Original scientific paper

A Plackett-Burman Design to Optimize Wood Chipper Settings

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Abstract

The wood-chipping process is affected by several factors, notably chipper settings and wood characteristics. It is often difficult to test all of these factors in a full factorial experimental plan, due to the large number of trials required. On the other hand, a screening design of the experiment makes it possible to manage a large number of variables in a small number of trials. Hence, this approach is used to test six factors, in order to optimize the productivity and chip quality of a drum wood-chipper. These factors are: feeding speed, screen size, PTO-speed, wood species, wood moisture content, and wood diameter. Productivity was significantly affected by screen size, while chip quality was related to feeding speed, screen size, PTO-speed, and wood species. The results suggest that the optimal configuration can be achieved by adjusting feeding speed, the PTO-speed, and the wood species, as these settings maximize chip quality. Screen size requires further analysis, as larger sizes increase productivity but reduce quality, while the opposite is true for smaller sizes. Thus, the optimal screen size requires a consideration of costs and benefits that may change according to the retail price of premium and regular wood chips, and production costs.

Keywords: wood chips, screening designs, drum chipper, chip quality, productivity

1. Introduction

Wood-chips are the products obtained by the comminution of biomass. The International Organization for Standardization (ISO) describes them as »chipped woody biomass in the form of pieces with a defined particle size produced by mechanical treatment with sharp tools such as knives« (ISO 17225-4 2014). Wood chips are usually 5 to 50 mm long, relatively thin (i.e. 2–5 mm), and with a sub-rectangular shape. The ISO standard (Part 4: Graded wood chips) defines the concept of wood chip quality on the basis of technical specifications, and describes four classes: A1, A2, B1, and B2, where A1 denotes the highest quality. Furthermore, there are additional voluntary certifications with more restrictive specifications. For example, the AIEL (Italian AgroForEnergy Associations) proposes the biomass plus standard – based on the ISO17225-4 – with a quality class more restrictive than the A1, named A1+ class. The specific characteristics of this class are the following: moisture content lower than the 10% on fresh weight; ash content lower than the 1% on dry weight; a lower heating value higher than 16 MJ kg^{-1}; a bulk density higher than 150 kg m^{-3}; and some particle size requirements. Particularly, it consider A1+ chips with over than 60% – by weight – of particles in the range between 3.15 mm and 16 mm in length; less than 1% under 3.15 mm long; less than 5% longer than 16 mm, and no chips longer than 31.5 mm allowed. The particle size distribution is considered of particular importance in this standard since it affects storage, durability and fuel handling efficiency (Jensen et al. 2004). It also impacts the product drying phase (Lu et al. 2010), and combustion efficiency (Hartmann et al. 2006).

The comminution of wood into small pieces can be done with two groups of machines: chippers and grinders. As described by Pottie and Guimer (1985), grinders use blunt tools to comminute the wood material. Although they are less sensitive to wear due to contaminants, they produce a rather coarse product (Strehler 2000). Chippers use sharp knives to slice the wood, and the resulting chips are both cleaner and better-quality (Spinelli et al. 2011a). The chippers in most widespread use are disc and drum machines.

Most research has found that both – appropriately used – produce high-quality wood-chips (Eriksonn et al. 2013, Manzone and Balsari 2015). In contrast, Spinelli et al. (2013) found that operators report greater chip uniformity in disc, compared to drum machines. However, flexible materials that are fed into disc chippers can pass through uncomminuted and in this case, operators prefer drum chippers. Finally, disc chippers are more energy-efficient, while drum chippers have higher productivity (Spinelli et al. 2013).

The relationship between wood-chip quality, chipper settings, and wood characteristics has been widely described in the literature. Research has particularly focused on the size of the wood chip and wood parameters (i.e. tree parts, tree species, and wood moisture content), chipper type (Spinelli et al. 2005), and chipper configurations such as knife settings and screen type (Nati et al. 2010). However, a widespread finding is that the decrease of the size of chips produced usually decreases productivity (Facello et al. 2013).

The experiments presented in the literature typically assess the relationship between various physical factors (i.e. related to the machine or wood) and chipper performance (i.e. productivity and wood chip quality). However, these experiments usually test only one, or a few, variables at a time. For instance, two interesting studies tested the effect of three factors at two levels with five or six replicates. These studies required 40 and 48 trials, respectively (Spinelli et al. 2016, Spinelli et al. 2012). Performing so many trials is time-consuming and expensive (Antony 2014). This poses a problem for researchers, as a large number of factors affect chipper performance, and it is very difficult to include all factors in a single experimental plan. Furthermore, it is often difficult to understand the importance of each factor with respect to the others and therefore, which to select to optimize the system. Against this background, this paper aimed to find the optimized settings (in term of productivity and wood chip particle size) in actual operative conditions for a high-quality wood-chips production. Both the chipper settings and the wood characteristics were considered as variables. The method uses an experimental design that simultaneously tests a large number of variables. Specifically, Plackett-Burman screening design was used to test, with eight trials, the effect of seven factors at two levels on chipper performance.

2. Material and Methods

2.1 Trials

Trials were conducted during spring 2017 at Villa Basilica, Italy (43°92 N, 10°65 E) on trees grown and cut in Villa Basilica. Whole trees without roots (*Castanea sativa* Mill., 1768, and *Pinus nigra* J.F. Arnold, 1785) were used during the tests. A Gandini CT40-75 drum chipper was powered by a tractor with power take-off (PTO) of 154 kW (New Holland, T7.210). Productivity was assessed as the weight of processed wood after 15 minutes. Chips were classified using the ISO 17225-4 (2014) norm. The forest consortium that hosted the trials has two target products: a premium-quality wood chip that meets the A1+ specifications; and the remainder (i.e. regular chip quality). The productive process of premium-quality wood chip mainly consists of three phases: comminution, sorting, and drying. The trials regard the comminution step, where the highest amount of target-sized chips (i.e. between 3.15 mm and 16 mm) have to be obtained. The other requirements to match the A1+ specifications are adjusted during the following steps, but these steps fall outside the scope of this paper. At the time of the trials, high-quality wood chips could be sold at 155 € t^{-1}, while regular quality chips were sold at 65 € t^{-1}. The »best« chipper settings were chosen as those that maximized the income for the forest consortium.

2.2 Experimental design

A Plackett-Burman screening design (or $2^{(7-4)}$ fractional design) was adopted. This design made it possible to test seven factors at two levels using eight trials. The chosen variables and their settings for the two levels are shown in Table 1, while the combinations used in the eight trials are shown in Table 2. Two feeding speeds (fast/ slow) were tested, and these were obtained by opening and closing valves operating the feed rollers. When the feeding rollers were left to spin freely, the feeding speed was 0.50 rad s^{-1} and 0.25 rad s^{-1} fast and slow trials, respectively. Two PTO-speeds were also tested, namely 99.5 rad s^{-1}, and 83.8 rad s^{-1}. Three out of six factors were referred to the material that is chipped: wood specie, moisture content and diameter. The chipped material was whole trees without root, and all the characteristics other than the previously mentioned were kept as constant as possible. Finally, a dummy variable was added to reach the seven factors required to adopt a Plackett-Burmann design. Two replicates were performed, making a total of 16 trials. Trials were performed in a completely randomized order. The other operational factors that could influence productivity and particle size were kept as constant as possible. For example, all the trials were conducted by the same operator, and the chipper was continuously fed by a conveyor belt ensuring a constant load frequency. The knife blade was the same

Table 1 Tested factors with maximum (+) and minimum (–) values

	+	–
Feeding speed	Fast	Slow
Screen size, mm	40	25
PTO-speed, rad s^{m-1}	99.5	83.8
Moisture content, %	>40	<40
Wood species	Chestnut	Pine
Wood diameter, cm	>25	<25

Table 2 Settings of tested variables during trials

Feeding speed	Dummy variable	Moisture content	Wood diameter	Screen size	Wood species	PTO-speed
+	–	–	+	–	+	+
+	+	–	–	+	–	+
+	+	+	–	–	+	–
–	+	+	+	–	–	+
+	–	+	+	+	–	–
–	+	–	+	+	+	–
–	–	+	–	+	+	+
–	–	–	–	–	–	–

»+« represents the upper bound, while »–« is the lower bound

Table 3 ANOVA analysis of the effect of the six variables on chipper productivity

	Df	Sum Sq	Mean Sq	*F* value	Pr (>*F*)	
Wood species	1	2.52	2.52	1.152	0.311082	
Moisture content	1	1.27	1.27	0.578	0.466405	
Wood diameter	1	4.31	4.31	1.968	0.194186	
Screen size	1	59.24	59.24	27.062	0.000562	***
Feeding speed	1	1.7	1.7	0.777	0.40091	
PTO-speed	1	0.25	0.25	0.114	0.742864	
Residuals	9	19.7	2.19			

Significance: 0.001 »***«; 0.01 »**«; 0.05 »*«; 0.1 ».«

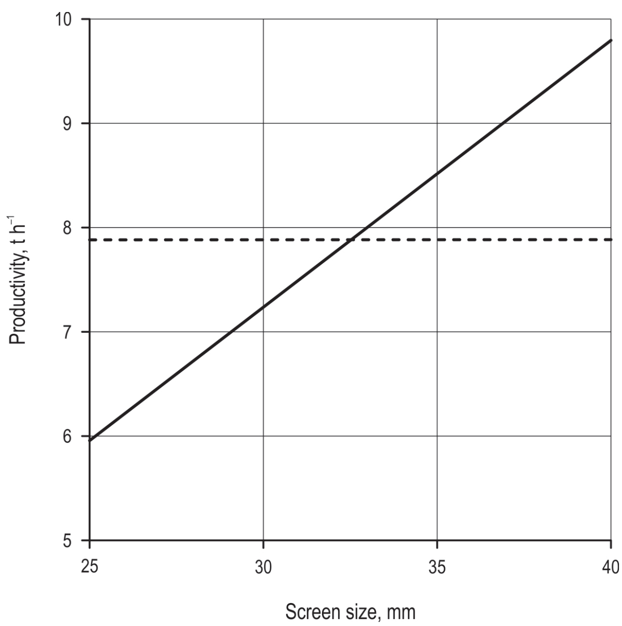

Fig. 1 Effect of screen size on productivity

for all the tests; the randomized order of the trials distributed randomly the error caused by the change in performance due to their wearing.

3. Results and Discussion

3.1 Chipper productivity

Table 3 shows the ANOVA results for chipper productivity. This clearly shows that screen size is the key factor in optimizing machine productivity. An increase in screen size (from 25 mm to 40 mm) increased average productivity from 5.96 t h^{-1} to 9.81 t h^{-1} (roughly 64%, Fig. 1). Very little impact was found for the other factors. For instance, the *F*-value of screen size was 59.24, while the second factor was the diameter of the wood with an *F*-value of 4.31 (roughly 14 times smaller).

The effect of screen size on productivity is well-known in the literature and many papers describe a positive relationship (Eliasson et al. 2015, Kons et al. 2015). Some other+ tested factors relate to wood characteristics (Spinelli et al. 2016, Manzone and Balsari 2015, Spinelli and Magagnotti 2012, Spinelli et al.

7< n747492011b) and chipper settings (Spinelli et al. 2016, Spinelli and Magagnotti 2012, Nati et al. 2010). However, these factors were not found to be significant in our tests. In our study, only one out of six factors significantly impacted productivity, while the others showed a very limited impact. Therefore, despite earlier, conflicting studies, screen size is the only parameter considered in the optimization of productivity.

3.2 Wood-chip quality

The trails aimed to determine how to configure the machine in order to produce the most high-quality wood chips in term of particle size. For this reason, we divided the chips from each test into three size classes; undersized, target, and oversized. The ANOVA results are shown in Table 4. Feeding speed, screen size, and wood species had the greatest effect on the dimensions of chips. In particular, screen size had a significant effect on all size classes, while feeding mode and wood species affected both the target class and the oversize class. Undersized significantly decreases from roughly 10% to 4% when the adopted screen size is changed from 25 mm to 40 mm. Fig. 2 shows, in a bar chart, the absolute values regarding the relative importance of all six factors on chip size. It highlights that feeding speed is crucial for the production of target-sized chips. In fact, an increase in feeding speed from slow to fast led to a dramatic reduction (from 64% to roughly 23%, respectively) in target-size chips. The data on oversized chips shows the opposite trend: as feeding speed increases, there is an increase in oversized chips (from roughly 30% to 70%) (Fig. 3). The wood specie (pine or chestnut) also affects the distribution of chip size. Chestnut produced a higher percentage of target-size chips compared to pine (Fig. 3).

3.3 Chipper optimization

During the tests, two different process optimizations were studied: the productivity and the yield in target chips (i.e. the ratio between the target chips and the total chips weight). According to Gasslander et al. (1979) the efficiency of the process could be improved at 4 different levels: physical level, machine level, cycle level, and operational level. Potentially, all the tested

Table 4 ANOVA analysis of the effect of six variables on chipper productivity

	Df	Sum Sq	Mean Sq	*F* value	Pr (>*F*)	
Undersized						
Wood species	1	2.89	2.89	1.969	0.1941	
Moisture content	1	1.32	1.32	0.901	0.3673	
Wood diameter	1	6.25	6.25	4.258	0.0691	.
Screen size	1	134.56	134.56	91.676	5.13E-06	***
Feeding speed	1	6	6	4.09	0.0739	.
PTO-speed	1	0.9	0.9	0.615	0.4531	
Residuals	9	13.21	1.47			
Target						
Wood species	1	1796	1796	24.167	0.000829	***
Moisture content	1	6	6	0.086	0.776217	
Wood diameter	1	33	33	0.441	0.523231	
Feeding speed	1	6786	6786	91.327	5.21E-06	***
Screen size	1	1386	1386	18.65	0.001937	**
PTO-speed	1	372	372	5	0.052171	.
Residuals	9	669	74			
Oversized						
Wood species	1	1938	1938	23.836	0.000869	***
Moisture content	1	14	14	0.175	0.685295	
Wood diameter	1	10	10	0.12	0.736891	
Feeding speed	1	7195	7195	88.489	5.94E-06	***
Screen size	1	2384	2384	29.317	0.000425	***
PTO-speed	1	407	407	5.006	0.052068	.
Residuals	9	732	81			

Significance: 0.001 »***«; 0.01 »**«; 0.05 »*«; 0.1 ».«

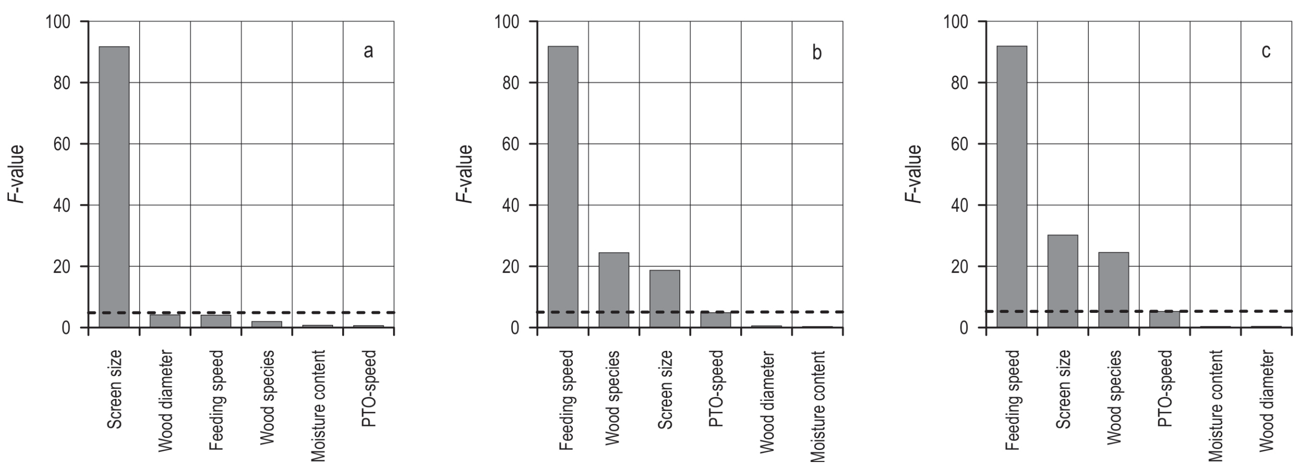

Fig. 2 Bar charts of factors affecting chip quality: a) undersize chips, b) target chips, c) oversize chips; dashed line represents the significance level ($p<0.05$)

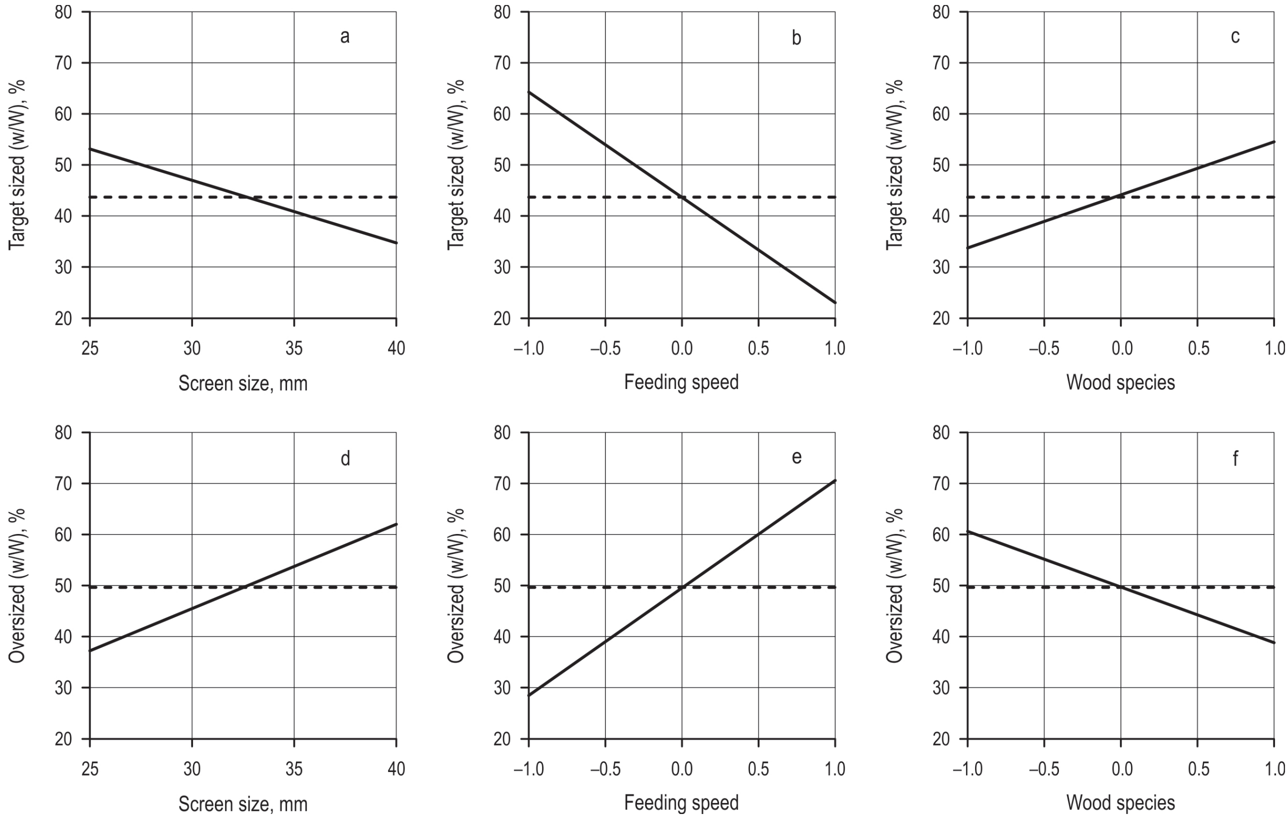

Fig. 3 Effect of screen size (a, d), feeding speed (b, e), and wood species (c, f) on chip quality (the Y-axis reports the amount of chips belonging to the specific class (i.e. target sized or oversized) in term of percentage by weight; feeding speed level –1 is the lower speed, while +1 is the higher; wood species +1 is chestnut, while –1 is pine)

factors could affect the process efficiency at machine level. For 3 out of 6 factors (PTO-speed, screen size and feeding speed), the machine efficiency can be increased by choosing the appropriate setting directly on the machine. For the remaining 3 wood-related factors (moisture content, wood species and wood diameter), there are not machine regulations to increase the chipper efficiency. However, the increase in process efficiency could be achieved at cycle level (i.e. in term of work organization) for these factors.

The data suggests that the optimal chipper settings seem to be a low feeding speed, and chestnut wood. These settings increase wood chip quality without affecting productivity. On the other hand, the choice of screen size requires a calculation in term of profitability. A smaller screen size produces, on average, 52.79% of high-quality chips, with the remainder being low quality. On the other hand, the bigger screen size produces, on average, 34.18% of high quality chips. At current prices, labor costs, and fuel costs the 25-mm screen optimizes production. However, the choice of the optimal screen size may change over time as a function of the price of wood chips and costs (i.e. labor and fuel).

3.4 Limitations of the fractional design approach

The adopted approach makes it possible to evaluate a large number of variables with a small number of tests. In particular, it makes it possible to optimize the settings of chipping process in order to maximize

Table 5 Confounding variables

Feeding speed	Main + Wood species x Screen size + Moisture content x PTO-speed + HOI *
Screen size	Main + Wood diameter x PTO-speed + Wood species x Feeding speed + HOI
PTO-speed	Main + Moisture content x Feeding speed + Wood diameter x Screen size + HOI
Moisture content	Main + Wood species x Wood diameter + Feeding speed x PTO-speed + HOI
Wood specie	Main + Moisture content x Wood diameter + Screen size x Feeding speed + HOI
Wood diameter	Main + Wood species x Moisture content + Screen size x PTO-speed + HOI

* Higher Order Interactions

production value based on eight trials, rather than 64. However, there are several limitations. Specifically, it is a resolution III design (Antony 2014), which means that the main effects may be confounded with two-factor, and higher-order interactions. This pattern is reported in Table 5. Thus, the adoption of this experimental design requires the assumption that interactions between variables have little impact on the process, or can be confirmed by further tests.

4. Conclusions

The fractional factorial experimental design reveals important information on the optimal settings for many variables based on only a few trials. Prior to testing, six factors were thought to be important in order to optimize chipper productivity and chip quality. Four factors (feeding speed, screen size, PTO speed, and wood species) were found to be important for chip quality, while only screen size affected productivity. In this experiment, the highest quantity of target-size chips was found when the feeding speed was slow, and chestnut wood rather than pine wood was used. The choice of screen size may vary according to the price of high-quality chips compared to regular-quality chips, and labor and fuel costs.

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