gutsell and Johnson 2002; Larsen and Kristoffersen 2002). The regression allows users to calculate the best fit of model parameters to data (Neter and Wasserman 1974; Sokal and Rohlf 1981; Lomnicki 2002; Motulsky and Christopoulos 2003). It is necessary to say that there is hardly any research available to present the same issue from the reverse perspective, estimating age based on dendrometric parameters. Such an approach was adopted, for instance, by Loevenstein et al. (2000), however, with reference to forest environment.
Still lacking is an accurate in situ method based on the relationship between age and tree size. Such a method should provide an acceptable margin of error and enable rapid results. Were one available, the work of arborists would be facilitated. The present research is focused toward forecasting the age of selected streetside tree species based on dendrometric parameters: dbh and tree total height. This article presents a nondestructive method for estimating tree age based on nonlinear model of multifactorial regression and its graphic interpretation—nomograms.

OBJECTS AND METHODS OF RESEARCH

The research aimed to find a method for determining the relation between tree age and two dendrometric parameters: dbh and height. These were subdivided into three basic stages:

Stage 1: field measurement of street tree populations (three selected species) in the range of known ages from young to mature, living on grass planting stripes along streets and roads, in comparable site conditions;

Stage 2: statistical analysis of collected data and determining the interdependencies as described with the mathematical equation of tree growth over time; and

Stage 3: verification (model validation) on separate tree group with known age to verify to what extent age forecasts comply with reality.

Identification of Research Sites and Field Measurements

The first stage of research done between years 2002 and 2005 consisted of determining areas for research, defined as single-species streetside tree plantings of uniform age. The selection of research sites accounted for plant frost resistance zones in the country. Heinze and Schreiber (1984), based on USDA Frost Hardiness Zone Map (1960), divided Poland’s territory into three climactic zones with subzones. Subzone 6b covers approximately 60% of the territory of Poland and is characterized by an average minimum long-term air temperature from −20.5°C (−4.9°F) to −17.8°C (−0.0°F). All the examined trees were located in climatic subzone 6b, which eliminated differences in tree growth caused by varying climactic conditions in different regions of Poland. Research sites were selected also by their similar microclimactic and soil conditions (subsoil density and grass planting stripes along streets and roads, in comparable site conditions; Kaennel and Schweingruber (2004) was necessary for the increased by 5. This increment suggested by Assman (1968) or Kannel and Schweingruber (2004) was necessary for the average time that is needed for tree seedling to grow up to 1.3 m (4.3 ft).

The research involved three tree species most frequently planted along streets: common lime (Tilia cordata Mili.), common ash (Fraxinus excelsior L.), and horsechestnut (Aesculus hippocastanum L.). Field measurements performed between years 2004 and 2006 included dbh and circumference at 1.3 m (4.3 ft) height and spacing between trees of representative age groups made respectively with a calliper, altimeter, and measuring tape. Trees had no visible symptoms of internal wood decay (e.g., cavities) and with no more than 20% crown dieback. The final inventory included 388 trees from three selected species that were used to construct the database. Initial characteristics of tree age classes involved in the research are presented in Table 1.

Many researchers (e.g., Shigo 1996; Cermak et al. 2000; Kosmala 2001; Szczepanowska 2001; Grabowsky et al. 2002) indicate that the main rooting zone of the majority of tree species is located in climactic subzone 6b, which eliminates differences in growth caused by varying climactic conditions in different regions of Poland. Research sites were selected also by their similar microclimactic and soil conditions (subsoil density and grass planting stripes along streets and roads, in comparable site conditions; Kaennel and Schweingruber (2004) was necessary for the increased by 5. This increment suggested by Assman (1968) or Kannel and Schweingruber (2004) was necessary for the average time that is needed for tree seedling to grow up to 1.3 m (4.3 ft).

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<table>
<thead>
<tr>
<th>Age class number</th>
<th>Actual age (years)</th>
<th>Sample size</th>
<th>M ean dbh ± (m)</th>
<th>M ean tree total height ± (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>3.0 (1.2)</td>
<td>3.3 (10.9)</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>17.0 (6.8)</td>
<td>5.7 (18.9)</td>
<td>0.85</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>21.0 (8.4)</td>
<td>8.0 (26.4)</td>
<td>1.14</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>29.0 (11.6)</td>
<td>9.7 (31.9)</td>
<td>1.09</td>
</tr>
<tr>
<td>5</td>
<td>34</td>
<td>24.0 (9.6)</td>
<td>10.1 (33.3)</td>
<td>0.73</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>31.0 (12.4)</td>
<td>14.1 (46.5)</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td>53</td>
<td>38.0 (15.2)</td>
<td>12.5 (41.2)</td>
<td>1.52</td>
</tr>
<tr>
<td>8</td>
<td>58</td>
<td>48.0 (19.2)</td>
<td>14.5 (47.7)</td>
<td>1.11</td>
</tr>
<tr>
<td>9</td>
<td>75</td>
<td>54.0 (21.6)</td>
<td>13.8 (45.5)</td>
<td>1.60</td>
</tr>
<tr>
<td>10</td>
<td>85</td>
<td>72.0 (28.8)</td>
<td>20.7 (68.2)</td>
<td>1.08</td>
</tr>
</tbody>
</table>

*The actual age of trees taken from historical records or/and tree rings number (Pressler borer).

The total number of trees in age-homogenous population - class, taken into inventory.

dbh = diameter at breast height.

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contained in 0 to 30 cm (12 in) of the soil’s surface layer. Results provided by laboratory analyses of soil structure in this layer indicate in all locations a domination of sandy clay with little humus addition (above 2%) and pH value over 7.2. In each location, measurements of soil compaction with a penetrometer were performed. The average results for all measuring points were 3.6 kg/cm² (51.3 lb/in²) or 0.35 MPa (SD = ±0.3). The collected results show that soil compaction in the layer 0 to 30 cm (12 in) is much lower than the level of 0.7 MPa indicated by other researchers as decreasing by 50% penetration of soil by tree roots (Taylor and Ratliff 1969; Greacen and Sands 1980; Craul 1999; Coder 2000).

Data Analysis
At this stage of research, each of three streetside tree species was represented by a collection of populations—age classes (Table 1). Every age-homogenous population was randomly divided with statistical software into two parts: a test and a control group. Afterward, test groups of each species served for developing a nonlinear model of multifactorial regression. The other half of the trees (control groups) were to serve as practical model validation.

Regression model presented here is mathematically reflected as a formula with parameters determined with appropriate modules of STATISTICA 7.0 (StatSoft Inc., Tulsa, OK). For the nonlinear regression model, we used the exponential regression module. In this article, we used two ways for presenting the regression model:

• mathematical equation (Equation 1);
• graphic interpretation—nomograms (Figure 1, an example and Figures 2, 3, and 4).

Formula 1. The mathematical equation of non-linear regression model.

\[ \text{Age} = -a + e^{\frac{b\times \text{DBH}^c}{100} + d} \]
RESULTS
Determining of Multifactorial Regression Model
The obtained nomograms (Figures 2, 3, and 4) are an attempt to transfer a tridimensional interrelation (three parameters: age, dbh, height) onto a flat surface, which by nature requires using a two-coordinate system. For this reason, it is impossible to read tree age as a continuous parameter and an approximate readout is enforced, e.g., in 5-year intervals, as used in this article. The lines separating age brackets on the nomograms were obtained in a range of 10 to 60 years. The area limited with hashed lines contains 95% calculated age values of all unrelated trees of known age taken from a control group.

Veriﬁcation of the Multifactorial Regression Model
The credibility of elaborated multifactorial regression model was tested. The veriﬁcation did not consist of determining whether the regression model is “true” but in seeing whether it generated a fair, verifiable hypothesis on the determination of tree age based on dendrometric parameters.

Initially, we compared the age of trees as determined with the model and the actual age of trees using the control group chosen randomly from the researched tree populations of each species. The control group was not involved in developing the regression model. The dendrometric data of trees from the population were marked on the coordinate system in which the X-axis reﬂected the age values of 10 and 85 years. Afterward, age division lines were marked on the coordinate system in which the X-axis reﬂected dbh values and the Y-axis reﬂected total tree height. The area between thick broken lines contains 95% of tree age values from the control group. The lines were drawn based on prediction intervals for the dbh/height relation.

Application of Nomograms
Subsequently is a sample method of a potential ﬁeld application of a chart with a nomogram. Reading the age with the use of the nomogram should be done especially for these trees complying with the conditions set up in this work (e.g., six streetside common limes). Measurement of dbh and height (H) for each tree is taken. Then mean dbh and mean height for all measured trees in this population is calculated with the result that, for six investigated common lime trees, mean dbh values is 50 cm (20 in) and the mean height values are 16 m (52.8 ft). Next we ﬁnd the values of the mean dbh and the mean H of trees on the corresponding axis at the common lime nomogram and draw perpendicular lines. The crossing point for both dendrometric parameters (marked with arrows) in this example is pointed at the “65 years” line (Figure 1). Therefore, the mean age of six streetside common limes is 65 years (range of error is described in the veriﬁcation part). If the crossing point falls between the age lines, the value should be interpolated.

Table 2. Equation factors of regression model for each tree species in which Age – the calculated age of street tree population (years); DBH – mean dbh (cm) taken from street trees population; H – mean total height (m) of street tree population.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Common lime</th>
<th>Common ash</th>
<th>Horsechestnut</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>264.073</td>
<td>210.115</td>
<td>54.2714</td>
</tr>
<tr>
<td>b</td>
<td>5.8534</td>
<td>5.3523</td>
<td>4.0709</td>
</tr>
<tr>
<td>c</td>
<td>0.3397</td>
<td>0.2655</td>
<td>0.7988</td>
</tr>
<tr>
<td>d</td>
<td>0.0026</td>
<td>0.0064</td>
<td>0.0209</td>
</tr>
<tr>
<td>r</td>
<td>0.9491</td>
<td>0.9857</td>
<td>0.9635</td>
</tr>
<tr>
<td>P</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>r²</td>
<td>0.9009</td>
<td>0.9716</td>
<td>0.9284</td>
</tr>
</tbody>
</table>

dbh = diameter at breast height.
regression model under examination was described by two values of the age parameter:

- actual value (known from the source documents and field research); and
- value calculated with the model under verification (Table 3).

The subsequent stage of verification determined the accuracy of the developed regression model. In presented research, accuracy determines the degree of concordance of calculated tree age with actual tree age value. It was described as bias in percentage value calculated with the application of Equation 2.

**Formula 2. The accuracy of the method interpreted as bias (%).**

\[
\text{BIAS} = \left( \frac{\text{Age}_{\text{calculated}} - \text{Age}_{\text{actual}}}{\text{Age}_{\text{actual}}} \right) \times 100 \%
\]

For all populations of sample trees, the calculated age is very close to the actual age; however, accuracy for horsechestnut is less than for other two species. Table 3 presents mean results of age readouts. The verification of independent control groups demonstrated that the model shows accuracy in determining the average age of street side trees. For each species, the concordance between the average age estimate and actual age described by mean bias did not exceed 15%. At this stage of research, it seems that achieved accuracy (mean bias values) indicate good application potential.

**DISCUSSION**

According to the literature (e.g., Brack and Wood 1998; Banks et al. 1999; Peper et al. 2001a, 2001b; Larsen and Kristoffersen 2002; Grabosky and Gilman 2004; Linsen et al. 2005), dbh, basal area, and tree height parameters can be used to predict growth or size of tree dimensions, including height, crown height and radius, leaf area, and so on. Researchers (e.g., Pigott 1989; Peper et al. 2001a, 2001b; Gutsell and Johnson 2002; Larsen and Kristoffersen 2002) focus primarily on examining the growth of dendrometric parameters over time, but they hardly ever examine the issue in reverse order, that is, as time flow (tree aging), as described by changing dendrometric parameters. Undoubtedly, planting dates are one of the key sources of information on tree age. However, the field methods of determining tree age in situ seems to be particularly important in the case of incomplete, fragmented, or lack of inventory data on the actual calendar year of planting trees.

This article presents a model of multifactorial regression, which is rarely found in other research work on the growth of urban trees (e.g., Neely 1988; Banks et al. 1999; Peper et al. 2001b; Larsen and Kristoffersen 2002, Linsen et al. 2005). The presented model allows to effectively determine the age of tree populations based on two dendrometric parameters: dbh and H. The use of two parameters simultaneously on nomograms makes for a more reliable outcome of tree age assessment. If the compliance of investigated trees to those ones used by authors is good, the crossing point of mean dbh values and mean H values should be located between hashed lines (95% calculated age values of all unrelated trees of known age taken from a test group) as shown in Figure 1. If this is not the case (age readout outside an area bordered with hashed lines), it means that investigated trees are different (e.g., different density of tree stand, pruning effect, or incomparable site conditions) and their age readout could be biased with significant error.

Potential expansion of research shall take into account different planting locations and site conditions, including downtown areas (very unfavorable for trees) and park areas (optimal conditions for tree growth). In this way, the age assessment of each investigated tree species shall be described by at least three sets of coefficients for the presented regression model. The next step should make it possible to elaborate computer software allowing us to determine tree age based on dendrometric parameters.

It is possible in the future to increase the number of tree species included in the regression model as presented. In the first place, species planted most commonly along streets in Warsaw shall be mentioned (e.g., Norway maple (*Acer platanoides* L.), Sycamore (*Acer pseudoplatanus* L.), Silver lime (*Tilia tomentosa* Moench.), Crimean lime (*Tilia × euchlora* Koch.), Red oak (*Quercus rubra* L.), Rowan (*Sorbus aucuparia* L.), False acacia (*Robinia pseudoacacia* L.)). Besides dbh and height parameters, further research shall take into account the possibility of the

| Table 3. Comparison of street trees common lime, common ash, and horsechestnut age classes known and calculated age with multifactorial nonlinear regression model. |
|---------------------------------|----------------|----------------|----------------|----------------|
| Age class number | Actual agea (years) | Calclt. ageb (years) | Age class number | Actual agea (years) | Calclt. ageb (years) | Age class number | Actual agea (years) | Calclt. ageb (years) |
| 1 | 7 | 7.2 | 1 | 10 | 8.0 | 1 | 16 | 17.8 |
| 2 | 18 | 21.9 | 2 | 16 | 18.0 | 2 | 22 | 27.6 |
| 3 | 25 | 27.9 | 3 | 20 | 21.0 | 3 | 25 | 26.9 |
| 4 | 34 | 35.2 | 4 | 26 | 29.1 | 4 | 30 | 36.0 |
| 5 | 34 | 35.2 | 5 | 43 | 43.5 | 5 | 38 | 33.5 |
| 6 | 36 | 42.2 | 6 | 45 | 45.3 | 6 | 58 | 59.4 |
| 7 | 53 | 49.8 | 7 | 80 | 81.2 | 7 | 60 | 67.3 |
| 8 | 58 | 59.4 | 8 | 58 | 59.4 |
| 9 | 75 | 66.7 | 9 | 58 | 59.4 |
| 10 | 85 | 79.5 | 10 | 60 | 67.3 |

*aThe actual age of trees taken from historical records or/and tree rings number (Pressler borer). 

bAge calculated with developed multifactorial regression model applied on trees’ dbh and height of each species taken from the control group. 

dbh = diameter at breast height.

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prediction of tree crown radius with age, because this is a useful parameter in urban designs.

CONCLUSIONS

The described method of determining the age of streetside tree populations based on the multifactorial regression model can find its use in situations when we have a positive knowledge about the origin of trees but the age remains unknown, whereas the invasive methods could be used in other cases, especially for single trees.

The developed model is accurate and precise enough to determine the mean age of tree populations of low density such as the streetside and roadside locations (6b hardness subzone). In such cases, the age readout error does not exceed ±15%.

Graphic presentation of the nonlinear multifactorial regression model as nomograms has no equivalent in the cited analysis of professional literature. Nomograms find practical application in field conditions (as it is presented in the provided example; Figure 1), allowing for easy readouts of the age of homogenous populations of roadside trees.

Further investigation should provide a comparison of tree species mentioned in this article to see if they share any growth characteristics similar to those reported here, the method has a general application to tree population in any city.

This research serves as a basis for developing a more universal method. The method is, at present, at its developmental stage and can be expanded with additional tree species. Currently obtained results should serve as a starting point for more extensive research of the streetside tree population to determine the relation between their age and dendrometric parameters and environmental factors.

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Jan Lukaszkiewicz
Assistant Professor
Department of Landscape Architecture
Warsaw University of Life Sciences—SGGW
ul. Nowoursynowska 159/37
02-776 Warsaw, Poland
jan_lukaszkiewicz@sggw.waw.pl

Marek Kosmala (corresponding author)
Associate Professor
Department of Landscape Architecture
Warsaw University of Life Sciences—SGGW
ul. Nowoursynowska 159/37
02-776 Warsaw, Poland
marek_kosmala@sggw.pl

Résumé. Cet article évalue la possibilité de déterminer l’âge d’un arbre en se basant simultanément sur le DHP (mesuré à 1,3 m du sol) et la hauteur totale, et ce dans le cas du citronnier commun, du frêne commun et du marronnier d’Inde. La première étape a été d’identifier et de mesurer des groupes d’arbres croissant dans des conditions similaires (arbres de rues à Varsovie en Pologne) et dont l’âge de plantation était connu (la plupart du temps à partir d’archives). Par la suite des modèles multifactoriels de régression ont été développés afin de décrire la croissance des deux paramètres des arbres (DHP et hauteur) dans le temps. Dans la majorité des cas, l’âge des lots d’arbres par rapport au diamètre et à la hauteur a donné une valeur de coefficient de régression r et permis de déterminer une valeur de coefficient r² supérieure à 0,9.

Des nomogrammes ont été appliqués pour l’interprétation graphique des modèles multifactoriels élaborés. Ce type de graphique permet d’expliquer l’âge des arbres en se basant à la fois sur le DHP et la hauteur des arbres. Une autre étape a été celle de l’identification et de l’étude des modèles qui ont résulté ont été appliqués à des groupes non reliés d’arbres dont l’âge était inconnu. Des valeurs moyennes ont été établies pour chaque modèle. La différence entre l’âge réel et l’âge calculé à partir du modèle était de ±15%. Les modèles présentés, même s’ils ne sont conçus pour s’appliquer à des arbres individuels, peuvent s’avérer utiles pour déterminer l’âge des groupes d’arbres le long des rues et des routes.


Resumen. Este reporte evalúa la posibilidad de determinar la edad del árbol con base en el diámetro al nivel del pecho (DHP, por sus siglas en inglés) (1,3 m [4.3 pies]) y la altura total del árbol, usando especies comunes de lima, fresno y castaño. El primer paso fue la identificación y medición de grupos de árboles creciendo en condiciones similares (lado de la calle en el área de Varsovia, Polonia), de los que la edad de plantación fue conocida (principalmente por archivos). Enseguida se emplearon modelos de análisis multifactorial describiendo el crecimiento de varios parámetros de los árboles (DHP y altura) sobre el tiempo. La mayoría de los casos, el ploteo de la edad del árbol contra el diámetro y la altura dieron un valor r del coeficiente de regresión y coeficiente de determinación r² arriba de 0,9. Por interpretación gráfica fueron aplicados los nomogramas de los modelos multifactoriales elaborados. Este tipo de gráfica permite explicar la edad del árbol con base en el DHP y la altura de los árboles. Otro paso fue una verificación. Los modelos resultantes fueron aplicados en grupos no relacionados de árboles de edad conocida. Los valores medios RTAS fueron establecidos para cada modelo. La diferencia entre la edad real y la edad media calculada con el modelo fue menor a ±15%. Los modelos presentados, aunque no pueden ser aplicados a árboles individuales, pueden ser útiles para determinar la edad de grupos de árboles que crecen en calles y avenidas.