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Strategies to standardise bamboo for manufacturing process chains

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Abstract

The manufacturing challenges industry face need to be addressed in the multifaceted context of sustainability. In order to stay relevant and competitive the manufacturing industry is investigating several types of sustainable hybrid materials for structural components. Bamboo is a versatile plant with thousands of applications, but is produced in various shapes and sizes with different mechanical characteristics. Therefore, the objective of this study is to investigate strategies to standardise bamboo for manufacturing process chains. The treatments that bamboo must undergo in order to be used in high quality and resilient products were investigated. Sustainable and environmental friendly approaches to deal with pests and different drying methods of bamboo are discussed. Factors to be standardized are identified and strategies to standardize this in each phase before the manufacturing process chains are elaborated on. Benchmarking is done on the diameter and wall-thickness of the different tubes and an allowable variance is identified for each tube.

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Keywords: Standardisation of supply; Bamboo; Bamboo bicycle; Process chain development

1.Introduction

Bamboo is the most versatile and fastest growing plant on the earth. It has played an integral part in millions of lives for the past millenniums. In the last few decades it is exploited with renewed interest to serve as a substitute for timber [1]. This paper aims to serve as a stepping stone to further research on how to standardize this wonderful plant and increase the utilization of bamboo in the future. This paper is also a puzzle piece in a bamboo bicycle project [2].

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The fibres of bamboo grow unidirectional and are embedded in a lignin matrix. This makes bamboo a viable alternative to carbon fibre. The fibrous walls of bamboo are dividend in segments that contributes to the flexural strength and rigidity of bamboo, it also adds to the bamboo's résistance to impact. These segments help to dampen the vibrations caused by the road, while still providing a reasonable stiffness for a bicycle frame. The ultimate average tensile strength of bamboo is between 300-350 MPa. It has an average density of 0.4 (g/cm^3). Bamboo does not have any ray or knots like wood. This gives it the capacity to withstand more stress then wood, through the length of each stalk. Aluminium, a material commonly used to construct bicycles has an ultimate tensile strength of 310 MPa and an average density of 2.7 (g/cm^3). Thus concluding; bamboo has a higher strength-to-weight ratio than aluminium, which makes it a very good substitute for bicycle frames [3].

2. Problem statement

Bamboo like any other plant can differ from plant to plant or culm to culm with regards to diameter and wall thickness. Certain acceptable variances must be established for each of these varying factors. These allowable variances will be established for each of the bamboo components of the bicycle. Another issue that must be discussed is shrinkage and the prevention of splitting which is important to consider when using bamboo for manufacturing. Figure 1 shows certain areas of concern on the bicycle frame. Standardising strategies must be identified and linked to these factors with regards to the level of influence it has on the factors.

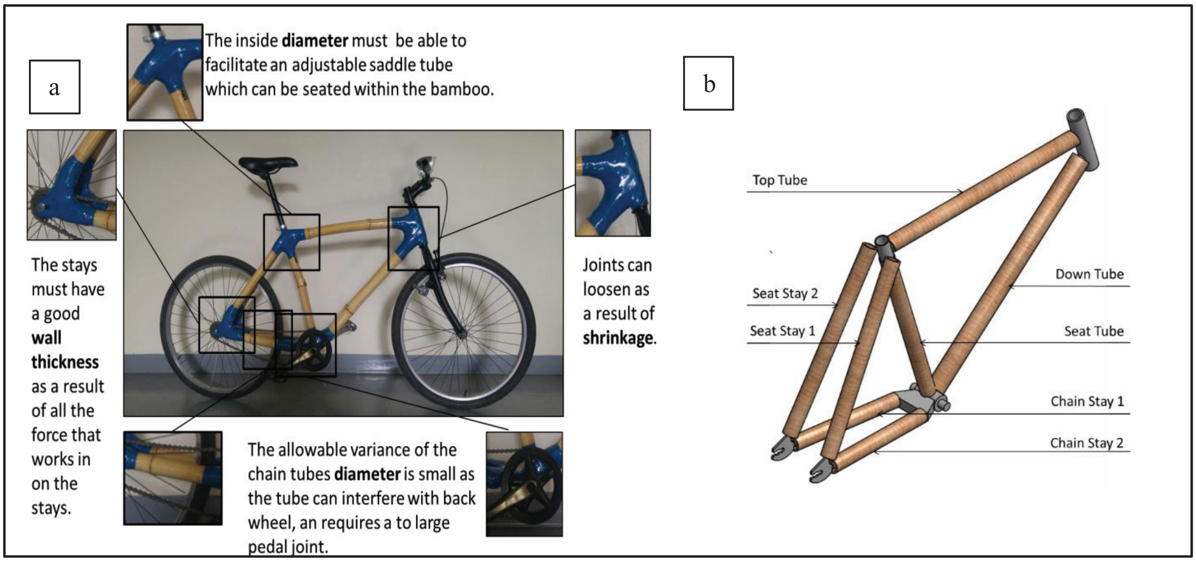

Figure 1. (a) Depicts the potential problems in the absence of standardisation; (b) the components of a bicycle frame.

3. Research objectives

- To benchmark the bamboo bicycle that was manufactured by Bamboo Bikes for Africa with regards to the shrinkage, diameter and the wall thickness with 3 other bamboo bicycles
- Developing a process chain for preparing bamboo for manufacturing of a bamboo bicycle
- Understanding the effect that each standardising strategy has on shrinkage, diameter and the wall thickness of the bamboo.

4. Research methodology

The methodology followed in constructing this article is depicted in figure 2. The problem arose as the team realized that there must be a means to standardise certain aspects of the bamboo in order to make it more useful for the bamboo bicycle production. The process chain that the bamboo follows before utilized for manufacturing was mapped. The factors that influence standardisation at each step were identified. Certain factors such as the diameter and the wall thickness were compared to that of other bamboo bicycle manufactures. These identified factors were then linked to strategies in each step of the process chain.

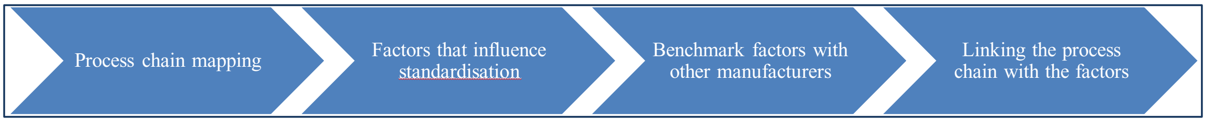

Figure 2. Methodology used to find strategies to standardise bamboo for manufacturing process chains.

5. Standardising the supply of bamboo

This section aims to establish strategies to aid in the standardisation process of sourcing the supply of bamboo before the primary manufacturing process chain commences. There are certain aspects in each of the following process steps that prevents the sourcing of bamboo from being standardised.

5.1. Growing the Bamboo

There are certain bamboo bike manufactures that cut bamboo in the wild (a source that is not cultivated), hence they do not pay attention to the growing of the bamboo. Large variation in diameter and height can be observed within different species. The lower the density of the culms the greater the diameter-at-breast-height (DBH) will be, but the lower the total biomass per unit area. A higher culm density will give a reduced DBH and a higher total biomass. This means that the culm density influences the diameter of the bamboo. It should be mentioned that the diameter of existing culms does not increase as it gets older. If bamboo is specially grown for bamboo bicycle production then the quickest growing time and most effective agricultural methods, which facilitates easy harvesting will be pursued [1]. An irrigation schedule will also be followed especially during the dry season.

Bamboo reach its maximum strength when it is mature. This depends from specie to specie but is usually from the age of 3 years. If bamboo is older than 6 years, it might have suffered damage caused by insects [1]. Lopez suggests that the location of the bamboo has an influence on the strength properties of bamboo [4]. Research done on *Dendrocalamus* showed that the best bamboo of this species grew in drier areas.

The only indigenous bamboo in South Africa is *Thamnocalamus tessellatus*. The Bamboo source in South Africa that can be utilized is *Bambusa balcooa, which* was introduced to the country in the 1660's for paper pulp production and has since been naturalized to South Africa's climate, although it's natural habitat is in more tropical climate areas [5]. The plant itself can reach a height of 12m to 20m and a diameter of 6 cm to 15 cm [6]. In some circles *Bambusa balcooa* is also referred to as giant bamboo [5]. This offers a unique challenge when it comes to bicycle manufacturing which generally requires thinner diameter tubes especially at the chain and seat stays at the rear section of the bicycle.

5.2. Cutting or harvesting the bamboo

Bamboo is harvested based on selection, and certain factors that are important to consider in the harvesting process are: the felling cycle; the intensity of the felling; the method of the felling and the transportation of the felled bamboo to the factory. As previously discussed, identifying mature bamboo is important. In year four, which is a good age to harvest, *Bambusa Balcooa* has the following characteristics. The culm sheath is absent, branches have less leaves, most of the auxiliary and secondary branches transform into thorn like structures. Thick branches are usually dead and shed, leaving dead scars on the culm. The culm has a smooth surface and is dark green. Black or rotten adventitious root ring can be present on the basal 1 to 2 nodes [1].

During the morning bamboo starts transporting starch from the roots to the leafs as a result of photosynthesis. Thus the best time to harvest bamboo is before sunrise from 12am and 6am, most of the starch is then in rhizomes at the roots. The following advantages arise from harvesting bamboo this way are: The bamboo is less attractive to insects, the bamboo is lighter for transporting purposes, the bamboo will dry faster.

The starch (sugar) content in bamboo is also high in the growing season; the best season for harvesting bamboo is after the rainy season. The culms will then be more resistant to biological degrading organisms [1].

5.3. Treating the Bamboo

Bamboo has less natural durability than most woods. This is as a result of certain chemicals that is absent in bamboo, but that occurs in most woods. The starch in the bamboo attracts beetles and fungi. Another factor that contributes to the bamboo's low natural durability is the hollowness of the bamboo. If an insect or fungi destroys 2mm of the outer layer of wood it is still in good condition. When it comes to bamboo 2 mm is the quarter of the thickness in some instances. The hollow tube in the inside the bamboo serves as a good hiding place for the agents of destruction [7].

Untreated bamboo typically has the following life, depending on the environment that it is in:1-3 Years in the open air and in contact with soil, 4-6 years when it is under cover and not in contact with soil and 10- 15 years under very good conditions. There exist chemical and non-chemical methods to treat bamboo. The non-chemical methods can be conducted by untrained villagers without technical equipment and with little cost. This non-chemical treatment can considerably increase the resistance against fungal and beetle attack. The real cost saving benefit of these methods with regards to long-term usability must be carefully evaluated [7].

Water- based chemical solutions are divided in non-fixing and fixing to the bamboo tissue and uses organic or inorganic salts. When the water from the solution evaporates the salts are left, which are either fixing or non-fixing. Non –fixing preservatives wash away in rainy conditions and are hence only suitable for use under cover in-doors or in dry conditions. There are different methods to apply chemical preservatives [1].

- Soaking or diffusion: The freshly cut culms are stripped of branches etc. and is cut to size and submerged in a water based solution.
- The vertical soak or diffusion method: The whole culm is filled with solution, except the lowest node, which is fractured later to drain the solution.
- Hot and cold treatment: The bamboo is heated, the air in the cells escapes and leaves a vacuum when the bamboo is cooled. This results in the preservative draining into the cells.
- Pressure treatment: The pressure treatment results in deep and uniform penetration.

5.4. Drying the bamboo

The drying of the bamboo is a step in the manufacturing process that enhances the structural properties and the desirable appearance. Two major drying methods are to be considered: air drying and kiln drying.

1. Air drying: The moisture is removed by exposing it to atmospheric conditions. Stacking bamboo upright dries the bamboo in half the time when compared to stacking them horizontally. The drying time can range from several weeks, to several months. It goes without saying that air drying is quite dependant on the weather. A moisture content below 12% is required [1].

2. Kiln drying: It is more efficient than air drying, the bamboo can be dried to the required moisture content in a much shorter time. Kiln drying produces high level results. It is a basic process of stacking bamboo culms or splits in a chamber where the air circulation and the temperature are maintained and controlled so that the moisture content can be reduced to the required level. Drying Schedules are used to control the temperature and the relative humidity to the dry the bamboo in the shortest possible time with the least occurrences of degrades. Each specie has a unique drying behaviour and therefore requires a unique schedule [1].

6. The factors to be standardized for bamboo sourcing

6.1. Diameter

6.1.1. Benchmarking on dimensions

The dimensions with regards to length depend on the size of the design, with other words from a small to a large bicycle frame as preferred by the customer. This can easily be cut to size and is not the main concern. The concern is the diameter and the wall thickness of the bamboo tubes. The bike frame consists out of 7 bamboo tubes. They are the following: 1 Top Tube the Down Tube, 1 Seat Tube, 2 Chain Stays and 2 Seat Stays. Table 1 displays the average diameters and wall thickness of the bamboo bicycle constructed with *Bambusa Balcooa* by Bamboo Bikes for Africa. This is compared to the dimensions given by other bamboo bicycle suppliers or the range where within the diameter of the bamboo bike tubes fall. The amount in brackets for bamboo bike Australia is the measurements of the bicycle that was used as an illustration. Note the significant difference in diameter that exits between the bicycle build by the research group and the bicycle frames provided by bamboo bicycle builders.

Table 1. The diameter at three different positions for each component of the bamboo bicycle constructed by the research group. It also includes the wall thickness of each component [mm].

Component	Bamboo bikes for Africa	Bamboo bikes for Africa wall thickness	Ghana Bamboo bikes **[8]**	Ghana Bamboo bikes wall thickness **[8]**	Bamboo Bike supplies **[9]**	Bamboo bike Australia (Measurements of bicycle used to illustrate) **[10]**
Unit	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
Top Tube	42.84	7.1	35-45	4-12	35-45	26-36(35)
Down Tube	50.66	5.6	35-45	4-12	35-45	35-45(41-43)
Seat Tube	39.87	7	35-45	4-12	35-45	40
Chain Stay 1	37.63	4.7	18-24	4-12	18-22	20-25(25)
Chain Stay 2	37.87	4.7	18-24	4-8	18-22	20-25(25)
Seat Stay 1	35.75	4.4	18-24	4-8	18-22	20-25(22)
Seat Stay 2	36.15	4.4	18-24	4-8	18-22	20-25(22)

6.2. Shrinkage

The shrinkage of bamboo can be 10 – 16 % in the diameter and 15-17% shrinkage in the wall-thickness [11]. If shrinkage occurs after the bicycle has been assembled, it can result in joints disengaging. This will lead to product failure. Shrinkage and splitting goes hand in hand, thus it is explained below.

6.2.1. The prevention of splitting

Bamboo can withstand great amounts of abuse however when bamboo fails it does so by splitting. It is very rare that a bicycle will crash hard enough for bamboo to split. The splitting can occur when the change in moisture content happens too fast. Bamboo must dry uniformly in the primary drying process. If it dries uniformly like losing moisture on one side it will contract unevenly. This will cause stress within the tube which in the end will lead to splitting. If moisture is allowed to enter into the vascular bundles even after the initial drying process it can once again cause splitting if it dries unevenly again. If variance in the moisture content of the bamboo takes place at a low tempo and not sudden or extreme, it can be repeated. This however is not how it will happen in a real world situation, thus bamboo must be properly sealed off from change in the moisture content, with a waterproof polyurethane varnish. The inside of the seat tube must receive special attention with regards to this as humid air can enter in and infuse the bamboo [12].

6.2.2. Thermal expansion

Bamboo has a high coefficient of thermal expansion, this means that it expands and contracts with changes in the temperature. This must be considered when designing the joints. [12]. Certain bamboo bicycle manufactures moved from carbon warps or lugs to more natural fibres like hemp in an attempt to solve this.

6.3. Wall thickness

The specific gravity, the tension and compression strength of the culm wall increase from the internal to the external surface of the culm. This basically means that the area of the culm wall with the lowest strength is the internal third of the culm. This has to do with the vascular bundles that gets smaller to the outside of the culm wall. Figure 3 illustrates images of a *Bambusa Balcoa* culm. The density of the bundles also increases when moving to the exterior of the bamboo. This must be considered when sanding the bamboo.

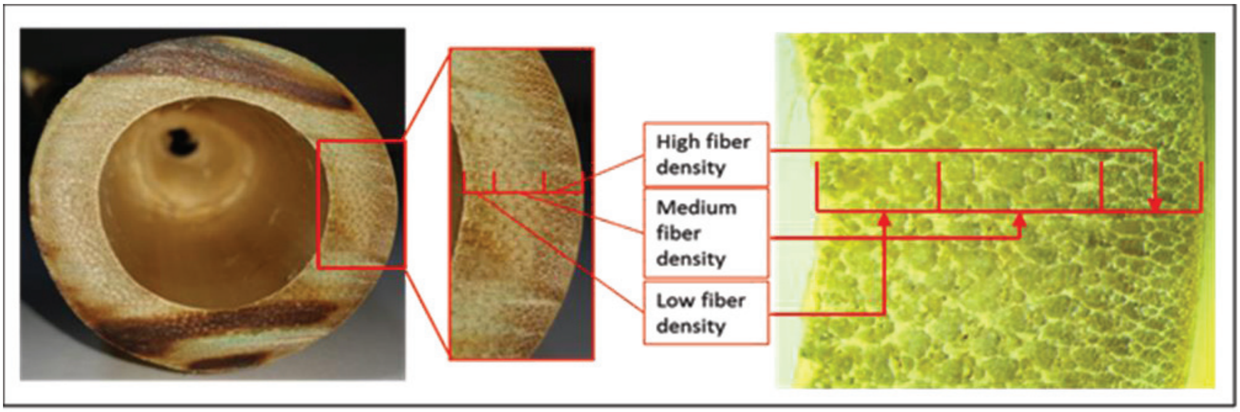

Figure 3: The diameter and the wall-thickness of a Bambusa Balcooa culm. Notice the hole in the diaphragm, inflicted for treatment.

The mechanical properties of the bamboo culm vary from the top to the bottom and culm can be divided into three equal sections. López [4] suggests that the top section has proven to be stronger with regards to compression and bending strength, than the central and lower parts. The central section has longer internodes and is the strongest with regards to tension. The lower section has the lowest values of mechanical properties. Garay et al. [13] contradict this and state that the basal region of the bamboo has the highest strength with a larger wall thickness and higher density. This is confirmed by another source which state that they utilise the bamboo they cut from the base of the bamboo culm to insure high fibre density and thick walls [9]. Bamboo culms with ticker walls are usually assumed to be able to handle more force than those with thinner walls [10]. It is suggested that the walls should be at least 3 mm thick and that the walls of the stays should be as thick as possible [14]. Beehive [15] suggests that the wall thickness should be around 5 mm and BNC [16] favours a wall thickness between 3 -5 mm for its mountain frame.

7. Experimental results and discussion

The findings are depicted in figure 4 and in table 2 and table3. Figure 4 shows the identified steps before the bamboo can be used for manufacturing. The different standardisation strategies are listed beneath each step. These listed strategies all effect the bamboo in some way or another. It can induce variation in bamboo. Thus if these can be standardised the bamboo will more usable for manufacturing. Table 2 depicts the effect that the strategies has on the diameter, wall thickness (or strength) and the shrinkage. The level of impact is classified as low, medium or high. Concluding on the benchmarking that has been done, table 3 displays the identified acceptable or allowable variances for the diameter and the minimum wall thickness for the given tubes of the bicycle.

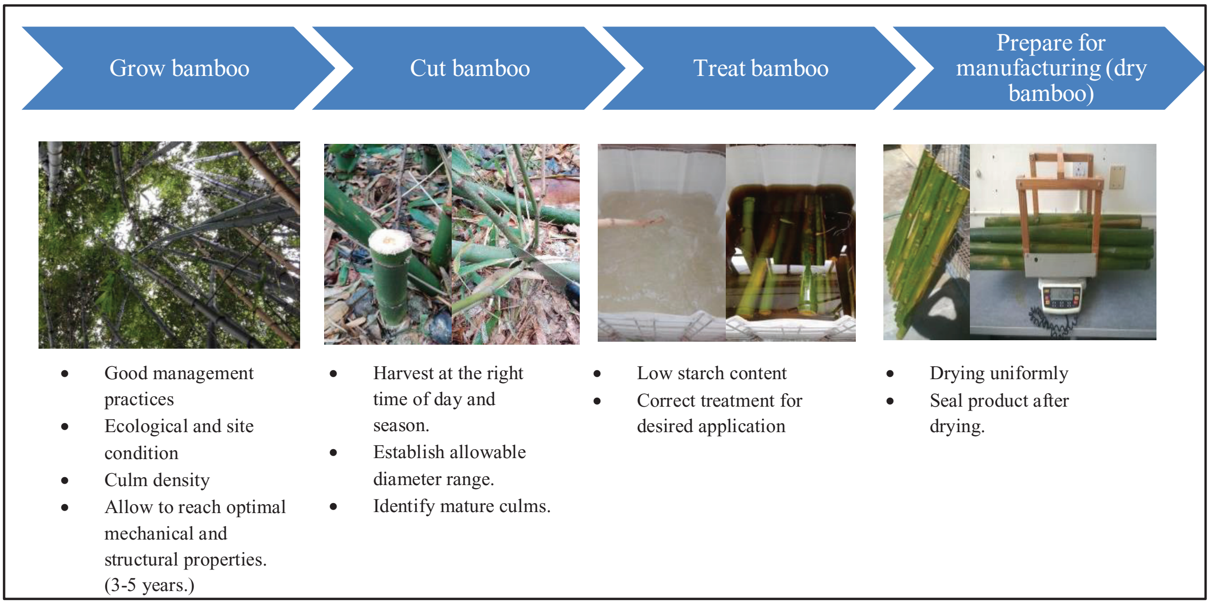

Figure 3: The four stages before the bamboo can be used for manufacturing and the accompanying standardising strategies.

Table 2: The standardising strategies are linked to the standardising factors.

Strategy	Diameter	Wall thickness	Shrinkage	Comment
1. Good management practices	Low	Low		
2. Ecological and site condition	Medium	Low		Drier conditions lead to a smaller diameter [4].
3. Culm density	High	Medium		The density of the culms influences the diameter [1].
4. Allow to reach optimal mechanical and structural properties. (3-5 years.)		Medium		The age has an effect on the primary tissue, which influences the strength of bamboo [4].
5. Harvest at the right time of day and season.				This is related to the starch content which effects the preservation [1].
6. Establish allowable diameter range.	High			An allowable diameter variance for each tube.
7. Identify mature culms.		Medium		Bamboo reach their maximum strength when they are mature [4].
8. Low starch content				This effects the preservation of the bamboo.
9. Correct treatment for desired application				
10. Drying uniformly			Medium	If it dries uniformly like losing moisture on one side it will contract unevenly [12].
11. Seal product after drying.			High	Bamboo must be properly sealed off to prevent change in the moisture content [12].

Table 3: The identified allowable diameter and wall thickness for each component.

Component	Allowable diameter [mm]	Allowable wall thickness [mm]
Top Tube	35-45	5
Down Tube	35-50	5
Seat Tube	35-45	5
Chain Stays	20-30	4
Seat Stays	20-30	4

8. Conclusion

In the effort to make bamboo more usable for manufacturing there are certain aspects that can be standardised in each step up until manufacturing. These strategies influence key factors such the diameter, wall-thickness and the shrinkage, which is important for manufacturing. Allowable tube specifications were established for each tube of the bicycle. This will contribute to the Stellenbosch University's Bamboo Bikes for Africa project. This paper is the first paper in a series of papers on the journey of harnessing the full potential bamboo has to offer manufacturing in our current day and age.

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