Experimental Investigation of Parameters Impacting the Roughness of *Pinus elliottii* Wood

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The wood sanding process entails a small reduction in the dimensions of the workpiece in the course of modifying its surface morphology, which affects the aesthetics and the subsequent application of a coating. However, sanding is costly, partly because it is performed empirically without standardization. Therefore, this study analyzed the influence of sandpaper factors on the behavior of wood surface roughness for *Pinus elliottii*. A complete factorial experiment was performed, varying two types of abrasives, aluminum oxide and silicon carbide, in three grit sizes (80, 100, and 120), and three sandpaper conditions (new, semi-new, and worn). The tests were performed using a flat sander with a pneumatic circuit and monitoring system for data acquisition, which were analyzed through multiple Tukey tests. The results were organized in a consultation table that compared the combination of factors analyzed, informing whether they produced roughness of the wood equal to or distinct from each other. The results showed that new aluminum oxide sandpapers with grit sizes of 80, 100, and 120 produced roughness of the wood different from each other, while the carbide did not. Therefore, there is no need to trade or buy silicon carbide sandpaper in these grit sizes.

Keywords: Factorial experiment; Wood sanding process; Surface roughness of wood

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INTRODUCTION

Sanding is a manufacturing process employed in various industrial sectors, used for metallic, ceramic, polymeric, and composite materials such as wood. It is classified as an unconventional machining or abrasion machining, as sandpaper is a cutting tool formed by abrasive grains that do not present a defined geometry (D'yakonov 2014). The function of the abrasive grain is to remove excess material from the surface through friction carried out between the part and the grain, seeking to wear, polish, or clean the surface, contributing to the production of parts with superficial quality and dimensional precision (Koshin *et al.* 2011).

Among the industrial sectors, the sanding process is most applicable for timber, mainly for furniture manufacturers, panels, frame(s), and doors, to mitigate the damage caused during wood processing, reach the desired dimensions, and make it superficially homogeneous. Thus, sanding provides an ideal process for finishing a given product in as accurate and economical manner possible (Ratnasingam *et al.* 2002). According to Kiliç (2015), the use of the sander together with other wood surface treatment techniques, such as the use of circular saws and planers, are the most used machines in wood processing to carry out finishing processes.

Therefore, sanding is one of the most important steps for the wood processing industry, as it is a prerequisite for subsequent processes involving the application of varnish, paints, adhesives, glue, sealants, or even with the intention of improving the appearance of the wood used in the raw state, and receiving the application of colorless varnish to further highlight its visual aspect (Varasquim *et al*. 2012). However, wood sanding is treated empirically in industries, as it affects the quality and cost aspects of the timber sector due to the lack of standardization that reduces quality and increases costs, especially when it comes to sandpaper. Sandpaper is a material that quickly wears out, requiring continuous replacement, which is why it is one of the most expensive aspects of processing wood. Therefore, knowing how to handle the sandpaper properly, making the exchange or replacing it correctly, combined with considering the techniques that prolong the durability of the abrasive, is of great benefit to the wood industry. Such findings would result in energy saving, a reduction in the amount of sandpaper used, and the optimization of sandpaper setups, in addition to providing a superficial quality finish (Saloni *et al*. 2011).

Considering this scenario, and seeking to provide continuous improvement to the timber sector, this work was intended to analyze the influence of sandpaper parameters on the behavior of superficial roughness after the sanding process for *P. elliottii* wood. To do this, this study must answer the following question: how does sandpaper influence the value of the superficial roughness of wood with respect to the abrasive grit, particle size, and its condition (new, semi-new, or worn)?

To answer this question, a full factorial experiment was conducted, which is an experimental planning method that is widely employed in engineering to better understand the behavior of process factors, as well as its impact on product quality characteristics and process in analysis (Montgomery *et al*. 2000).

The complete factorial planning allows one to include all possible combinations of the factors in the experiment, allowing one to study the effects of various factors on a variable response of interest. This includes studying the graphs of interaction, which enables researchers to identify whether there is an interaction between the analyzed factors or whether they are independent. In this work, the factors are related to the characteristics of the sandpaper, and the variable response corresponds to the value of the roughness of the wood (Farooq *et al.* 2016).

The roughness profile constitutes geometric micro-irregularities that can be measured *via* means of medium roughness (R_a), whose value represents the arithmetic mean of the absolute values of the deviations found along the path of measurement on the surface (Xavior *et al*. 2017).

The values of R_a directly influence the quality of the wood's surface finish, because surfaces with smaller values allow a greater angle of contact on the surface. This reduces the quantity of products used for finishing and creates more resistant connections between the sanded surface and the adhesive, providing greater mechanical resistance to the product. However, ultra-soft or rough surfaces produce the opposite effect (Tiryaki *et al*. 2014). Thus, Kiliç *et al.* (2006) argue that analyzing the effect of surface machining techniques, including sanding, is important in controlling the quality of other subsequent processes, such as painting or bonding wood of two species.

Then, a second question arises: do the different combinations of sandpaper, in relation to the particle size, abrasive grain, and condition of use, produce equal or different roughness values?

To answer this question, it is necessary to perform multiple comparisons between averages, which are of great interest in applied research when the goal is to compare conditions. Among the most commonly used tests is the Tukey test, which is used in this work to specify which conditions either differ or do not differ statistically with each other (Thomas and Sinha 1991).

EXPERIMENTAL

Materials

For the performance of the sanding tests, Norton Saint-Gobain (Paris, France) and DEERFOS Co., Ltd. (Incheon, South Korea) brand silicon carbide and aluminum oxide sandpaper, respectively, were used. These sandpapers were properly air-conditioned and packed to meet the ideal conditions of use, according to the recommendation of the norm NBR 14960 (2003).

The wood used was a *P. elliottii* tree from a planted forest in the southeast of the state of São Paulo, approximately 40 years old, with a breast height of 50 cm and a basic and apparent density of 355.91 and 463.83 kg/m^3. The wood log was processed, obtaining 800 specimens in rectangular form, 54 mm long, 30 mm wide and 23 mm thick in the longitudinal, tangential and radial directions. The specimens were conditioned at a temperature of 40 ºC and maximum Relative Humidity of 70%, to stabilize the equilibrium moisture in 12% according to the norm NBR 07190 (1997). From the 800 test specimens, a random sample of 120 pieces was taken, which were sent to the sanding process.

Methods

Experimental procedure

A complete factorial planning was adopted to perform the sanding tests parallel to the fibers of the *P. elliottii* with the randomly distributed (tangential and radial) cutting planes. The sandpaper factors and levels are shown in Table 1.

Table 1. Factors and Levels Stipulated in the Creation of the Paper Sanding Table

Sanding Factors	Levels	Initials of Levels
Grit size	80	80
	100	100
	120	120
Types of abrasive	Silicon carbide	CA
	Aluminum Oxide	OX
Condition of use of sandpaper	New	C1
	Semi-new	C2
	Worn	C3

The new and worn sandpapers were tested using a 4340 tempered and tempering steel bar with 54 HRc hardness, during the 4- and 8-min times, respectively. For each combination, six repetitions were made, totaling 108 experiments. The 18 combinations used in the experiment are presented in Fig. 1.

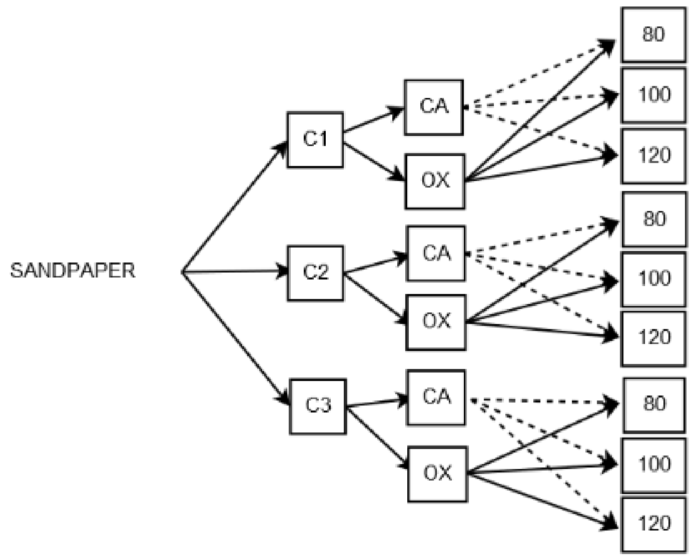


Fig. 1. Full factorial planning flowchart adopted for sanding tests

Structure of the test

To conduct the tests, a flat sander was connected to a database for the collection of information throughout the tests. The components are explained below and can be seen in Fig. 2.

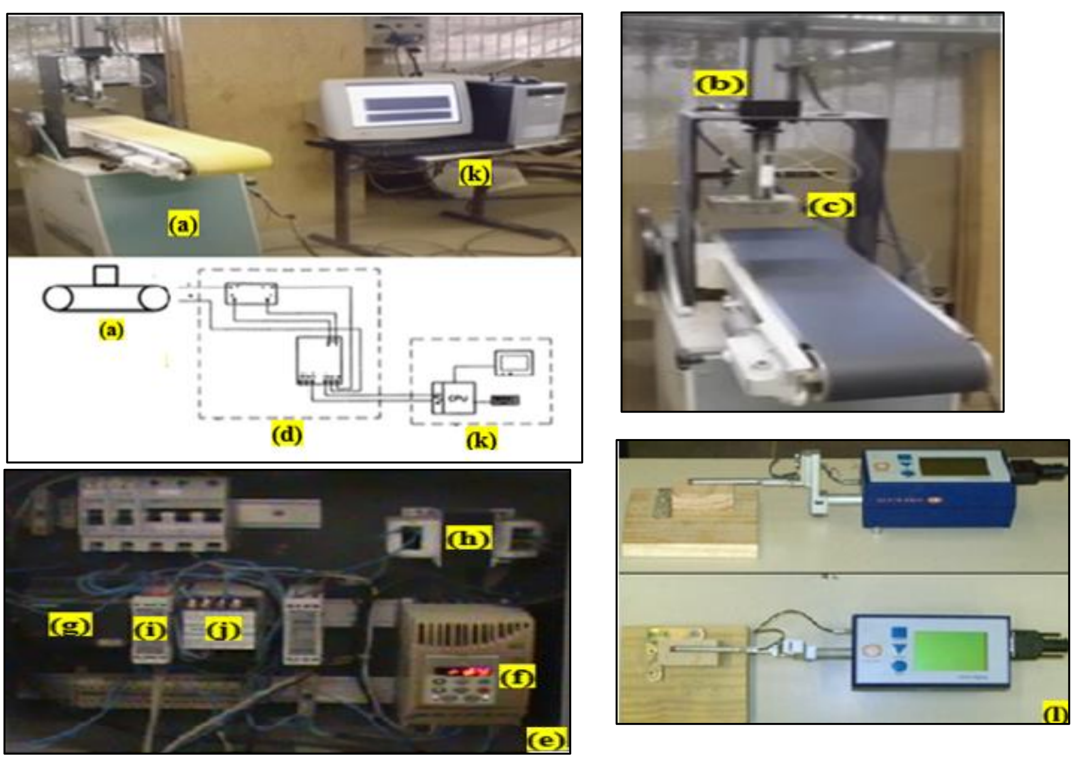


Fig. 2. The components of the test structure include a flat sander, monitoring system, and data acquisition, together with the roughness used in the sanding process. The diagram key is as follows: (a) Flat sander, (b) pneumatic cylinder, (c) sample fixing rod, (d) monitoring system, (e) electric panel, (f) frequency inverter, (g) power supply, (h) transformer, (i) load cell transducer, (j) current cell transducer, and (k) microcomputer with LabVIEW software installed

The structure of the test bench was composed of a flat sander model LFH-2 (Baldan, Guariba, Brazil) containing a bracket adapted with a pneumatic cylinder that has in its rod a structure to affix the samples of wood for sanding. This supports a pneumatic circuit to ensure the height of the sanded material, engage the piston responsible for exerting pressure on the 1 Kg/cm² part, and accurately control the 12 m/s cutting speed and the sample output on the sandpaper.

To capture the output variables, sound emissions, and vibration, a monitoring system was used that consisted of a variable source 0 to 30 direct current voltage (DCV) with three independent outputs from the power supply model MPL3303 (Minipa Co., Ltd., São Paulo, Brazil) for the feeding of vibration and emission modules Acoustic E, and an electric panel to drive the sander and control of the acquisition system. This panel contained one frequency inverter M line (WEG S.A., Jaraguá do Sul, Brazil) with a power supply voltage of 380 V and 3 ampere, for the control of the sander speed. Additionally, the panel had a power supply (Siemens, Munich, Germany) with a 110 to 220 alternating current voltage input transformer with 24 DCV output for the load cell amp power supply, and a load cell transducer and current.

The monitoring of the sanding process was carried out through the board (model: NI PCI 6220; National Instruments, Austin, United States), with the function of receiving the analog signals from the sensors and turning them into digital signals to be interpreted by the program developed in LabVIEW software (version 2014, National Instruments, Austin, TX, United States), installed on a microcomputer. The surface roughness measurements were obtained *via* a Taylor Hobson (Surtronic 25 +; Leicester, England) measuring rod with a spherical diamond cone palpation tip with a 2-μm tip radius.

Three distinct measurements were taken along the surface of each sanded sample, then the values of the average roughness (R_a) were obtained for each condition established using complete factorial planning. For the measurements, the robust Gaussian filter was established for the roughness profile and the sampling length (Le) or λ_c "cut-off" was 2.5 mm. After the experiments were conducted, the data were statistically analyzed by the software R (version 3.4.1, Auckland, New Zealand), in relation the analysis of variance (ANOVA), interaction graph, and Tukey test.

RESULTS AND DISCUSSION

Analysis of the Interaction Graphs

To analyze the significance of the factor interactions stipulated in the sanding process in regards to the roughness of the wood *P. elliottii*, the analysis of variance (ANOVA) was employed, and the results can be seen in Table 2.

Figure 3a illustrates the behavior of the interaction between the abrasive factors and the grit size of the sandpaper with respect to roughness. Crossing lines of the abrasive factors and particle size indicated that there was an interaction between these factors in the analysis of the roughness. In addition, it was possible to note that silicon carbide (CA) sandpapers provided higher surface roughness values when compared to aluminum oxide sandpaper (OX) in the grit sizes of 80 and 100. However, for the particle grit size 120, the behavior was the inverse, *i.e.*, CA sandpapers produced surfaces with less roughness than the OX sandpapers.

Table 2. ANOVA of the Factorial Planning of the Sanding Parallel to the Wood Fibers of the *Pinus elliottii*

Variables	Df	Sum Sq	Mean Sq	F value	Pr(> F)
Grit size	2	54.4	27.18	95.415	< 2 e-16*
Abrasive	1	0	0	0.005	0.943207
Condition of sandpaper	2	331.8	165.89	582.406	< 2 e-16*
Grit size: Abrasive	2	29.1	14.55	51.068	1.90 e-15*
Grain: Sandpaper condition	2	9.6	4.80	16.866	6.30 e-07*
Grit size: Sandpaper condition	4	12.9	3.21	11.283	1.95 e-07*
Grit size: Abrasive: Sanding condition	4	5.9	1.48	5.180	0.000855*
Waste	88	25.1	0.28		

* Significance of 5%

Through Table 2 it was noted that the interactions between the factors were significant, mainly between the particle size and abrasive used, whose Pr value (> F) was the smallest presented. Analyzing the significance of the factor combination, the researchers wanted to understand the behavior of their interactions in relation to the roughness, through the interaction graph that is presented in Fig. 3.

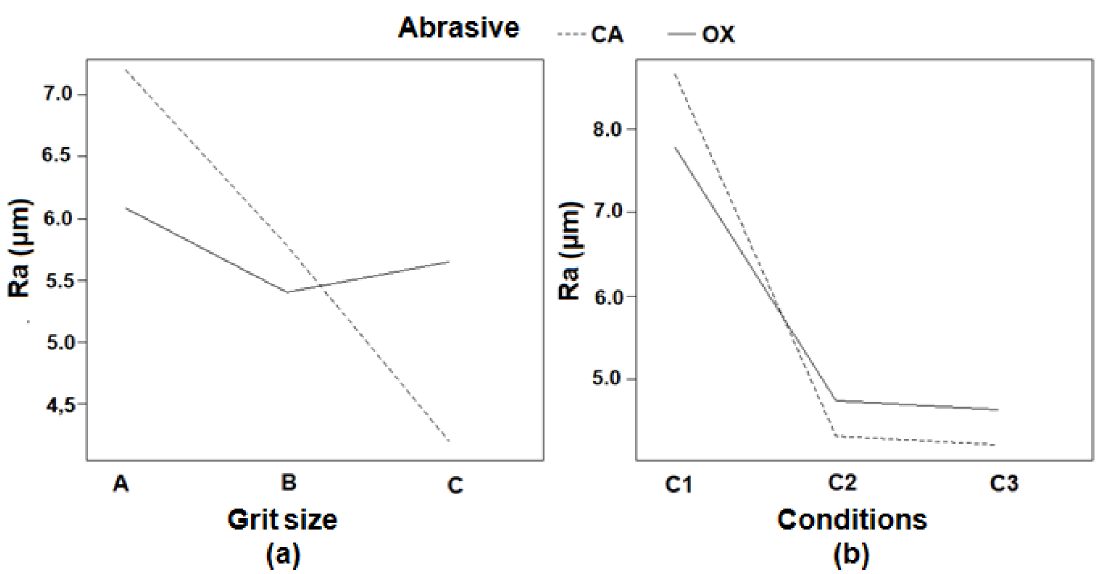


Fig. 3. Interaction graph in relation to the behavior of surface roughness during the parallel sanding of the wood *P. elliottii* to: (a) abrasive and grit size; (b) abrasive and condition

This finding was attributed to the fact that the silicon carbide grain has a pointed shape, creating deeper grooves, especially in thinner woods such as *P. elliottii*. However, due to the friability of the abrasive, it wears out faster, especially in larger numerical grades, in which its grains are smaller. On the other hand, the abrasive aluminum oxide because of the rounded shape, does not affect the surface of the wood so sharply, therefore, the least roughness in the sandpaper of 80 and 100 grit size. However, due to its higher mechanical strength and lower friability, it prolongs its cutting function, reducing its wear even in larger grades, resulting in greater roughness. It is for this reason that the new aluminum oxide sandpaper provided lower surface roughness, and when sandpapers having larger roughness were worn, when compared to the silicon carbide.

In Fig. 3b, the behavior of abrasive factors and sandpaper conditions is shown in relation to roughness. It should be noted that new AC sandpapers provided higher roughness values when compared with new OX sandpapers. However, when the sandpapers were frayed (conditions C2 and C3), a reversal of results occurred, as the AC sandpapers provided surfaces with less roughness than the OX sandpapers.

Explanation of the Operation of the Sandpaper Query Table: Result of Multiple HSD Tukey Test

The multiple HSD Turkey test was applied to determine which factors influenced the roughness of the collected wood samples.

As the comparison between the different sanding conditions garnered a range of results, only a few were selected and arranged in a sandpaper query table (Table 3). However, it is necessary to follow the following steps:

Step 1: Analyze the column "sanding factors" that was divided into groups, according to the factors of sandpaper, which can be equal (=) or different (≠), and the conditions of the new sandpaper (C1), semi-new (C2), and worn (C3).

Step 2: After choosing the group of "sandpaper factors" to analyze, one must check the possible combinations in the column "comparison between the sandpaper factors." If the ratios are equal (=), then one can use any sandpaper, as there will be no statistical difference between the values of the wood's surface roughness after sanding. If they are different (≠), the column "influence of factors in R_a" should be consulted.

Step 3: To analyze the column "influence of the sandpaper factors," just follow the symbology indicated by the arrows that show whether the sandpaper factors increase or decrease the roughness value. The information in this column was obtained through the graphical analysis of Figs. 3a and 3b, which can be consulted to estimate the roughness values of the work sandpaper condition.

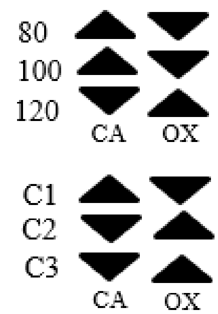
For example, the sandpaper will fit into Group 1 and Line 1 of Table 3 if there are respectively "sandpaper factors" (particle size = abrasive ≠ and new sandpaper (C1)) and "comparison of the sandpaper factors" (80 grit size: OX: C1 = 80 grit size: CA: C1). The authors discovered that 80 grit size sandpaper of both CA and OX can be used because the average roughness of the surface of *P. elliottii* will not be different, as it is represented in the column "influence of the factors in the R_a" *via* the symbol **(≈)**.

If one wants to know the approximate roughness value, one can simply refer to Fig. 3a, in which the approximate range of roughness is shown, which was between 5 to 7.5 µm. However, if the sandpapers fall into the second line of the same group, therefore 100 grit size: OX: C1 ≠ 100 grit size: CA: C1, the sandpapers will produce different a roughness.

Knowing which sandpaper was chosen in the process allows one to analyze the column "influence of factors in R_a" that provides the information *via* a scheme that the CA sandpaper of 100 grit size produces roughness greater than the OX sandpaper of 100 grit size.

To understand the approximate average roughness value produced by the sandpaper in these conditions, simply refer to Fig. 3b, which shows that CA produced close to 8.8 (µm) and OX 7.7 (µm).

Table 3. Sanding Paper Table for the Sanding Process Parallel to the Fibers of *Pinus elliottii* wood in Relation to Surface Roughness (R_a)

Group	Sanding Factors	Line	Comparison Between Sandpaper Factors	Influence of Factors on R_a
1	Grit size = Abrasive ≠ Sanding paper: new (C1)	1	80:OX:C1 = 80:CA:C1	≈
		2	100:OX:C1 ≠ 100:CA:C1	
		3	120:OX:C1 ≠ 120:CA:C1	
2	Grit size = Abrasive ≠ Sanding paper: semi-new (C2)	4	80:OX:C2 ≠ 80:CA:C2	
		5	100:OX:C2 ≠ 100:CA:C2	
		6	120:OX:C2 ≠ 120:CA:C2	
3	Grit size = Abrasive ≠ Sanding paper: worn (C3)	7	80:OX:C3 ≠ 80:CA:C3	
		8	100:OX:C3 ≠ 100:CA:C3	
		9	120:OX:C3 ≠ 120:CA:C3	
4	Grit size ≠ Abrasive = Sanding paper: new (C1)	10	120:OX:C1 ≠ 80:OX:C1	
		11	120:OX:C1 ≠ 80:OX:C1	
		12	120:OX:C1 ≠ 100:OX:C1	≈
		13	100:CA:C1 = 80:CA:C1	
		14	120:CA:C1 = 80:CA:C1	
		15	120:CA:C1 = 100: CA:C1	
5	Grit size = Abrasive = Sanding paper: C1 ≠ C2 ≠ C3	16	80:CA:C2 = 80:CA:C1	≈
		17	80:CA:C3 = 80:CA:C1	
		18	100:CA:C2 = 100:CA:C1	
		19	100:CA:C3 = 100:CA:C1	
		20	120:CA:C2 = 120:CA:C1	
		21	120:CA:C3 = 120:CA:C1	
		22	80:OX:C2 = 80:OX:C1	
		23	80:OX:C3 = 80:OX:C1	
		24	100:OX:C2 = 100:OX:C1	
		25	100:OX:C3 = 100:OX:C1	
		26	120:OX:C2 = 120:OX:C1	
		27	120:OX:C3 = 120:OX:C1	

Interpretation of the Sandpaper Consultation Results

Table 3, in relation to group 1, showed that the 80-grit size sandpaper, independent of the abrasive grit, produced the same surface finish (line 1). However, the sandpapers of 100 and 120 grit size (lines 2 and 3) differed, with AC of 100-grit size responsible for producing surfaces with greater roughness than those of OX. The opposite behavior was shown for the particle grit size of 120, as shown in the diagram indicated in the column "influence of the factors in R_a."

When analyzing groups 2 and 3 in Table 3, it was observed that the sandpapers in conditions C2 and C3 (semi-new and worn) differed statistically from the average of the roughness. The new and worn CA were responsible for producing less roughness and the OX sandpaper produced more roughness, as the column "influence of the factors in R_a" indicated.

For group 4 of Table 3 it was noted that all conditions differed except lines 13, 14, and 15, which showed that there was no need to exchange or buy silicon carbide sandpaper in the grit sizes of 80, 100, and 120, because if these are in the new condition, there will be no difference in the value of roughness in parallel sanding the fibers of *P. elliottii*. Therefore, it was more advantageous to use the OX sandpaper in the particle grit size of 80, 100, and 120, as these produced different average roughness values, as shown in lines 10, 11, and 12.

Group 5 of Table 3 shows that sandpaper factors with the same particle size and abrasive in different sandpaper conditions did not exhibit a difference between the roughness values, *i.e.*, semi-new and worn sandpapers produced the same surface finish as the new sandpaper. Therefore, frayed sandpapers (at a certain use limit) have the ability to sand similar to new sandpaper. It then becomes necessary to have control of the sanding process so that there is no wasting of usable sandpaper, contributing to a cost increase of the process.

Therefore, this research encourages the creation of tables like this, in an industrial perspective, varying the conditions of sanding in relation to different species of wood, sense of sanding, sizing or analyzing other factors like power, strength, vibration, removal rate, and among others. The aim of this research was to condense information that contributes to the standardization of the sanding process in the furniture industry, which is carried out empirically, and is generally not aware of the influence of sandpaper in the process, thus affecting the cost and quality of the process. Such necessity was shown decades ago by Ratnasingam *et al*. (1999), however it is still present.

For future research, it is recommended to construct consultation tables for other wood species to contribute to the standardization of the sanding process.

CONCLUSIONS

1. The grit sizes of 80, 100, and 120 aluminum oxide sandpapers generated profiles of different roughness. Such a differentiation based on grit size was not found in the case of silicon carbide sandpaper, as there was no significant difference between the grit sizes. Therefore, it is not necessary to make sandpaper changes during the process, nor buy them in different sizes. In addition, 80-grit aluminum oxide sandpapers produced a surface finish equal to the grit size of 80 sandpaper of silicon carbide.

2. Aluminum oxide sandpapers generated surfaces with less roughness than silicon carbide, in the grit sizes of 80 and 100, and larger in grit size of 120.
3. New or worn aluminum oxide sandpapers produced surface finishing with higher values of average roughness than silicon carbide sandpapers under the same conditions.
4. The value of the wood surface average roughness was not altered when the sandpapers were new, semi-new, and worn, up to a certain limit of usage, for the same particle size and even abrasive. If necessary, one must make an exchange of sandpaper, to avoid the disposal or unnecessary purchase of the material.
5. Finally, the guide table for consultation of sandpapers can be used to assist in the correct choice of sandpaper, contributing to the reduction in costs and increase of the quality in the surface finish of the wood.

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