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MATHEMATICAL ALGORITHM TO OPTIMISE BAMBOO SPLITTING FOR STRIPS PRODUCTION

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INTRODUCTION

Bamboo belongs to the *Bambusoideae* subfamily of the perennial evergreen grass family *Poaceae* (formerly known as *Gramineae*). With more than 1200 species in over 70 genera, bamboo grows natively in all continents, except Europe and the Antarctica (McClure 1966). It has been used to make a wide range of products, traditionally and also in modern time, from cottage vegetable basket to high-end floorings.

According to INBAR (International Bamboo and Rattan Organisation), the average annual global trade (import-export) of bamboo and its products is about USD3 billion (Gauli et al. 2018). From this figure, about 10% or USD313 million is generated by bamboo floorings (Anon 2017).

Currently, most of the floorings are made from a type of engineered bamboo lumber, namely, laminated bamboo strip lumber (LBSL). As the name implies, LBSL is made using strips of bamboo glued and laminated to each other to form billets or boards (Wan Tarmeze 2005 and Lin et al. 2010) of specific sizes as required by the users. To produce the strips, as shown in Figure 1, a cut length of bamboo pole is split into a number of pieces. Each of the splits is then planed to form a strip with rectangular cross-section profile.

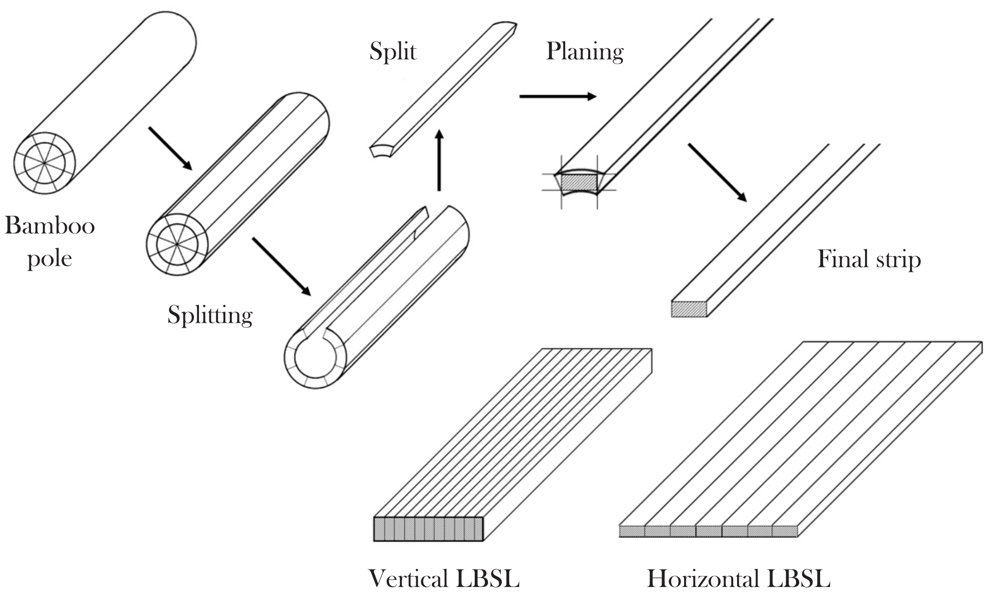


Figure 1 A process of making Laminated Bamboo Strip Lumber*
*Also named as Laminated Bamboo Lumber (Mahdavi et al. 2011, Asmah et al. 2016, Li et al. 2016) and Laminated Bamboo Timber (Anokye et al. 2016)

Due to the necessity to have the strips that are uniform in shapes and sizes and to maximise the recovery of bamboo, it is important to know how many splits can be produced from a bamboo pole of a diametrical size and wall thickness. For instance, if a LBSL manufacturer wants to produce strips with rectangular cross-section of 15 mm × 5 mm (width x height), then he should ask "what are the minimum diameter and wall thickness of bamboo pole required?". On the other hand, if a LBSL manufacturer has a stock of bamboo poles with diameter ranging from 100 mm to 120 mm and wall thickness of about 7 mm, hence he should be asking "what number of splitting should be applied to maximise recovery?"

This paper aims at answering the above questions through a mathematical algorithm describing the splitting of bamboo poles and planing of the splits to produce strips of desired cross-sectional dimension. The method is then verified by comparing its results with that obtained using AutoCAD.

MATERIAL CHARACTERISTICS OF BAMBOO CULM WALL

Before discussing further into the development of the bamboo splitting algorithm, it is essential to understand the bamboo culm wall materials and how they should be included in or removed from the strip. As depicted in Figure 2, bamboo culm wall can be divided into several parts. Moving inwards radially (towards the centre of the bamboo pole), the parts are: epidermis, cortex, flesh (the most usable woody bamboo part) and pith ring.

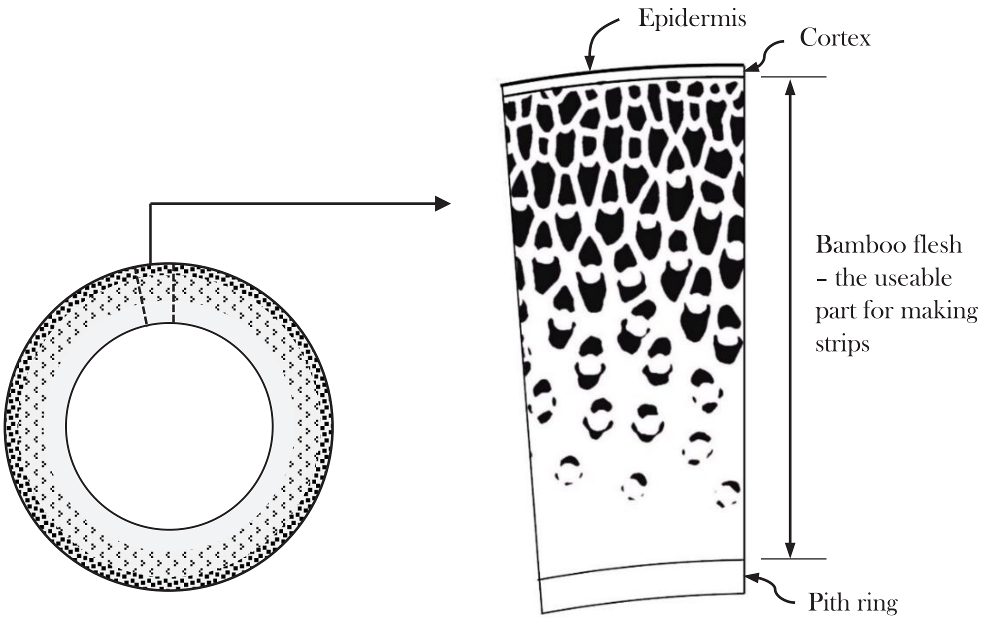


Figure 2 Anatomy of bamboo culm wall. (a) Bamboo culm cross-section featuring a split (dashed lines), (b) details of the bamboo split.

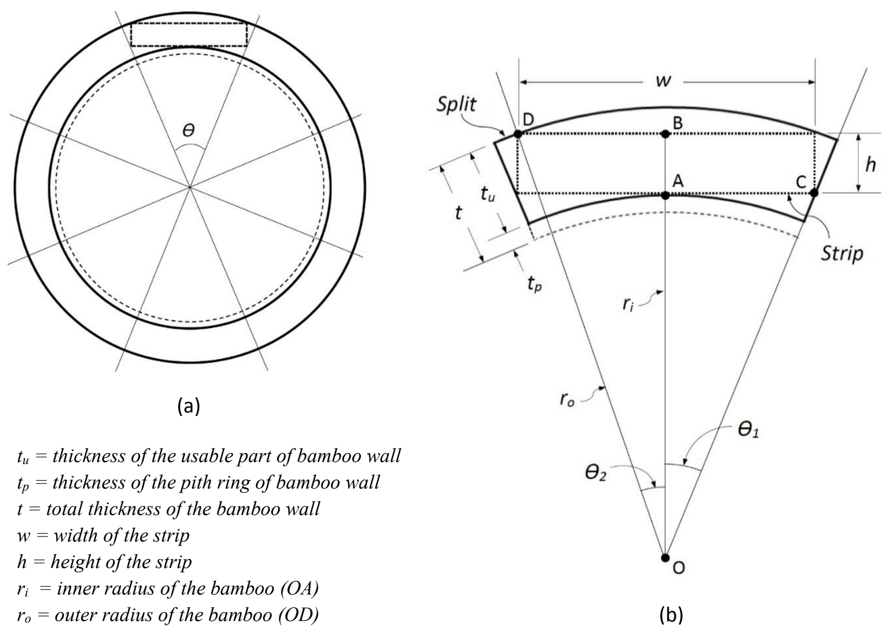
The epidermis, often called "bamboo skin", is the outermost part of bamboo culm (Liese 1980), and it is characterised by a very thin layer consisting of a single row of radially elongated cells. This wax coated skin has a function to prevent moisture loss from the bamboo. Immediately below the epidermis is the cortex, a compacted layer of tissues that serves as a protection to the bamboo flesh underneath.

Bamboo flesh that makes up the most of bamboo culm wall contains vascular bundles (the black coloured elements in Figure 2b) of which shape and distribution are changing gradually towards the bamboo pole centre (Liese 1987). In terms of mechanical properties, the vascular bundles in the peripheral region (nearer to the cortex) are stiffer and stronger than those found towards the centre (Li & Shen 2011).

The innermost layer of bamboo culm wall is called pith ring, pith periphery or "bamboo yellow", a non-vascular tissue composed of parenchyma cells, which are often thickened and lignified (Liese 1998). The short and square thick-walled cells are stacked in 8 to 15 layers (Li et al. 1997). Like the epidermis, pith ring is also rich in silica (Lwin et al. 2001, Yin et al. 2016); a substance that often not favoured by bamboo product manufacturers because it causes the cutting tools to blunt faster. Bamboo pith ring is also water-impermeable (Fang et al. 2018) which means that its glue bonding property is poor. Furthermore, it is brittle and prone to crack and separated from the flesh (Wang et al. 2012). Hence, the pith ring should not be included as part of the strip processed for making LBSL.

BAMBOO POLE SPLITTING MATHEMATICAL ALGORITHM

To get the highest recovery of bamboo, i.e., the most number and biggest volume of strips produced, bamboo pole should be split as shown in Figure 3. The strip (w x h rectangle) is cut from the thickness of bamboo flesh (t_u) excluding that of the pith ring (t_p). Recovery is percentage value of the volume (or the area per unit length) of strips produced over that of unprocessed (unsplit) pole.



t_u = thickness of the usable part of bamboo wall
t_p = thickness of the pith ring of bamboo wall
t = total thickness of the bamboo wall
w = width of the strip
h = height of the strip
r_i = inner radius of the bamboo (OA)
r_o = outer radius of the bamboo (OD)
Θ = arc angle of the split
$Θ_1$ = arc angle of the half split
$Θ_2$ = angle created by OD and OB intersection
N = number of splits (in this case, is 8)

Figure 3 Splitting of bamboo pole. (a) Culm cross-section featuring a split (shown as dashed lines), (b) details of the bamboo split and the optimum planing configuration to produce strip.

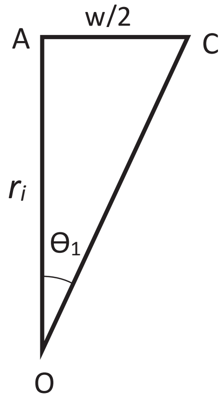
The bamboo pole splitting and strip planing configuration shown in Figure 3b is considered optimum as far as maximum recovery is concerned, and it is consistent for all combination of the number of splitting (N), bamboo diameter (Ø) and wall thickness (t). By carefully observing the drawings, we should be able to list down the known or pre-determined values as follows.

N = number of splits (also strips)
$Θ$ = 360° divided by the number of splits = 360° ÷ N (1)
$Θ_1 = Θ ÷ 2$ (2)
w = width of the strip (as specified)
h = height of the strip (as specified)

From the above values, we should then be able to calculate the bamboo dimensional properties below:

$t_u = r_o - r_i$ (3)
$t = t_u + t_p$ (4)
$Ø = r_o \times 2$ (5)

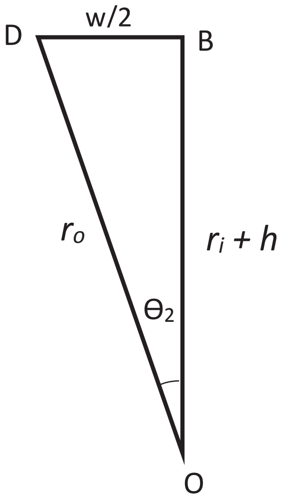
Referring to the OAC triangle,



$$\tan\Theta_1 = \frac{\left(\frac{w}{2}\right)}{r_i}$$

$$\text{Thus, } r_i = \frac{w}{2\tan\Theta_1} \qquad (6)$$

Now, look at the OBD triangle,



$$\tan\Theta_2 = \frac{\left(\frac{w}{2}\right)}{(r_i + h)}$$

$$\text{Thus, } \Theta_2 = \tan^{-1}\left[\frac{w}{2(r_i + h)}\right] \qquad (7)$$

$$\sin\Theta_2 = \frac{\left(\frac{w}{2}\right)}{(r_o)} \qquad (8)$$

$$\text{Thus, } r_o = \frac{w}{2(\sin\Theta_2)}$$

ALGORITHM VERIFICATION

Calculation

Let's calculate the minimum bamboo thickness (t) and diameter (Ø) that able to produce 16 strips of 15 mm × 5 mm.

1. Number of splitting N is 16,
   a. Using (1), calculate the angle of split

      $\Theta = 360^o \div 16 = 22.5^o$

   b. From (2), find Θ_1

      $\Theta_1 = \Theta \div 2 = 11.25^o$

2. Strip final dimension → $w = 15$, $h = 5$,
   a. Using (6), find the bamboo inner radius

      $$r_i = \frac{15}{2(\tan 11.25)} = 37.7 \text{ mm}$$

   b. Plug r_i in (7), find Θ_2

      $$\Theta_2 = \tan^{-1}\left[\frac{15}{2(37.7 + 5)}\right] = 9.96^o$$

3. Substitute Θ_2 into ⑧, calculate the bamboo outer radius,

$$r_o = \frac{w}{2(\sin 9.96)} = 43.36 \text{ mm}$$

4. Using ③, find the thickness of bamboo usable part,

t_u = 43.36 – 37.7 = 5.65 mm

5. Finally, calculate the bamboo diameter using ⑤,

Ø = 43.36 × 2 = 86.7 mm

6. Calculate the total thickness t of the bamboo wall by substituting t_u and t_p into ④. The value of pith ring thickness t_p should be decided by the bamboo product manufacturers. There are not many bamboo research literature that give the value of t_p. However, it can be estimated by looking at the photographs of anatomical features in papers such as by Yin et al. (2016) and Liese (1998), and using the value measured by Brea & Zucol (2007). For the sake of this mathematical algorithm development, the t_p values are set as 0.0 mm (no pith), 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm. Therefore, using ④,

$t_{(p0.0)}$ = 5.65 + 0.0 = 5.65 mm, $t_{(p0.5)}$ = 5.65 + 0.5 = 6.15 mm,
$t_{(p1.0)}$ = 5.65 + 1.0 = 6.65 mm, $t_{(p1.5)}$ = 5.65 + 1.5 = 7.15 mm
$t_{(p2.0)}$ = 5.65 + 2.0 = 7.65 mm

7. The above calculation are repeated for N = 3, 4, 5,…, 38, 40, 42 using MS Excel. The results are as shown in Table 1 and Figure 4.

Table 1 Number of splitting (N) and the corresponding bamboo diameter, wall thickness and pith ring thickness for maximum 15 mm × 5 mm strips recovery.

N	Ø (mm)	Pith ring thickness (t_p) (mm)									
		No pith (0.0 mm)		0.5 mm		1.0 mm		1.5 mm		2.0 mm	
		t (mm)	r_i (mm)	t (mm)	r_i (mm)	t (mm)	r_i (mm)	t (mm)	r_i (mm)	t (mm)	r_i (mm)
3	23.94	7.64	4.33	8.14	3.83	8.64	3.33	9.14	2.83	9.64	2.33
4	29.15	7.08	7.50	7.58	7.00	8.08	6.50	8.58	6.00	9.08	5.50
5	34.12	6.74	10.32	7.24	9.82	7.74	9.32	8.24	8.82	8.74	8.32
6	38.98	6.50	12.99	7.00	12.49	7.50	11.99	8.00	11.49	8.50	10.99
7	43.80	6.32	15.57	6.82	15.07	7.32	14.57	7.82	14.07	8.32	13.57
8	48.59	6.19	18.11	6.69	17.61	7.19	17.11	7.69	16.61	8.19	16.11
9	53.36	6.08	20.61	6.58	20.11	7.08	19.61	7.58	19.11	8.08	18.61
10	58.13	5.98	23.08	6.48	22.58	6.98	22.08	7.48	21.58	7.98	21.08
12	67.66	5.84	27.99	6.34	27.49	6.84	26.99	7.34	26.49	7.84	25.99
14	77.19	5.74	32.86	6.24	32.36	6.74	31.86	7.24	31.36	7.74	30.86
16	86.72	5.65	37.71	6.15	37.21	6.65	36.71	7.15	36.21	7.65	35.71
18	96.25	5.59	42.53	6.09	42.03	6.59	41.53	7.09	41.03	7.59	40.53
20	105.78	5.53	47.35	6.03	46.85	6.53	46.35	7.03	45.85	7.53	45.35
22	115.31	5.49	52.16	5.99	51.66	6.49	51.16	6.99	50.66	7.49	50.16
24	124.84	5.45	56.97	5.95	56.47	6.45	55.97	6.95	55.47	7.45	54.97
26	134.38	5.42	61.77	5.92	61.27	6.42	60.77	6.92	60.27	7.42	59.77
28	143.91	5.39	66.56	5.89	66.06	6.39	65.56	6.89	65.06	7.39	64.56
30	153.45	5.37	71.36	5.87	70.86	6.37	70.36	6.87	69.86	7.37	69.36
32	162.99	5.35	76.15	5.85	75.65	6.35	75.15	6.85	74.65	7.35	74.15
34	172.53	5.33	80.94	5.83	80.44	6.33	79.94	6.83	79.44	7.33	78.94
36	182.07	5.31	85.73	5.81	85.23	6.31	84.73	6.81	84.23	7.31	83.73
38	191.61	5.29	90.51	5.79	90.01	6.29	89.51	6.79	89.01	7.29	88.51
40	201.15	5.28	95.30	5.78	94.80	6.28	94.30	6.78	93.80	7.28	93.30
42	210.70	5.27	100.08	5.77	99.58	6.27	99.08	6.77	98.58	7.27	98.08

From Table 1, one could find that strips of 15 mm × 5 mm are able to be produced from bamboo with diameter as small as 24 mm to as large as 211 mm and beyond (possibly for a very large diameter bamboo such as *Dendrocalamus giganteus* or giant Burma bamboo). From the smallest diameter bamboo, only 3 pieces of strips can be made, provided that the wall thickness is more than 7.6 mm. On the other hand, the 211 mm in diameter bamboo with wall thickness of 5.3 mm could produce 42 pieces of strips. Another information provided by Table 1 is that thicker bamboo wall is required when processing smaller diameter bamboo.

Now, let's proceed to answer the second question mentioned in the fourth paragraph of this paper. From Figure 4, the diameter range (100 to 120 mm) falls between N of 19 to 23. In other words, to maximize the recovery, 5 different splitters with N equals to 19 (for Ø = 100 mm), 20 (100 ≤ Ø < 105 mm) , 21 (105 ≤ Ø < 110 mm), 22 (110 ≤ Ø < 115 mm) and 23 (115 ≤ Ø < 120 mm) should be used. However, in a real bamboo product manufacturing factory, having too many splitters may not be economically practical. We may then opt to use only two splitters, i.e., 20 and 22. If this is the case, then it is recommended that the bamboo poles are segregated into 2 diameter groups: 100 ≤ Ø < 110 mm and 110 ≤ Ø < 120 mm, to be split into 20 and 22, respectively. The 7 mm wall thickness with t_p assumed value of 1.0 mm should be sufficient.

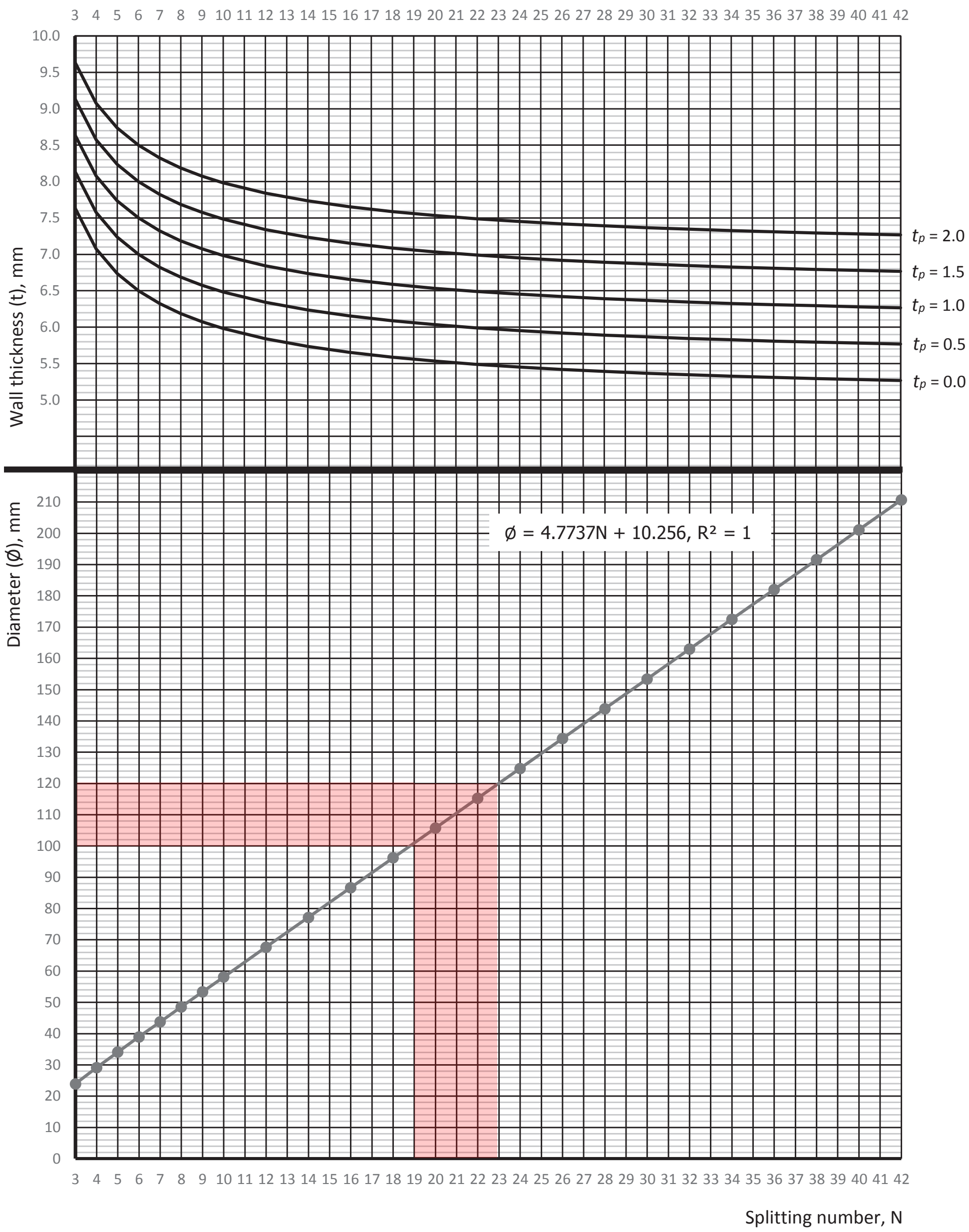
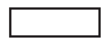


Figure 4 Optimised splitting number - bamboo diameter - wall thickness configuration for maximum recovery of 15 mm × 5 mm strips.

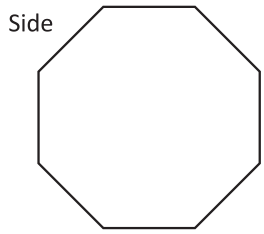
Measurement by AutoCAD

AutoCAD software (Onstott 2016) has a feature that allows the user to measure distances between points in the drawings. The following steps were developed to enable verification of the bamboo splitting algorithm.

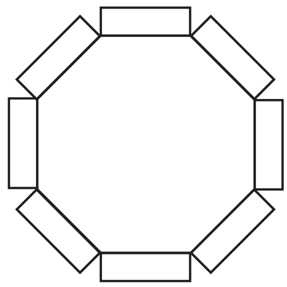
STEP 1- Draw a ractangle with a known width and height values, i.e, 5 mm × 15 mm.



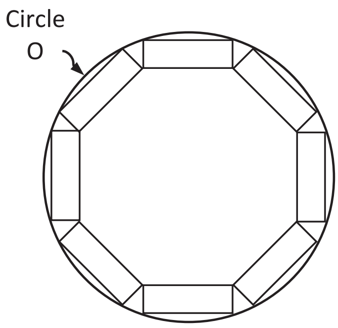
STEP 2 - Draw a Polygon with a number (N) of sides, e.g., 8.



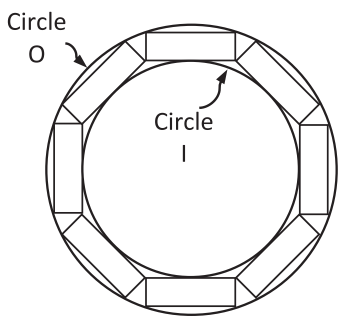
STEP 3 - Place the rectangle on the top side of the polygon, adjusting the polygon size so that the length of rectangle bottom is equal to the length of the polygon top side. Repeat for the rest of the sides.



STEP 4 - Draw a circle O with its circumference just barely touching the outer edges of the rectangles.



STEP 5 - Draw another circle I with its circumference just barely touching the inner sides of the rectangles.



STEP 6 - Measure diameter (Ø) of outer circle and radius of inner circle (r_i) and the wall thickness (t) (difference of radial distance between outer and inner circle) of the final bamboo splitting drawing (Figure 5).

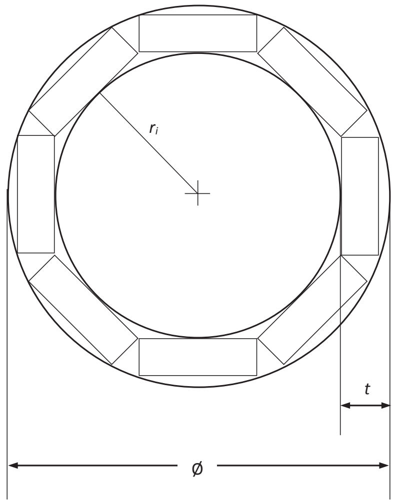


Figure 5 Final AutoCAD drawing of bamboo splitting and the measurements made

Bamboo splitting drawings were produced in AutoCAD for the following splitting number N, namely, 5, 8, 16 and 24. The selected dimensions, i.e., diameter, thickness and internal radius were measured and the values are as shown in Figure 6. These values are identical with those calculated by the bamboo splitting algorithm (see Table 1), thus verifying the validity of the method.

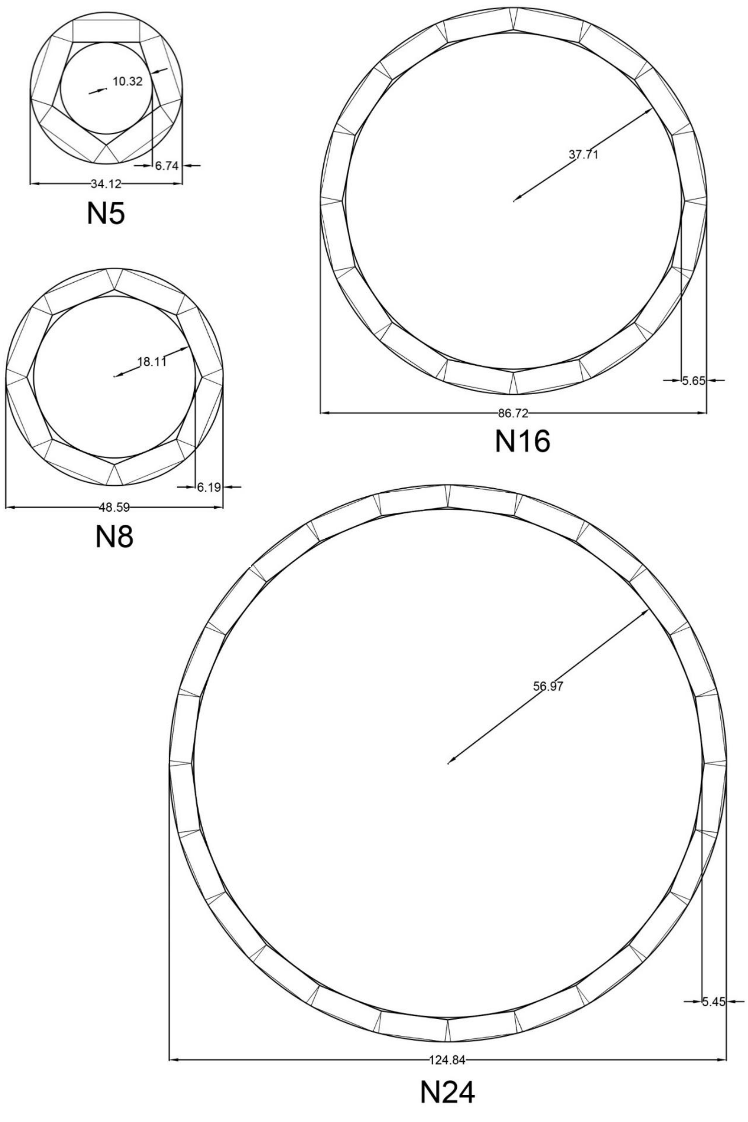


Figure 6 Actual AutoCAD print-outs of the bamboo splitting model for N equals to 5, 8, 16 and 24

CONCLUSION

The mathematical algorithm for optimised bamboo splitting has been successfully developed and could be used as a means to estimate the maximum number of splitting allowed for a bamboo pole with a known dimensions (diameter and wall thickness) for making strips and *vice-versa*. Since the algorithm is based on a perfect circle, but in reality some bamboo poles are not; it is recommended that the bamboo product manufacturers use the smallest diameter and thickness values measured from the pole as the input for the calculations. The manufacturers should also decide wisely on the pith ring thickness value to prevent the weaker layer from being included in the strips. This algorithm could be applied for other strip sizes and for calculating the recovery too.

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A mathematical algorithm that describes bamboo pole splitting process to produce bamboo strips is disclosed. Using this algorithm, a manufacturer of bamboo products such as laminated bamboo strip lumber (LBSL) would be able to determine the maximum number of strips that can be produced from a bamboo pole with known diameter and thickness.

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