REVISTA FLORESTA
Engenharia Florestal

ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

AN ALGORITHM FOR CALCULATING THE STEREO FACTOR

Thomaz Correa e Castro da Costa [1*], Natalia Carolina Oliveira Abreu [2]

[1*]Embrapa, CNPMS, Sete Lagoas, MG, Brazil –thomaz.costa@embrapa.br
[2*] Federal University of São João Del Rei, Department of Agronomy, Sete Lagoas, MG, Brazil – natalia.oliveira.abreu@aluno.ufsj.edu.br

Received for publication: 28/03/2024 – Accepted for publication: 28/06/2024

Resumo

Um algoritmo para cálculo do fator estéreo. A informação do volume de madeira é imprescindível na atividade florestal, principalmente na comercialização de produtos madeireiros. No entanto, é um desafio medir o volume sólido no período da colheita. O parâmetro viável para medição é o volume estéreo, que se refere à quantidade empilhada de madeira, incluindo os espaços vazios entre as toras. Porém, a relação volume estéreo – cubicado (sólido), que é influenciada pela forma, uniformidade e dimensão das árvores, precisa ser obtida por meio de um ensaio de campo, na maioria dos casos, se o usuário não optar por um valor de referência, de menor confiança. Neste trabalho, apresenta-se um algoritmo que estima a relação volume estéreo-cubicado a partir de dados do inventário florestal associados a cubagem de árvores. O algoritmo foi implementado em Visual Basic for Applications (VBA) para simular o empilhamento virtual de toras. Avaliou-se sua acurácia em três ensaios de campo, o primeiro e o segundo em um povoamento de eucalipto e o terceiro em um povoamento de Bambu. Pelas três formas de cálculo, a amplitude de erros foi de -12.34 a 8.33% para o fator de cubicação, e de -8.94 a 15.64% para o fator de empilhamento, sendo este o primeiro grau de confiabilidade para um parâmetro que exige um alto nível de acerto, pelo impacto na relação de compra e venda de madeira. O algoritmo é de fácil utilização, mas precisa de novas validações, em áreas de colheita florestal.

Palavras-chave: cubicação, empilhamento, bambu, floresta plantada, colheita florestal.

Abstract

Information on wood volume is essential in forestry activities, especially in the sale of wood products. However, measuring solid volume during a harvest period is challenging. The viable parameter for measurement is stereo volume, which refers to the stacked quantity of wood, including the empty spaces between the logs. However, the stereo volume–cubic volume (solid) ratio, which is influenced by the taper, uniformity, and size of the trees, needs to be obtained. In most cases, if a field tester does not choose a reference value, the result is less than reliable. In this work, an algorithm is presented that estimates the stereo–cubic volume relationship from forest inventory and tree stacking data. It was implemented in Visual Basic for Applications (VBA) to simulate virtual log stacking. Its accuracy was evaluated in three field trials: the first and second in a eucalyptus stand and the third in a bamboo stand. Implementing the three calculation methods, the errors ranged from -12.34 to 8.33% for the cubing factor and from -8.94 to 15.64% for the stacking factor, which was the first degree of reliability for a parameter that requires a high level of accuracy because of the impact on wood buying and selling. The algorithm is easy to use but needs further validation in forest harvesting areas.

Keywords: cubing, stacking, bamboo, planted forest, forest harvesting**.**

INTRODUCTION

The volume of wood is necessary information in all operations that involve timber harvesting, whether for firewood, chips, charcoal, or round or sawn wood. Operations such as regulating stocks, projecting growth and production, and exploring and marketing forest products use volume as the main parameter.

However, the cubic volume to be harvested from a forest stand is not obtained directly from the field. Preharvest forest inventories, or forest inventories for growth monitoring, provide an estimate in advance per tree and per area through a sample that provides only the maximum volume. The losses inherent in harvesting can reduce the volume from 11.92% to 15.62% because of stumps, tree tips, trunk breaks, and sawdust in the cuts (VATRAZ; BORGES, 2014; SERPE *et al.*, 2018). To obtain the harvested volume, the parameter measured is the stereo or stacked volume, with spaces between the logs as defined in Ordinance no. 130 (BRAZIL, 2011). This volume varies with the uniformity of the forest and the age, shape and deformity of the trees. Conical, tortuous and bifurcated tree shapes generate greater disparities between the cubic volume and the stereo volume.

Stereo measurements, which are usually performed on a truck or other transport vehicle, are a viable way to quantify the solid volume removed from an area (LISBOA *et al.*, 2009). To obtain this volume, it is necessary to know the conversion factor, either from stereo to cubic meter (cubing) or from m^3 to stereo (stacking). An alternative is to use reference factors closer to the forest of interest, with the risk of greater errors in the conversion to volume, or to obtain the site factor with a field trial, which is more reliable but not very representative because operationalization requires the individual measurement of sawn pieces and their standardized stacking, which makes replicability difficult because of cost.

The conventional method to obtain these factors is to demarcate a cube or parallelepiped on the ground, filling it with logs of the same length to be explored (1 m or 2 m, or 3.10 m, etc.), noting their extreme diameters to calculate volume via the Smalian formula (SANDIM *et al.*, 2019). Finally, the accumulated cubic volume is obtained, which, divided by the volume of the demarcated solid, results in the cubing factor. The stereo volume is obtained by dividing 1 m^3 by the cubing factor.

Stacking and cubing factors are still widely used in logging, but there are other direct methods used to calculate the solid volume of wood in an area, such as the difference in mass between the loaded and unloaded trucks, when density is used for conversion in volume and a weighing scale (FOELKEL, 2015).

The efforts to obtain these factors through forest inventory data were scored by Paula Neto and Rezende (1992) and Paula Neto *et al.* (1993), who modeled the factors as a function of the diameter and height of the trees, fixing the spacing with the same function of volume per tree as Schumacher and Hall. They reported that there may be a large variation in the values of these factors, which depend mainly on the uniformity of the pile with respect to the diameter of the logs.

Other more modern, indirect methods have emerged as alternatives to reducing operating costs when obtaining timber volume in forest harvesting. One example of a photo-optical measurement system that began in Brazil was software developed at the Federal University of Viçosa, Digitora, and tested by Soares *et al.* (2003) and Berola *et al.* (2003). These systems operate officially because the parameter requires high-accuracy measurement. An examples is the Logmeter® platform, which uses laser technology to scan and estimate the volume of a truck trailer (FOELKEL, 2015; KUNICKAYA *et al.*, 2022).

In some European countries, photo-optical measurement systems (sScale™, Dralle A/S and LogStackPro, HD Silva) have been calibrated to meet legal requirements in the commercialization of wood. Other photo-optical systems, some based on smartphones, have gained popularity in Europe and Brazil (KNYAZ; MAKSIMOV, 2014; ACUNA; SOSA, 2019; KARHA *et al.*, 2019, BERENDT *et al.*, 2021, CREMER et al., 2021, CREMER *et al.* , 2021). Some examples with photo-optical principles include Timbeter and Trestima (TIMBETER; TRESTIMA®, 2024). which, through a photo of the pile captured by a smartphone, process the image via an algorithm to determine the solid volume of the pile.

The algorithm proposed in this study is an indirect method that recovers the use of forest inventory data to calculate the cubing and stacking factors, such as those used by Paula Neto and Rezende (1992), Paula Neto *et al.* (1993) and Nunes and Soares (2017). The difference is that regression models were not used; virtual stacks of logs obtained from trees measured in forest inventory plots associated with taper data were acquired via computational methods. The objective of this study is to present the implemented methodology and validate the results obtained by the algorithm, which are compared with those of the field method, with the goal of generating stereo–cubic factors with an accurate degree of reliability in relation to the factors measured in the field.

MATERIALS AND METHODS

Algorithm

The "StackTora" algorithm, developed in Visual Basic for Applications (VBA), offers three calculation methods. The 1st stacks the sections by referring to the diameters at breast height (dbh) in samples of 9 trees (2D); the 2nd randomly selects one log per tree and the diameter of the log end in the horizontal direction, subsequently repeating the procedure in the vertical direction for the block of 9 logs (3D method 1). The 3rd method performs stacking with the logs exactly as in the field procedure, randomly selects the diameters at the ends of the logs, and obtains the largest dimensions in the horizontal and vertical axes of each face of the pile by the contact between the diameters of the logs to obtain the stereo volume (Figure 1). The input data are derived from plots of a forestry inventory and rigorous cubing.

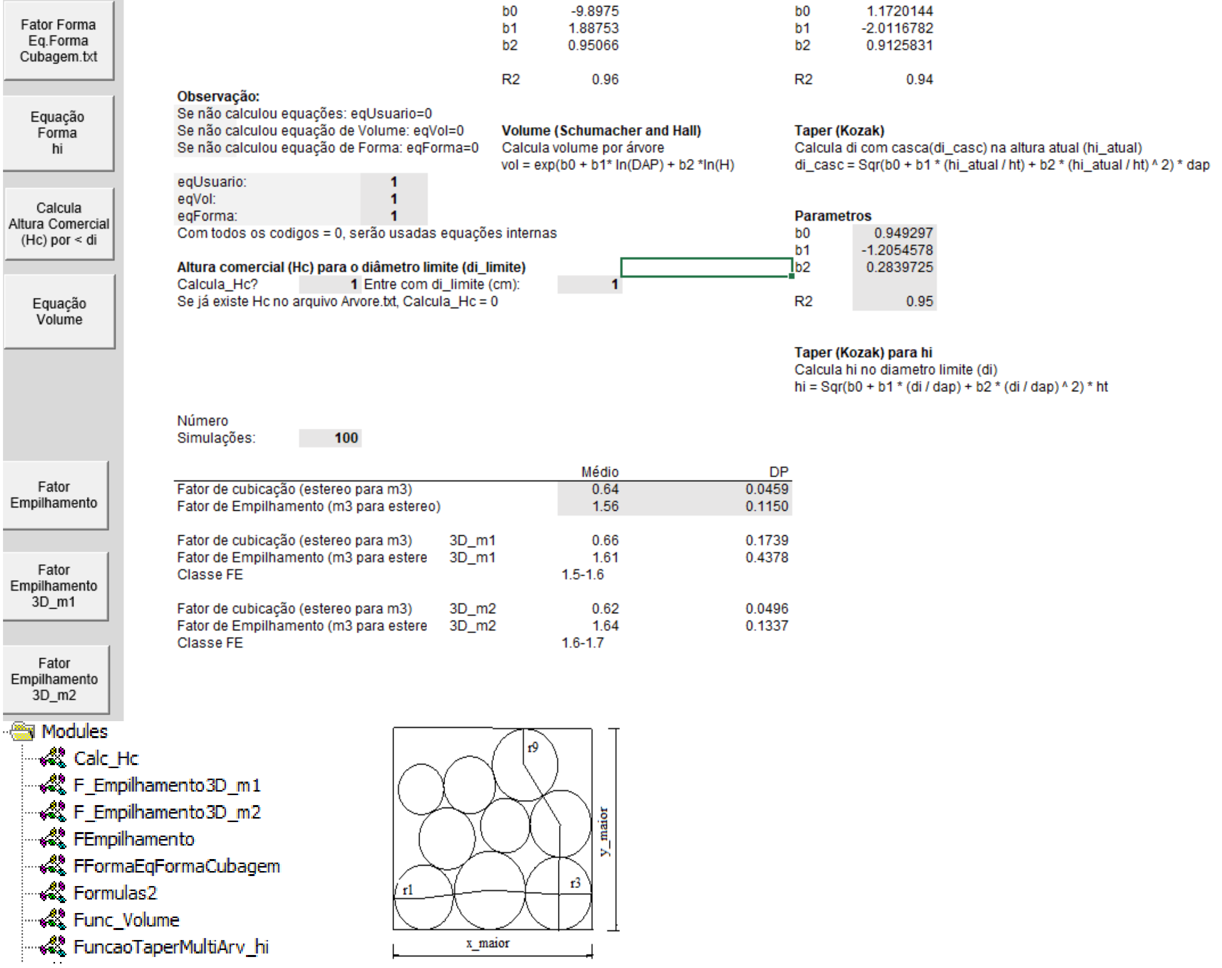
For the random selection of logs per sample, in the interface, the cubing routines are called through the data file Taper.txt (Table 1) to generate the coefficients of the equation of the Kozak model (Eq. 1), which are used to slice 1-m logs randomly selected from the dbh and height of the trees (Arvore.txt), which constitute the input data for the forest inventory plot (Table 1).

REVISTA FLORESTA
Engenharia Florestal
ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

Table 1. Partial files Arvore.txt and Taper.txt for the sample from the bamboo stand.
Tabela 1. Arquivos Arvore.txt e Taper.txt parciais da amostra do povoamento de bambu.

butcher	Share	Arv	dap	ht (m)	hc(m)	Share	Arv	hi (m)	di (cm)	ht (m)
1	1	1	3.9	8.7	7.1	1	1	0.3	3.5	8.7
1	1	2	2.5	7.7	5.5	1	1	0.7	3.9	8.7
1	1	3	3.6	9.6	7.7	1	1	1.3	3.9	8.7
1	1	4	2.6	7.7	5.6	1	1	2.3	4	8.7
1	1	5	3.9	8.8	7.1	1	1	3.3	3.6	8.7
1	1	6	1.9	6.7	4.2	1	1	5.3	1.9	8.7
1	1	7	3.0	8.4	6.4	1	1	6.3	1.2	8.7
1	1	8	2.9	7.7	5.8	1	3	1.3	3.6	9.6
1	1	9	1.8	6.1	3.7	1	3	2.3	3.4	9.6
1	1	10	2.1	7.3	4.8	1	3	3.3	3.3	9.6
						1	3	4.3	3.1	9.6
						1	3	5.3	2.7	9.6
						1	3	6.3	2.1	9.6
						1	3	7.3	1.6	9.6
						1	3	8.3	1	9.6

For each sample taken from the tree file, the pieces are included in the stack until they reach the limit of 9, and the rectangle with spaces is computed to calculate the stacking factor. The diameters of the sections (largest and smallest) are randomized to fit into the pile. If the number of trees is not sufficient for at least three samples, the dispersion measure (standard deviation) is not generated. EmpilhaTora generates *n* simulations of three-dimensional stacking estimates through random repetitions of the sample, each with distinct configurations of pieces and stacked through trigonometric relationships.



b0 -9.8975
b1 1.88753
b2 0.95066

R2 0.96

b0 1.1720144
b1 -2.0116782
b2 0.9125831

R2 0.94

Observação:
Se não calculou equações: eqUsuario=0
Se não calculou equação de Volume: eqVol=0
Se não calculou equação de Forma: eqForma=0

Volume (Schumacher and Hall)
Calcula volume por árvore
vol = exp(b0 + b1* ln(DAP) + b2 *ln(H)

Taper (Kozak)
Calcula di com casca(di_casc) na altura atual (hi_atual)
di_casc = Sqr(b0 + b1 * (hi_atual / ht) + b2 * (hi_atual / ht) ^ 2) * dap

eqUsuario: 1
eqVol: 1
eqForma: 1
Com todos os codigos = 0, serão usadas equações internas

Parametros
b0 0.949297
b1 -1.2054578
b2 0.2839725

R2 0.95

Altura comercial (Hc) para o diâmetro limite (di_limite)
Calcula_Hc? 1 Entre com di_limite (cm): 1
Se já existe Hc no arquivo Arvore.txt, Calcula_Hc = 0

Taper (Kozak) para hi
Calcula hi no diametro limite (di)
hi = Sqr(b0 + b1 * (di / dap) + b2 * (di / dap) ^ 2) * ht

Número
Simulações: 100

		Médio	DP
Fator de cubicação (estereo para m3)		0.64	0.0459
Fator de Empilhamento (m3 para estereo)		1.56	0.1150
Fator de cubicação (estereo para m3)	3D_m1	0.66	0.1739
Fator de Empilhamento (m3 para estere	3D_m1	1.61	0.4378
Classe FE		1.5-1.6	
Fator de cubicação (estereo para m3)	3D_m2	0.62	0.0496
Fator de Empilhamento (m3 para estere	3D_m2	1.64	0.1337
Classe FE		1.6-1.7	

Figure 1. StackTora algorithm (Interface, modules and logic).
Figura 1. Algoritmo EmpilhaTora (Interface, módulos e lógica).

Validation

Three trials were conducted. The 1st and 2nd rows of *Eucalyptus urograndis*, clone GG100, were 9 years of age and had 3 × 20 m spacing in the ILPF system (Integration Crop-Livestock-Forest) in the city of Maravilhas, Minas Gerais. In the third trial, bamboo (Bambusoideae) was used instead of trees as a way of replacing the tree trunks, thus increasing the repeatability of the piles and consequently achieving an accurate field truth with reduced operating costs. This trial was conducted at Embrapa Milho e Sorgo, located at Rod. MG 424, km 45, Sete Lagoas, Minas Gerais, in an area containing a spontaneous bamboo plantation.

In the 1st trial, 24 trees were measured in the row next to the cubed trees, representing an inventoried plot. In the 2nd trial, the 10 trees cubed were used to generate 2 resamplings of 10 trees with replacement via the bootstrap technique, totaling 30 trees (inventory portion). This procedure allowed the algorithm to calculate the cubic volume and stereo volume with the respective standard deviations, which was not possible with 10 trees. In the 3rd trial, 30 bamboo stems representing an inventoried plot were measured.

In this study, 100 simulations were selected for each test. In each simulation, the cubic volume and the stereo volume were generated, with the respective standard deviations.

Shape of eucalyptus trees and bamboo stalks

To simulate the cubic volume and the stereo volume with methods 2 and 3, rigorous cubing data are needed. For the 1st and 2nd trials, 10 representative trees were cubed, and for the 3rd trial, 30 bamboo stems were cubed, whose dimensions were measured through the diameter at a height of 1.30 m (dbh). The total height and the diameter along the trunk were measured at heights of 0.3, 0.7, and 1.3 m, and from 1.3 m, the height was increased by 1 meter until the diameter reached 1 cm.

The Kozak model (Eq. 1), which was adopted for the trees and bamboo stalks, was applied to simulate the logs (pieces) via the algorithm. For this purpose, the taper data are read by another algorithm, which is transported from CalcMadeira (COSTA *et al.* 2022), to generate the equation and estimate the diameter along the trunk (or stem).

$$(d_i/dap)^2 = b_0 + b_1 * + \frac{h_i}{ht} + b_2 * \left(\frac{h_i}{ht}\right)^2 \qquad \text{(Eq. 1)}$$

where d_i represents the diameter along the trunk or stem; *dap* represents the diameter at a height of 1.3 m; h_i represents the height along the trunk or stem; *ht* represents the total height; and b_0, b_1, and b_2 represent the coefficients to be estimated.

Observed data (field truth)

In the 1st and 2nd trials, an observed value (population mean, without the respective standard deviation) was obtained via logs from the 10 cubed trees, and the length and diameter at the ends were measured to calculate the volume via the Smalian formula (Eq. 2). The logs were stacked in dimensions of 1 × 1 m × log length (≈ 3.10 m). The cubic volume is the sum of the volume per log, contained in the stereo volume (1 m^3 st), and is considered the population mean.

In the 3rd trial, representative bamboo stems of different heights and thicknesses were felled, and the dbh and total height were measured following a methodology similar to that of the first trials. The stems were sectioned into 1-m-long piles, which involved cutting with a chainsaw, thinning with a machete, and tracing via a circular saw. After the piles were mixed to assemble the piles (Figure 2), the diameters of the ends of each pile were measured with tape to calculate the volume via the Smalian formula (Eq. 2) at 0.5 m wide × 0.2 m high × 1.0 m long. After reaching a height of 0.2 m, the piles were removed, and a new pile was formed. Eight piles of bamboo cuttings were measured. The volume of cubing was obtained as the sum of the volumes of the piles in the pile (ΣV), which subsequently expanded, considering 1 m^3 st.

$$V = \frac{\pi}{40.000}\left(\frac{{D_1}^2 + {D_2}^2}{2}\right) * L \qquad \text{(Eq. 2)}$$

where V represents the volume in m^3 of the pile; D_i represents the diameter at the end of the pile; and L represents the length of the cuttings (1 m).

When bamboo is adopted as a substitute for trees, an inadequacy is observed: the knot is the first contact between cuttings, which can be between nodes or from node to node. We chose not to measure the diameters of the piles above the node at the tip because we considered the contact between the nodes to be less likely to occur. This error was assumed, which was considered nonprohibitive for the execution of the assay.

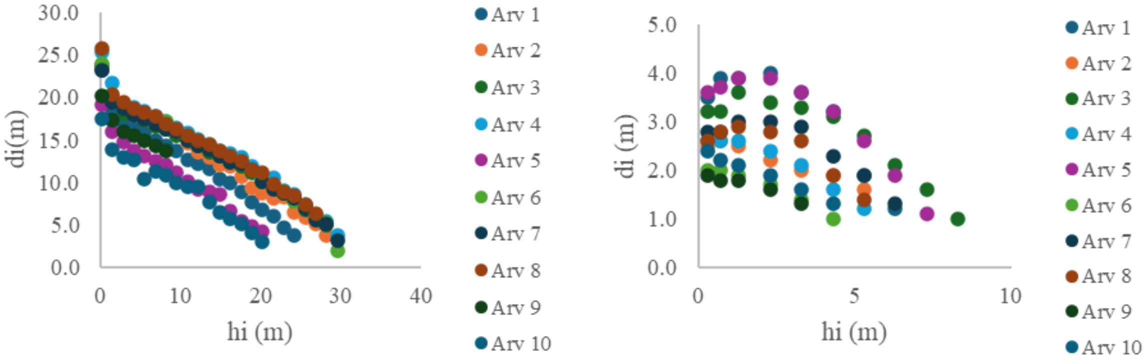
Figure 2. The bamboo pieces were stacked with dimensions of 0.20 × 0.50 × 1.0 m for the 3rd test.
Figura 2. Peças de bambu empilhadas nas dimensões de 0,20 x 0,50 x 1,0 m, para o 3º ensaio.
Source: Author

To evaluate the difference between the means of the simulated values and the values obtained via field tests, the percentage relative error (Eq. 3) was used.

$$E\% = \left(\frac{\text{valor simulado} - \text{valor observado}}{\text{valor observado}}\right) \text{x } 100 \qquad \text{(Eq. 3)}$$

RESULTS

Figure 3, which shows the taper of eucalyptus trees (A) and bamboo stems (B), shows that the shape of the bamboo in some stems thickens after the base and then decreases. This stem profile differs from that of standard eucalyptus trees, which have a wider base and inflection point near the dbh. The coefficients of Eq. 1 for eucalyptus were b_0 =1.17201439; b_1 = -2.01167817; b_2 = 0.91258308; the coefficient of determination (R^2) was 0.941; for bamboo, b_0 = 1.10321741; b_1 = -0.98942999; b_2 = -0.32757981; and the coefficient of determination (R^2) was 0.919. Even with the morphological difference between the bamboo stems and the eucalyptus stems, the quadratic Kozak model showed a satisfactory fit, reaching an R^2 of 91.9%, which was close to the 94.1% obtained for eucalyptus.



A B

Figure 3. Trunk profile of 10 square eucalyptus trees for the 1st and 2nd assays (A) and profile of the first 10 cubed bamboo stems of the 3rd assay (B).
Figura 3. Perfil do tronco de 10 árvores cubadas de eucalipto para o 1º e 2º ensaio (A); e perfil das 10 primeiras hastes cubadas de bambu do 3º ensaio (B).

The calculation of the cubic volume for eucalyptus (field truth) by stacking logs of approximately 3.10 m was performed as follows: the seven greatest heights of the pile and the three greatest lengths on both sides of the pile were measured to the most accurate measurement possible with a fixed width (1.34 m). The volume with space was obtained via the largest measurements, with the weight between the sides multiplied by the maximum width, resulting in a stereo volume of 4.67 m^3. The cubic volume was calculated as the sum of the ten total cubic volumes per tree, resulting in 3.50 m^3, a stacking factor (stereo) of 1.34 m^3, and a cubing factor of 0.746 m^3, which were assumed to be the real values (population).

For the 3rd trial, Table 2 shows the field data consisting of nine piles, the number of piles per pile, the average diameter of the piles, the cubing and pile factors per sample and the averages, with the respective standard deviations.

Table 2. Sampled piles, number of stems per pile (n), average stem diameter (Dm), and cubing and stacking factors (Fc, Fe).
Tabela 2. Pilhas amostradas, número de estacas por pilha (n), média dos diâmetros das estacas (Dm), fator de cubicação e fator de empilhamento (Fe).

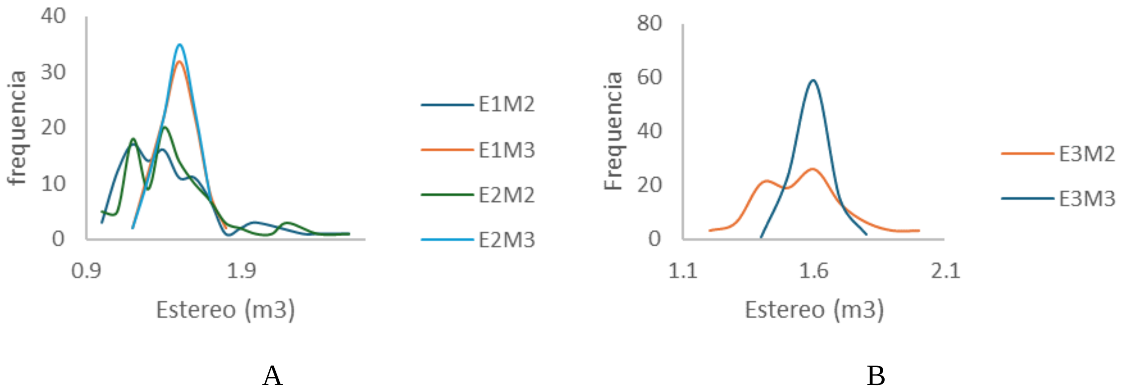
Stack	n	Dm	Fc (m^3)	Fe (m^3)
1	80	2.68	0.503	1.988
2	83	2.66	0.496	2.015
3	87	2.49	0.457	2.186
4	97	2.67	0.592	1.689
5	106	2.54	0.58	1.723
6	92	2.78	0.608	1.645
7	104	2.78	0.884	1.132
8	86	3.03	0.676	1.48
9	99	2.77	0.637	1.57
average	92	2.71	0.604	1.714
D. standard			0.127	0.318

Table 3 shows the 24 trees (inventory data) for the 1st trial and the 30 trees resampled from the 10 cubed trees, referring to the 2nd test. Both datasets were used to calculate 100 simulations of the stacking factors for the 3 methods.

Table 3. DBH and total height of 24 trees measured in the row adjacent to the cubed trees (1st trial) and 20 trees generated via the bootstrap technique from 10 cubed trees (2nd test).
Tabela 3. Dap e altura total de 24 árvores mensuradas no renque vizinho ao das árvores cubadas (1º ensaio); e de 20 árvores geradas pela técnica do Bootstrap a partir das 10 árvores cubadas (2º ensaio).

Arv	db(cm)	ht (m)	Arv	db(cm)	ht (m)	Arv	db(cm)	ht (m)
				1st rehearsal				
1	25.1	31	9	15.5	26	17	15.1	22.5
2	14.9	28	10	16.0	27.5	18	16.4	25.5
3	9.0	12	11	18.0	29.5	19	20.8	30
4	19.0	27	12	17.4	27	20	19.9	29.6
5	18.7	30	13	17.8	28.5	21	21.8	29.5
6	21.6	30	14	15.7	26	22	22.8	29.5
7	18.5	27.5	15	17.2	26.5	23	18.0	20
8	16.1	27	16	15.9	27	24	21.8	16.5
				2nd rehearsal				
1	18.7	26.5	11	19.9	30.0	21	19.9	30.0
2	19.9	30.0	12	19.6	31.5	22	14.1	21.0
3	19.6	31.5	13	19.9	30.0	23	19.9	30.0
4	21.0	30.0	14	21.0	30.0	24	19.6	31.5
5	15.9	22.0	15	19.4	30.0	25	21.0	30.0
6	20.5	30.5	16	19.9	30.0	26	21.0	30.0
7	19.4	30.0	17	14.1	21.0	27	20.5	30.5
8	20.7	28.5	18	19.9	30.0	28	20.7	28.5
9	14.1	21.0	19	19.4	30.0	29	15.9	22.0
10	19.4	30.0	20	19.4	30.0	30	19.6	31.5

Figure 4 shows the frequency distribution of 100 simulations for the stereo factor generated by the algorithm in the three tests, using methods 2 and 3 (method 1 generates one result per test). The largest dispersion of values occurs in method 2 due to randomness on each face of the stack and in the horizontal and vertical directions of the stacking.



A B

Figure 4. Frequency distributions of the results of 100 simulations for the stacking factor, stereo (Fe), in tests 1 and 2 (A) and in test 3 (B) via methods 2 and 3.

Figura 4. Distribuições de frequência do resultado de 100 simulações para o Fator de empilhamento, estereo (Fe) nos ensaios 1 e 2 (A); e no ensaio 3 (B), por meio dos métodos 2 e 3.

The average values of the cubing factor (Fc) and stacking factor (Fe) obtained in the simulations and the respective percentage relative errors (E%) are presented in Table 4. The largest errors occurred in method 3 in the tests with eucalyptus, which was an unexpected result because this method is the closest to the procedure for calculating stacking in the field. Method 1, which calculates from the stacking of sections by dph instead of logs, presented lower errors than the other methods did in some cases. Because this method is further away from the stacking structure, larger errors in the results were expected.

The greatest stability occurred in trial 3, with lower errors, especially for method 3. Trial 2, which used cubed trees for stacking, systematically presented lower errors than did trial 1, with one exception. The bias was inverted across trials 1, 2 and 3 but was not systematic across methods.

Table 4. Results of 100 simulations of the cubic (Fc) and stereo (Fe) factors for the three assays and the three methods, with respective percentage relative errors (E%) in relation to the population value.

Table 4. Results of 100 simulations of the cubing (Fc) and stereo factors (Fc) for the three tests and three methods, with respective percentage errors (E%) in relation to the population value.

Method	M1(2D)	M2(3D)	M3(3D)	Population value
Assay	F. Cubification (m ^{3})			
E1(Eucalyptus)	0.69	0.73	0.66	0.75
E2(Eucalyptus)	0.73	0.74	0.66	0.75
E3(Bamboo)	0.64	0.65	0.61	0.60
	Accuracy (E%)			
E1(Eucalyptus)	-8.22	-2.66	-12.34	
E2(Eucalyptus)	-2.16	-1.22	-11.64	
E3(Bamboo)	6.50	8.33	1.29	
	F. Stacking (m^3)			
E1(Eucalyptus)	1.47	1.47	1.54	1.34
E2(Eucalyptus)	1.37	1.50	1.53	1.34
E3(Bamboo)	1.56	1.61	1.65	1.71
	Accuracy (E%)			
E1(Eucalyptus)	9.78	10.16	15.64	
E2(Eucalyptus)	2.37	12.55	14.72	
E3(Bamboo)	-8.94	-6.13	-3.99	

DISCUSSION

In the first and second trials, the stacking factor observed in the field for eucalyptus was 1.34. This value is in agreement with the results obtained by Paula Neto and Rezende (1992), Paula Neto *et al.* (1993) and Bertola *et al.* (2003), who reported values ranging from 1.25 to 1.38, and in recent studies by Filho *et al.* (2022), who reported similar values ranging from 1.29 to 1.49.

The simulations for these tests presented values ranging from 1.37 to 1.54, with errors between 2.37 and 15.64%, which tends to estimate more space between the pieces than that observed in the field. The causes for these results may be from different sources. In the field, the logs were organized with alternating smaller and larger diameters. In the algorithm, the position is defined randomly, and repetitions of stacks with larger log diameters may occur on the same face of the pile. The taper equation, even with high R^2 values, overestimates *di* near the base (“shoe”), a region that is difficult to model, and underestimates *di* in the lower third of the bole (data not shown), generating random logs with greater tapers than the real value, causing the simulation to estimate more spaces between the selected logs in this region of the bole than expected. These are assumptions for the trend of higher stacking factors than those observed for trials 1 and 2.

The cubing factor in the second trial was more accurate than that in trial 1 because the 10 selected trees were cubed and used to assemble the pile, which increased the representativeness of the data used by the algorithm through the coefficients of the taper equation. For the first test, data were collected from 24 trees in a neighboring row to obtain a simulation via the algorithm and a comparison with a stack of 10 trees.

Digitora, Bertola *et al.* (2003) obtained errors with a maximum of 2%, and Silva *et al.* (2005), using a digital camera, reached errors of -3.26 to 5.08% compared with the values obtained by rigorous cubing, accuracies much higher than those obtained in this study. On the other hand, Soares *et al.* (2003), with a digital camera but in a production unit, applied the technique to truck cubes and obtained a less precise error range between -6.36% and 15.56%.

One possible reason the optical method presented smaller errors is that the spaces observed in the photos indirectly incorporate two factors that interfere with the stacking: tortuosity and the taper of the log. In the case of the methodology presented in this study, only the taper is considered via the coupled taper function. Miguel-Díez *et al.* (2021) evaluated these factors in 1000 logs, simulating the participation of crooked logs and the taper in the pile, and observed the influence of these variables on the stacking factors in relation to the proportion of crooked and more conical logs in the pile, finding large differences.

In trial 3, with bamboo, the trend was the inverse of that observed in trials 1 and 2, with smaller errors between -3.99 and -8.94%; that is, the algorithm estimated greater accommodation (less space) than that observed. In this case, although with a less precise taper equation, the model does not predict the nodes of the stems, which, when coming into contact between piles in the pile, will increase the space, providing the first evidence for the underestimation of the stacking factor.

Another observation is that the field truth was expressed as a mean value (Table 2), with the respective standard deviation, so that the estimate of the 100 simulations is contained in the confidence interval of the parameter, an inverse situation to the parametric statistics, which compares a sample estimate associated with a variance with a population parameter, with unknown variance.

Imperfections were predicted in the assembly of the bamboo piles that did not significantly impact the estimates, even with the morphological diversity of the stems. Combined with the measurement methodology that considered the measurement of diameters at the internodes and not at the nodes, this test offered greater stability among the results and with lower errors.

The stacking factor is a parameter that requires great assertiveness because it is used for the timber trade. A methodology that proposes estimation needs to have an established degree of reliability, which should be within the expectations of forest traders. If the stereo factor is overestimated and the wood is traded in stereo, the seller will gain beyond the real value. The opposite will happen if the negotiation is in the form of cubic wood. Thus, the repetition of this method and of a photo-optical method in production areas will be able to define the degree of reliability compared with the company's measurement method. For this purpose, three approaches were used: the “EmpilhaTora”, with estimates based on the preharvest inventory of the test stand, estimates provided by the standardized log piles at the time of harvest, and the application of the photo-optical method after loading the log truck until the complete harvest of the field.

CONCLUSIONS

Based on the results of this study, the following conclusions were reached:

- The use of the “EmpilhaTora” algorithm simplifies processes to obtain the cubing and stacking factors, but the instability and magnitude of the errors found were still not satisfactory, requiring a new validation in production and in forest harvesting units.
- Bamboo stems proved to be an alternative data source to tree trunks for validation.

ACKNOWLEDGMENTS

The development of this study is part of the Technical Cooperation Agreement No. 21189.001651/2021-79 for the validation and marketing development of CalcMadeira software, together with a license for the use of the “Embrapa technology” trademark between the Brazilian Agricultural Research Corporation (Embrapa) and the Brazilian Agricultural Research Corporation (Embrapa) SIG Informática Ltda.

Repository: https://doi.org/10.48432/RRWDCH, Redape, V1

REFERENCES

ACUNA, M.; SOSA, A. Automated volumetric measurements of truckloads through multi-view photogrammetry and 3D reconstruction software. **Croatian Journal of Forest Engineering**, Zagreb, v. 40, p. 151-162, 2019.

BERENDT, F.; WOLFGRAMM, F.; CREMER, T. Reliability of photo-optical measurements of log stack gross volume. **Silva Fennica**, Helsinki, v. 55, n. 3, article 10555, 2021. https://doi.org/10.14214/sf.10555.

BERTOLA, A.; SOARES, C. P. B.; LEITE, H. G.; SOUZA, A. L. Determinação de fatores de empilhamento através do software Digitora. **Revista Árvore**, Viçosa, MG, v. 27, n. 6, p. 837-844, 2003. https://doi.org/10.1590/S0100-67622003000600010.

BRASIL. Instituto Nacional de Metrologia, Normalização e Qualidade Industrial. Portaria nº 337, de 29 de agosto 2011. **Diário Oficial [da] República Federativa do Brasil**, 30 ago 2011. Disponível em: http://www.inmetro.gov.br/LEGISLACAO/detalhe.asp?seq_classe=1&seq_ato=1727. Acesso em: 13 mar. 2024.

COSTA, T. C. C.; FRANÇA, L. F.; SANTOS, T.; RAMOS, L. B.; CAMPANHA, M. M. CalcMadeira: software for estimating lumber production. **Global Journal of Science Frontier Research: I Interdisciplinary**, Framingham, v. 22, n. 2, p. 1-17, 2022.

CREMER, T.; BERENDT, F.; MIGUEL DIEZ, F.; WOLFGRAMM, F.; BLASKO, L. Accuracy of photo-optical measurement of wood piles. **Environmental Sciences Proceedings**, Basel, v. 3, n. 1, article 90, 2021. https://doi.org/10.3390/IECF2020-08192.

GOUVEIA FILHO, K. V.; SOARES, T.; CRUZ, E. S.; MATHIAS, R. A. M. Determinação de fatores de empilhamento e volume de madeira empilhada por meio do processamento de imagens digitais. **Advances in Forestry Science**, Cuiabá, v. 9, n. 3, p. 1851-1858, 2022. https://doi.org/10.34062/afs.v9i3.13470.

FOELKEL, C. Medição da madeira na forma de toras empilhadas. **Eucalyptus Newsletter**, Eldorado do Sul, n. 48, p. 1-27, out. 2015.

KÄRHÄ, K.; NURMELA, S.; KARVONEN, H.; KIVINEN, V.-P.; MELKAS, T.; NIEMINEN, M. Estimating the accuracy and time consumption of a mobile machine vision application in measuring timber stacks. **Computers and Electronics in Agriculture**, New York, v. 158, p. 167-182, 2019. https://doi.org/10.1016/j.compag.2019.01.040.

KUNICKAYA, O.; POMIGUEV, A.; KRUCHININ, I.; STORODUBTSEVA, T.; VORONOVA; A.; LEVUSHKIN, D.; BORISOV, V.; IVANOV, V. Analysis of modern wood processing techniques in timber terminals. **Central European Forestry Journal**, Boston, v. 68, p. 51–59, 2022.

KNYAZ, V. A.; MAKSIMOV, A. A. Photogrammetric technique for timber stack volume contol, Int. Arch. Photogramm. Remote Sens. **Spatial Inf. Sci**., XL-3, p. 157–162, 2014.https://doi.org/10.5194/isprsarchives-XL-3-157-2014.

LISBOA, G. S.; DIAS, A. N.; VALERIO, A. F.; SILVESTRE, R. Comparação do fator de empilhamento sob diferentes condições para madeira de *Eucalyptus grandis*. **Ambiência**, Guarapuava, v. 5, n. 1, p. 81-91, jan./abr. 2009.

MIGUEL-DÍEZ, F. de; TOLOSANA-ESTEBAN, E.; PURFÜRST, T.; CREMER, T. Analysis of the influence that parameters crookedness and taper have on stack volume by using a 3D-simulation model of wood stacks. **Forests**, Basel, v. 12, n. 2, 238, 2021. https://doi.org/10.3390/f12020238.

NUNES, J. S.; SOARES, T. S. Estimativas volumétricas para um povoamento adensado de Eucalyptus sp. em regime de curta rotação. **Revista de Agricultura Neotropical**, Cassilândia, v. 4, n. 4, p. 77-86, 2017. https://doi.org/10.32404/rean.v4i4.1661.

PAULA NETO, F.; REZENDE, A. V. Equações de fatores de empilhamento e tabelas de volumes em metros estereo para árvores individuais. **Revista Árvore**, Viçosa, MG, v. 16, n. 1, p. 59-71, jan./abr. 1992.

PAULA NETO, F.; REZENDE, A. V.; CAMPOS, J. C. C.; REZENDE, J. L. P. Análise do comportamento dos fatores de empilhamento para *Eucalyptus grandis*. **Revista Árvore**, Viçosa, MG, v. 17, n. 1, p. 45-59, 1993.

SANDIM, A. S. A.; MOTA, A. C.; SANTOS, M. L.; BARROS, W. S.; COSTA, B. C.; ANDRADE, V. M. S. Stacked volume conversion fator for geometric volume of Eucalyptus sp. **Revista Agro@mbiente**, Boa Vista, v. 13, n. 0, p. 46-54, 2019.

SERPE, E. L.; FIGUEIREDO FILHO, A.; ARCE, J. E. Perdas volumétricas relativas à colheita florestal e seus reflexos econômicos. **Biofix Scientific Journal**, Curitiba, v. 3, n. 1, p. 172-176, 2018.

SILVA, M. C.; SOARES, V. P.; PINTO, F. A. C.; SOARES, C. P. B.; RIBEIRO, C. A. A. S. Determinação do volume de madeira empilhada através de processamento de imagens digitais. **Scientia Forestalis**, Piracicaba, n. 69, p. 104-114, dez. 2005. Disponível em: https://www.ipef.br/publicacoes/scientia/nr69/cap09.pdf. Acesso em: 13 mar. 2024.

SOARES, C. P. B.; RIBEIRO, J. C.; NASCIMENTO FILHO, M. B.; RIBEIRO, J. C. L. Determinação de fatores de empilhamento através de fotografias digitais. **Revista Árvore**, Viçosa, MG, v. 27, n. 4, p. 473-479, 2003. https://doi.org/10.1590/S0100-67622003000400007.

TIMBETER: the easiest solution for measuring roundwood digitally Disponível em: https://timbeter.com/timbeter/. Acesso em: 27 mar. 2024.

TRESTIMA®: stack measurement system. Disponível em: https://www.trestima.com/w/en/stack-measuring-system/. Acesso em: 27 mar. 2024.

VATRAZ, S.; BORGES, F. Q. Procedimentos de controle do volume de madeira estimado e colhido em um plantio de Pinus spp. no Paraná. **Ciência Florestal**, Santa Maria, v. 24, n. 2, p. 1-10, abr.-jun., 2014.