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THE INFLUENCE OF PLANTING DENSITY ON MODULUS OF ELASTICITY OF STRUCTURAL TIMBER FROM IRISH-GROWN SITKA SPRUCE

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ABSTRACT

As Europe moves towards more sustainable construction, there is an increasing demand for structural timber. The purpose of this research is to explore new forestry management strategies, which will produce an optimum balance of the quantity and quality of structural timber over a minimum period of time. The focus is on timber from Sitka spruce, which is the most important Irish commercial forest tree species. Planting density is an important factor affecting both structural timber quantity and quality. Trees with wider spacing get more light and grow faster, which affects annual ring width and knot size. These, in turn, affect the bending strength, modulus of elasticity and density of timber, which are the grade determining properties according to EN 338:2003. The current standard planting density in Ireland is 2500 stems/ha and the timber produced meets the requirements for the C16 strength class. For Irish-grown Sitka spruce timber, modulus of elasticity is the critical grade determining property, which dictates the strength class. This study has two aims, first to explore the possibilities of improving the strength class by increasing the planting density and second, to explore the possibility of keeping the same class while increasing the quantity of structural timber by reducing the planting density. The effects of different planting densities, ranging from 1550 to 3700 stems per hectare, on the structural properties of Sitka spruce timber originated from a forest in County Leitrim are examined. Overall, 72 trees were felled and cut into logs. Logs were non-destructively tested using acoustic tools and subsequently processed into structural timber. The timber boards were then tested using three different types of strength graders in order to examine the difference in timber modulus of elasticity between different planting densities. The results showed statistically significant effects of different planting densities on the variation in timber modulus of elasticity.
Keywords: irish grown sitka spruce, planting density, structural timber performance.

1 INTRODUCTION

In plantation forestry, spacing between trees is a very important factor that influences tree growth [1]. For light demanding species such as Sitka spruce, which is the most important Irish commercial forest tree species, occupying 52.4% of the forest area [2], trees in stands with wider spacing get more light and grow faster which affects many timber characteristics, such as timber density, knot size and juvenile wood amount [3]. Although the influence of tree spacing on timber density has been widely studied [4–6], the effects of knot size and juvenile wood zone have more influence on properties of sawn timber products for structural application [3]. Spacing between trees is controlled by planting density (initial spacing at stand establishment) and thinning (re-spacing) before or near time of canopy closure depending on the silvicultural practice chosen. In Ireland, the standard planting density of Sitka spruce plantations is 2500 stems/ha and the current thinning practice involves the systematic removal of every seventh line and the selective thinning of the crop between the lines created [7]. The influence of different types of thinnings on structural timber properties was studied on timber from a Sitka spruce stand in Northern Ireland [8]. They found a decrease in timber

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mechanical properties with increasing re-spacing intensity. Wind throw is a major issue in the management of Sitka spruce plantations in Ireland and it was estimated that the average annual volume wind thrown over the period 1948–1997 was 12.7% of the average annual volume sold [9]. One of the approaches that addresses this problem is to use a no-thin regime but there are concerns that higher proportions of juvenile wood can lead to a reduction in timber quality [10]. As Europe is moving towards the use of more sustainable construction materials, an increase in demand for structural timber can be expected. A shorter rotation length can be a solution for the growing market but there is also a risk of lower quality timber because of larger proportions of juvenile wood [11].

The aim of this study is to examine the effects of different initial planting densities of Sitka spruce stands on structural timber quantity and quality. Although basal area is often used in the literature as a measure of stand productivity, it is not the best indicator of structural timber quantity as most of the commercial sawmills in Ireland process only the logs that are larger than 14 cm in diameter. The yield of structural timber is related to factors influencing or affected by average tree size [12]. Therefore, in this study tree diameter at breast height (DBH) and individual tree volume were taken as measures of structural timber quantity. Also, the tree stem straightness was examined as the yield of structural timber depends on it to a large extent. Timber for structural uses is classified to the strength classes, which are defined by characteristic strength, characteristic density and mean value of modulus of elasticity (MOE) in bending in EN 338:2003 [13]. There is variety of different measurement techniques for determination of timber strength class properties. In this study, timber MOE was measured using non-destructive techniques such as longitudinal stress wave, X-ray and bending techniques [14].

As the study is in its early stages, only the results from the longitudinal stress wave and X-ray machines will be reported in this paper. Additionally, the intermediate results from the flatwise bending test will be shown.

2 MATERIAL AND METHODS

2.1 Site

The study was conducted on Sitka spruce (Picea sitchensis [Bong.] Carr.) trees originated from Lisgillock Glebe forest in County Leitrim, Republic of Ireland. The site was established in 1992 with the Queen Charlotte Island provenance with yield class 26, which corresponds to a maximum mean annual increment of 26 m^3/ha. Due to the problems with the construction of forest roads, the site was kept unthinned until 2014 when about 40% of the trees were removed. As the experiment started in 2015, the influence of thinning on the timber properties was negligible.

In total, 12 plots with 10 different planting densities, ranging between 1550 and 3700 stems per hectare were selected from the forest. In order to have better presentation of data, the main goal, during the selection of the plots, was to have three planting density groups with four plots in each group. Four plots with densities between 1550 and 1850 stems/ha were assigned to the low planting density group, four plots with densities between 2300 and 2550 stems/ha were assigned to the standard planting density group and four plots with densities between 3100 and 3700 stems/ha were assigned to the high planting density group. Determination of the planting densities in the forest was accomplished by counting trees and stumps.

2.2 Sampling

In 2015, when the stand was 23 years old, diameters at the breast height (1.3 m) were measured and stem straightness was assessed. From each plot six trees were selected for felling in accordance to dominance with respect to diameter: two dominant, two co-dominant and two sub-dominant trees were selected from each of 12 plots. All the trees within the plots larger than 15 cm in DBH were assessed visually for straightness of the bottom 6 m of the stem using a seven-point scoring system based on the UK Forestry Commission's Protocol [15] with modifications for the sample size and tree diameters at the time of felling. The scoring system signifies the maximum length of straight logs, with score 1 for no straight logs available and score 7 for at least 5 m of straight log available from the bottom 6 m of the stem. The trees with poor stem form were omitted from the selection. Overall, 72 trees were selected for felling. After the measurements on the felled tree, the 10-m-long log was cut starting from 25 cm above the ground level and fundamental frequency was measured using the MTG instrument (Brookhuis Micro-Electronics, The Netherlands) on the forest ground. Then, the 10-m-long log was cross cut into four 10 cm thick discs and three 3-m-long logs.

After the extraction from the forest, the fundamental frequencies of 213 3-m-long logs were measured using the MTG instrument in the sawmill yard. Finally, 198 3-m-long logs were processed using nine cutting patterns that maximised the boards output into 904 pieces of structural timber in two cross sectional dimensions, 100 × 44 mm and 75 × 35 mm (Table 1).

2.3 Testing

Tree volume was calculated over bark from ground to 7 cm diameter using the Tree Model software [16]. For selected trees, tree volume was calculated using DBH and height measured on each of the selected trees while average plot volume was calculated using average DBH of all the trees in a plot and average height of selected trees.

Table 1: Characteristics of planting density groups on stand, selected trees and boards level.

	Planting density group		
	Low	Standard	High
Stand level			
Stand density range (trees/ha)	1550–1850	2300–2550	3100–3700
No. of trees measured	83	114	157
Mean DBH (cm)	25.71 (4.24)	21.41 (3.40)	17.99 (3.93)
Mean tree volume (m^3)	0.550	0.347	0.266
Mean stem straightness score	6.17 (1.25)	5.63 (1.62)	5.49 (1.80)
Selected trees level			
Mean height to DBH (m/m)	78.38(8.47)	88.07 (8.65)	95.41 (10.39)
Selected tree mean volume (m^3)	0.621 (0.17)	0.420 (0.10)	0.343 (0.09)
Boards level			
Total number of boards cut	406	294	202
No. of 35 mm × 75 mm boards	171	157	97
No. of 44 mm × 100 mm boards	235	137	105

Standard deviations are shown in parentheses.

The dynamic modulus of elasticity of undried timber boards ($E_{dyn,undried}$) was calculated from the stress wave velocity ($v_{undried}$) and green density ($\rho_{undried}$) using the following eqn (1) [14]:

$$E_{dyn,undried} = \rho_{undried} v^2_{undried} . \quad (1)$$

Stress wave velocity and density were measured, using the MTG timber grader with a balance connected, on 899 pieces of timber. Direct adjustment of dynamic MOE ($E_{dyn,12,adj}$) to 12% moisture content (M.C.) was applied using the eqn (2) [17]:

$$E_{dyn,12,adj} = \frac{E_{dyn,udried}}{0.868} \cong 1.15 \cdot E_{dyn,udried} . \quad (2)$$

After kiln drying to 18% ± 2% M.C., the boards were graded with the X-ray machine (Microtec Goldeneye, Italy) in the sawmill from which the data on timber density ($\rho_{x\text{-ray}}$) and MOE ($E_{x\text{-ray}}$) were obtained. Visual override rejection was not performed and 898 boards were graded.

Then timber boards were delivered to the NUI Galway laboratory where they were stored in a conditioning room at 20 ± 2°C temperature and 65% ± 5% relative humidity. After the boards reached 12% ± 2% M.C., modulus of elasticity was determined using a Cook Bolinders grading machine. Machine settings for boards cross sectional dimensions were applied in accordance with [18] and the first batch of 294 boards were tested. Modulus of elasticity (E_{cb}) was calculated from the mean value of load required to produce a specific midspan deflection in 3-point bending measured by a loading cell (F_{mean}), span (l), deflection (δ) and beam breath (b) and thickness (t) using the eqn (3):

$$E_{cb} = \frac{F_{mean} \cdot l^3}{4 \cdot \delta \cdot b \cdot t^3} . \quad (3)$$

2.4 Data analysis

Data were analysed using SPSS statistical software. Extreme outliers were removed [19]. Then, homogeneity of variances and normality were tested. Regression analysis with F-test at $\alpha = 0.05$ level of significance was used to investigate the effect of different planting densities on the variation in timber MOE and density.

3 RESULTS

3.1 Timber quantity characteristics

There was a statistically significant explanation of variation in timber volume by different planting densities. Planting density explained 37.8% in tree DBH variation (Fig. 1). Tree DBH ranged from 7.6 to 37.0 cm, with mean values of 25.71, 21.41 and 17.99 cm for low, standard and high planting density groups, respectively.

The volumes of selected trees ranged from 0.155 to 1.015 m^3, with mean values of 0.621, 0.420 and 0.343 m^3 for low, standard and high planting density groups, respectively (Fig. 2). Values for average plot volume were 0.550, 0.374, 0.266 m^3 for low, standard and high planting density groups, respectively.

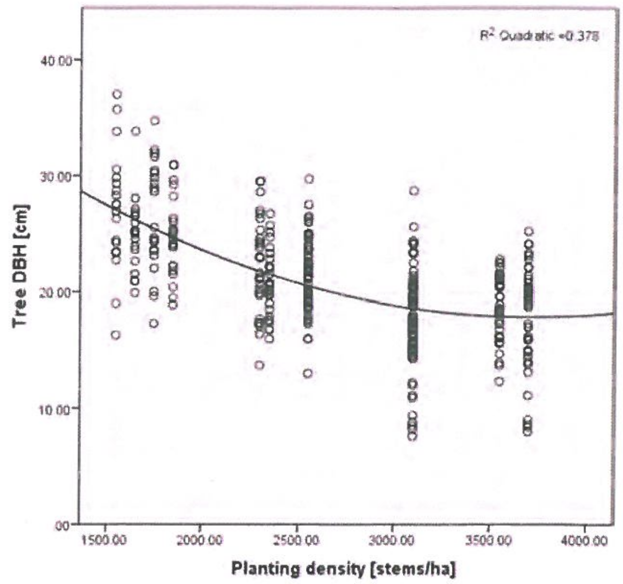

Figure 1: Relationship between planting density and tree DBH.

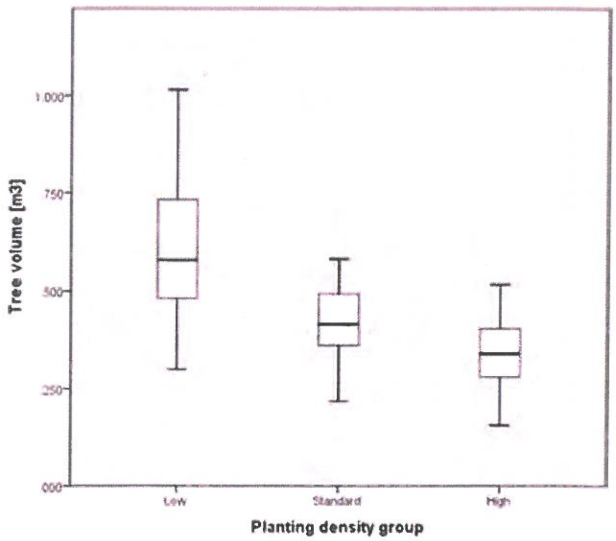

Figure 2: Comparison of tree volume of selected trees between different planting density groups.

There was a statistically significant explanation of variation in timber volume by different planting densities. The confidence intervals for tree volume from the three different planting density groups did not overlap. The mean value of tree volume from the low planting density group was 47.9% higher than the mean value of tree volume from the standard density group, while the mean value of tree volume from the high planting density group was 18.3% lower than the mean value of tree volume from the standard planting density group. Average stem straightness score ranged from 6.17 in the low planting density group to 5.49 in the high planting density group.

3.2 Timber quality properties

The $E_{dyn,undried}$ ranged from 4159 to 11168 MPa, with mean values of 7330, 7777 and 8149 MPa for low, standard and high planting density groups, respectively (Table 2). The mean values of $E_{dyn,12,adj}$ for low, standard and high planting density groups were 8458, 8969 and 9325 MPa, respectively. The confidence intervals for $E_{dyn,undried}$ and $E_{dyn,12,adj}$ between the three different planting density groups did not overlap. The explanation of variation in $E_{dyn,undried}$ and $E_{dyn,12,adj}$ by different planting densities was found to be statistically significant.

Values for the $E_{x\text{-}ray}$ ranged from 4063 to 12544 MPa. The explanation of variation in $E_{x\text{-}ray}$ by different planting densities was found to be statistically significant. The mean values of $E_{x\text{-}ray}$ for low, standard and high planting density groups were 7679, 7910 and 8312 MPa, respectively (Fig. 3). The confidence intervals for $E_{x\text{-}ray}$ between the three different planting density groups did not overlap. For all three planting density groups, the mean values of $E_{x\text{-}ray}$ exceed 7600 Mpa, which is one of the requirements for assigning timber population to C16 according to EN 338:2003 [14].

There was a statistically significant explanation of variation in $\rho_{x\text{-}ray}$ by different planting densities. The $\rho_{x\text{-}ray}$ ranged from 292 to 647 kg/m^3, with mean values of 408, 423 and 441 kg/m^3 for low, standard and high planting density groups, respectively. The confidence intervals for $\rho_{x\text{-}ray}$ between the three different planting density groups did not overlap. The characteristic (5-percentile) values for $\rho_{x\text{-}ray}$ were 326, 340 and 351 kg/m^3 for low, standard and high planting density groups, respectively.

For all three planting density groups, the characteristic values of $\rho_{x\text{-}ray}$ met the requirement for C16 strength class ($\rho_k \geq 310$ kg/m^3) from the EN 338:2003 [14].

The E_{cb} ranged from 3977 to 9944 MPa, with mean values of 6579, 7173 and 7265 MPa for low, standard and high planting density groups, respectively. The explanation in variation of E_{CB} by different planting densities was found to be statistically significant. However, the effect is not linear, with MOE of boards from high planting densities affected less by change in planting densities than MOE of boards from low and standard planting densities (Fig. 4).

Table 2: Properties of sawn timber for different planting density groups.

	Planting density group		
	Low	Standard	High
Total No. of boards tested	403	294	201
$E_{dyn,undried}$ (MPa)	7330 (1302)	7777 (1399)	8149 (1267)
Mean $E_{dyn,12,adj}$ (MPa)	8458 (1607)	8969 (1639)	9325 (1597)
Mean $E_{x\text{-}ray}$ (MPa)	7679 (1237)	7910 (1164)	8312 (1297)
Mean $\rho_{x\text{-}ray}$ (kg/m^3)	408 (58.8)	423 (54.7)	441 (65.0)
Characteristic $\rho_{x\text{-}ray}$ (kg/m^3)	326	340	351
No. of boards tested using Cook Bolinders	159	77	58
Mean E_{cb} (MPa)	6579 (953)	7173 (893)	7265 (879)

Standard deviations are shown in parentheses.

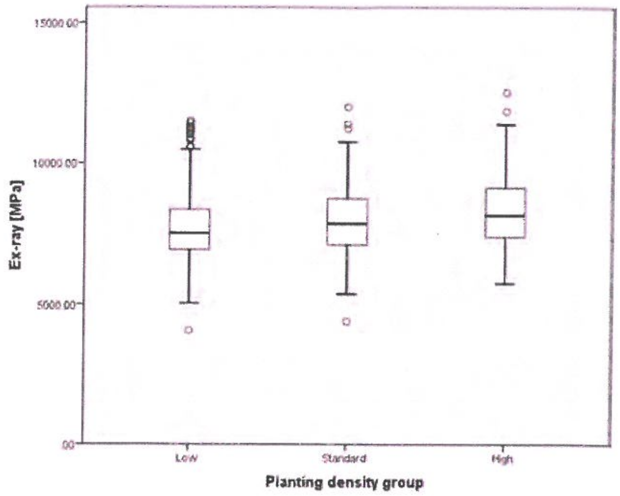

Figure 3: Comparison of $E_{x\text{-}ray}$ between different planting density groups.

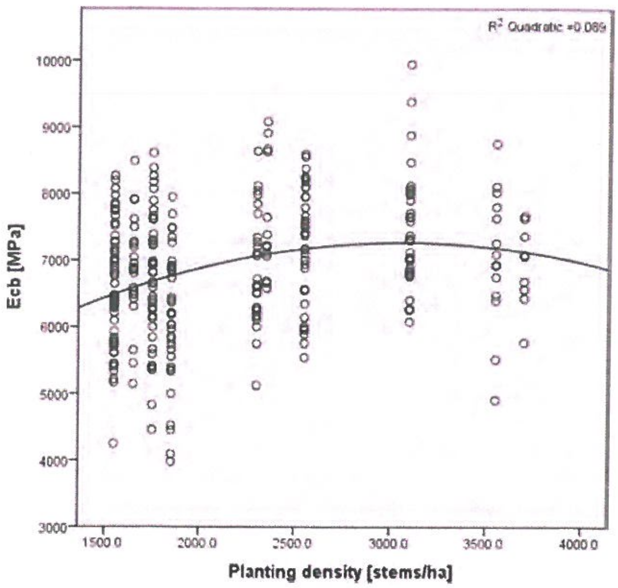

Figure 4: Relationship between planting density and E_{cb}.

Moderately strong correlation was found between $E_{dyn,undried}$ and $E_{x\text{-}ray}$ ($r = 0.466$). $E_{dyn,undried}$ explained 21.5% of variation in $E_{x\text{-}ray}$ ($R^2 = 0.217$) for all three planting density groups combined, while explanations of $E_{x\text{-}ray}$ by $E_{dyn,undried}$ for individual planting density groups was 10.7% for the low, 26.1% for the standard and 31.9% for the high planting density group.

4 DISCUSSION

The results from this study showed the increase in timber mechanical properties with increase of planting density. This is consistent with other studies that examined influence of planting density on structural timber properties [10, 12, 20, 21]. Results suggest better prediction of Ex-ray by Edyn, undried with the increase of planting density.

In Ref. [12] structural timber yields of unthinned 28-year-old Sitka spruce stands in Northern Ireland were examined using the Cook Bolinders grading machine. Planting density ranged from 2403 to 4565 stems/ha. It was found that higher yields of structural timber were negatively related to the initial stocking (planting density). On average, 44.8% of timber boards attained SC4 (Strength class 4 according to BS 5268, equivalent to C24 according to EN 338), compared to 24% in the lowest planting density stand with 2403 stems/ha. Average tree volume was 0.21 m^3, while in this study the results of high density group, which corresponded to the selected plots in Ref. [12], showed average tree volume of 0.266 m^3.

In Ref. [10] it was found that planting density of Sitka spruce stands in the UK is an important factor affecting the structural performance of timber cut from crops that had remained unthinned. However, the effect was not linear, with crops at both close (less than 1.5 m) and wide spacing (more than 3.0 m) affected less by change in planting distance than those established at spacings within this range. It was reported that planting density affects the number and size of large knots (≥ 25 mm in diameter) in the butt and second logs, from which, a negative effect of wider spacing on timber strength can be suggested. The results of MOE measurements using a Cook Bolinders grading machine in our study showed good agreement with the results from [10]. Both studies indicated that MOE can be controlled by planting density in a certain range outside of which further change in planting density does not affect timber MOE.

In Ref. [21], the influence of initial plant density on timber properties of 40-year-old Douglas fir in Bavaria, Germany was examined. Timber boards originated from three different planting densities: 1000 stems/ha, 2000 stems/ha and 4000 stems/ha were tested. It was found that high initial planting density results in lower knottiness, higher timber density and higher dynamic MOE and tensile strength. The early results from this study are consistent with these findings.

The results suggest that the timber from all three examined planting densities of 23-year-old Irish grown Sitka spruce meet the requirements for C16 strength class. However, in Ref. [22] it was reported that twist reduced the yield of structural timber by 25% from the 28-year-old Sitka spruce stand. Due to high proportion of juvenile wood, timber stability is affected and distortion seems to be a limiting factor for an increase in quantity of structural timber.

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REFERENCES

[1] Wardle, P.A., Spacing in plantations. *Forestry*, **40**, pp. 47–69, 1967. https://doi.org/10.1093/forestry/40.1.47

[2] ROI Forest Sevice, Ireland's forest - Annual Statistics, 2014.

[3] Macdonald, E. & Hubert, J., A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry*, **75**(2), pp. 107–138, 2002. https://doi.org/10.1093/forestry/75.2.107

[4] Ward, D. & Gardiner, J.J., The influence of spacing on tracheid length and density in sitka spruce. *Irish Forestry*, **33**(1), pp. 37–56, 1976.

[5] Gardiner, J.J. & O'Sullivan, P., The effect of wide espacement on wood density in sitka spruce. *Irish Forestry*, **35**(1), pp. 45–51, 1978.

[6] Javadi, Z., MacSiurtain, M. & Gardiner, J.J., The effect of tree espacement upon wood density in sitka spruce. *Irish Forestry*, **40**(2), pp. 92–97, 1983.

[7] Joyce, P.M. & OCarroll, N., *Sitka Spruce in Ireland*. Dublin: Coford, 2002.

[8] Moore, J., Achim, A., Lyon, A., Mochan, S. & Gardiner, B., Effects of early re-spacing on the physical and mechanical properties of Sitka spruce structural timber. *Forest Ecology and Management*, **258**(7), pp. 1174–1180, 2009.

[9] Hendrick, E., *The establishment, growth and stability of Sitka spruce (Picea sitchensis (Bong.) Carr.) in Ireland with particular reference to wet mineral soils*, NUI Dublin, 1999.

[10] Brazier, J.D. & Mobbs, I.D., The influence of planting distance on the structural wood yields of unthinned Sitka spruce. *Forestry*, **66**(4), pp. 332–352, 1993. https://doi.org/10.1093/forestry/66.4.333

[11] Ni Dhubháin, A.N., Magner, D. & Nieuwenhuis, M., Juvenile wood in Irish grown Sitka spruce and the impact of rotation length. *Irish Forestry*, **63**(1–2), pp. 26–36, 2006.

[12] Schaible, R. & Gawn, L.J., Variation of timber strength of Fast Grown Unthinned Sitka Spruce in Northern Ireland. *Irish Forestry*, **46**(1), pp. 43–50, 1989.

[13] CEN, *EN 338:2003 - Structural timber - Strength classes*. 2003.

[14] Ross, R.J., Nondestructive evaluation of wood: second edition," *General Technical Report FPL-GTR-238*. Department of Agriculture, Forest Service, Forest Products Laboratory., Madison, WI, U.S., p. 169, 2015.

[15] Macdonald, E., Mochan, S., Connolly, T. & Forest, O.F., Protocol for stem straightness assessment in sitka spruce. *Information Note-Forestry Commission*, pp. 1–8, 2000.

[16] COFORD and IFER, TreeModel - Irish Stem Profile & Single Tree Volume Equations, 2013.

[17] Unterwieser, H. & Schickhofer, G., Influence of moisture content of wood on sound velocity and dynamic MOE of natural frequency- and ultrasonic runtime measurement. *European Journal of Wood and Wood Products*, **69**(2), pp. 171–181, 2011. https://doi.org/10.1007/s00107-010-0417-y

[18] CEN, *EN 14081-4:2009 - Timber structures - Strength graded structural timber with regular cross section - Part 4: Machine grading - Grading machine settings for machine controlled systems*, 2009.

[19] Hoaglin, D.C. & Iglewicz, B., Fine tuning some resistant rules for outlier labeling. *Journal of American Statistical Association*, **82**, pp. 1147–1149, 1987. https://doi.org/10.1080/01621459.1987.10478551

[20] Simpson, H. & Denne, M., Variation of ring width and specific gravity within trees from unthinned Sitka spruce spacing trial in Clocaenog, North Wales. *Forestry*, 1997.

[21] Rais, A., Poschenrieder, W., Pretzsch, H. & van de Kuilen, J.W.G., Influence of initial plant density on sawn timber properties for Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). *Annals of Forest Science*, **71**, pp. 617–626, 2014. https://doi.org/10.1007/s13595-014-0362-8
[22] Hendrick, E. & Murphy, G., The effect of fast growth on structural yields of SS - a study on a yield class 30 stand - Report No. 8/91. Coillte Research and Development, Bray, p. 20, 1991.