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AN INNOVATIVE APPARATUS PROVIDED WITH A CUTTING AUGER FOR PRODUCING SHORT LOGS FOR BIOMASS ENERGY FROM FAST-GROWING TREE SPECIES

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ABSTRACT Cutting fresh wood into small pieces, rather than into chips, may help avoid fermentations occurring in storage. A prototype was developed for reducing tree trunks into pieces through an innovative cutting mechanism that performs a gradual and oblique cut. The device consists of a large auger in which a knife, with a triangular section, is inserted on the outer edge of the helicoid, protruding 70 mm from the flight. The trunks, fed perpendicularly into the machine, are pushed along the axis and slices are cut off against a fixed counter blade having a sharp edge. The main frame of the machine is the cylinder enclosing the auger, it is closed at one end where a heavy flywheel is inserted to deliver the energy coming from the tractor’s PTO. The pieces exit through the opposite end. The auger has a 700 mm diameter and a 300 mm pitch spacing. The logs are pushed into the machine by counter-rotating rollers placed in the feed funnel. Tests were carried out to establish operative performance and power requirements of the machine. The cutting method requires less power compared to wood chipping machines. Work capacity is grater when producing slices instead of chips and the system produces less noise and fewer vibrations in the machine. The auger reaches a constant velocity of 200 RPM, cutting fresh wood of different species easily, up to a maximum trunk diameter of 20 cm. The length of the slices of wood can range from 4 to 19 cm.

Keywords: biomass, wood fuel, wood chunks, productivity, work capacity

INTRODUCTION Freshly felled logs contain a large amount of water, which often constitutes over 50% of the woods actual weight, depending on the species. For a proper combustion the moisture content of wood should be lower than 25-30%. When fresh wood is harvested and contemporarily reduced into chips, the material is stored in large piles for a period of natural drying before use as fuel. Wood chips accumulated in large piles are associated with conservation problems, especially over long periods. The pile of material has a low porosity that doesn't allow a proper aeration of the mass for the natural drying of wood. In stacks placed in the open field without shelter from rainfall, the wood chips showed, even after a long storage period, a high moisture content. In these cases the fermentations that occur lead to the loss of dry matter in the woody mass, decreasing the calorific power of wood up to 30% (Jirjis et al., 2008).

Cutting fresh wood into short logs, intended as small pieces, could represent a technique alternative to material chipping. Supposedly, bigger pieces give a minor surface exposed to microbial agents that may promote fermentative processes. Further the permeability of the biomass is directly proportional to the dimensions of the material: piles of short pieces of wood hold greater spaces than piles of wood chips. The circulation of air across the wood pile is improved, giving a rapid removal of moisture and a higher drying rate.

The apparatus described in this paper was conceived for cutting wood into small pieces, such as logs into pieces of wood fragments, commonly indicated as wood billet. The method was intended for processing the wood biomass obtained from medium rotation forestry, as an alternative to the reduction into wood chips. At the time of harvest the 5-7 year old trees may reach trunk diameters, measured at 1.3 m from the ground, larger than 15 cm, and the reduction of the woody material into fragments is very convenient for handling and transportation aspects (Spinelli et al, 2006).

Scientific innovation The prototype cutting auger machine introduces an innovative method for chopping wood material. The cutting mechanism performs a gradual and oblique cut into the wood. In the apparatus the cutting action is made with the inclined running of the blade that penetrates the fibers in a progressive way.

Other machines have been developed for chopping green wood into fragments. These machines are generally based on a system that cuts the lumber by striking with a heavy sharp tool, similar to an axe. The cut generally occurs perpendicularly to the longitudinal axis of the fiber (Pari et al, 2007).

With orthogonal cutting, where the cutting edge is perpendicular to the direction of cutting, the workpieces are subjected to impulsive force and cause louder noise. With oblique cutting, where the cutting edge inclines at an oblique angle to the direction of cutting, steadiness and processing quality are improved, and cutting forces and noise are reduced (Jin, 1996).

Description of the machine The innovative prototype was designed by researchers at CRA-ING and constructed by O.N.G., agricultural machinery manufacturer. The machine is meant to be used stationary for cutting logs that have been previously harvested. The material can be fed into the machine either manually or mechanically, aided with a mechanical arm provided with clamps for embracing the logs.

The cutting apparatus of the machine consist of a large horizontally extending auger. The central longitudinal axis has a diameter of 220 mm, the helical flighting has an outside diameter of 700 mm, flight thickness is 30 mm and pitch spacing is 300 mm. A helical knife is inserted on the outer edge of the flight, welded on the face looking towards the product outlet side. The knife has a triangular section protruding 70 mm from the flight.

The apparatus comprises furthermore a heavy flywheel, positioned at the auger's end opposite to the outlet, that conveys the energy coming from the tractor’s PTO. The flywheel has a 900 mm outside diameter and a 0.7 t weight.

These apparatus are enclosed in a very robust hollow iron cylinder (30 mm wall thickness) that also functions as the machine's main frame. The cylinder, that extends orthogonal to the driving direction, has two sections: the part enclosing the auger that has an outside diameter of 800 mm and the part enclosing the flywheel that has a diameter of 1000 mm. The cylinder is closed at one end, where the flywheel is inserted, and it's opened at the opposite end through which the wood pieces exit (figure 1).

Figure 1. Rear view of the machinery (left) and side view from the opening end (right)

A feed funnel opens on the side of the cylinder enclosing the auger. The logs are fed perpendicularly into the machine through the feeding mouth, they are pushed by the auger along its axis and slices of wood are cut off by the helical blade running against a fixed counter blade. The counter blade is located at the delivery end of the feed funnel, on the opposite side relative to the direction of motion of the blade (figure 2).

Two horizontally extending counter-rotating rollers are placed in the funnel for continuously feeding the material to be cut. The rollers, positioned atop one another, are serrated and have an outside diameter of 400 mm. The axis of rotation of the lower roller is permanent, while the upper roller is pivotally mounted, so that the centre distance between the rollers can be changed. The upper roller is preloaded towards the lower for retaining the logs fed into the machine. A hydraulic cylinder is used to bring the rollers apart into an open position, whenever the feeding mechanism is obstructed and jammed.

The feeding rollers are mechanically connected to the driveshaft by means of a continuously variable transmission. The speed of the feeding rollers may be selected within a given range to change the cutting length of the material from a minimum to a maximum, the shortest pieces are obtained setting the slowest speed and vice versa.

The output of the tractor's PTO is transmitted via driveshaft connected to a right-angled gear box, which in turn drives the flywheel. The gear box changes the direction of rotation and also provides a 4.7:1 gear reduction. The chopping apparatus is normally used with the PTO operating at 540 RPM, although the machine may also bear application at 1000 RPM, in this case machine oscillation is increased.

Figure 2. Front view (left) and feed funnel with feeding rollers and auger (right)

A freewheel device is inserted in the transmission to disengage the Cardan shaft from the driven shaft connected to the flywheel. This safety device is needed for disconnecting the load, preventing the momentum of the flywheel being transferred in the reverse direction through the drive when the machine is halted.

The machinery was conceived for working in a fixed station, however it is fitted with a pair of wheels for short transfers on the field. The machine is connected to the tractor by means of a tow-bar, having a swing-away hitch. In the towing position the machinery is aligned with the tractor, in the work position the tow-bar swivels and the trailed apparatus is moved to a side, so that the funnel is accessible for feeding the logs into the machine.

In the current construction, the chopping machine is not provided with a loading mechanism, so that the material must be fed into the machine either manually or in a mechanically aided way, for example clamping pliers mounted on an auxiliary tractor. The future development of the project is intended for applying an automatic feeding mechanism by means of a conveyor belt and implementing the construction of a self-propelled harvester to combine the cutting and chopping operations.

MATERIALS AND METHODS The cutting machine was tested with the aim of evaluating its operative performance, the characteristics of the material obtained and the associated costs of production. The tests were carried out cutting 46 logs of Black Locust (*Robinia pseudacacia L.*). The feeding rollers were used at two different speeds for obtaining material with two different cutting lengths: short and long.

The time needed for cutting the material was gathered separately for each trunk, this method was used for the purpose of calculating the unitary costs related to cutting each single log. Working time was analyzed distinguishing between the time needed for loading the material into the funnel (loading), the time needed for the machine to cut the log (cutting), and the time wasted for stoppages, caused by the jamming of the feeding mechanism (stoppage). A chronometric table was used for collecting the working times, afterward verified with data collected in real time acquisition by the mobile laboratory.

The machine's productivity was calculated using the gross working time parameter. For each cutting type, linear regression functions were calculated for correlating the weight of the logs to the machine's productivity, expressed in tons of product per hour of work.

The machine was used in conjunction with a 4WD tractor, with nominal power of 110 kW and total mass of 58.860 N. The PTO speed was set at 540 RPM corresponding to an engine speed of 1944 RPM. Ahead of the cutting tests, the engine performances were verified at the dynamometric brake to provid updated characteristic curves of the engine.

The dynamometric brake was also used, after the tests, to reproduce the mean working conditions of fuel delivery, PTO and engine speed. In addition to the power required by the machine, directly measured by a torque meter, this simulation aimed at evaluating the total torque and power provided by the engine and the corresponding fuel consumption.

The tractor's PTO was equipped with a torque meter, with a full scale of 3 kNm, for the measuring torque and speed, necessary for calculating the power required. The data was collected by an integrated system based on two units, a field unit and a support unit (Watts, 1989; Al Janobi, 2000). The field unit (tractor) is equipped with the torque meter, a PC, having a PCI card for real time data acquisition, and LCD monitors. Transducer signals were recorded at a scan rate of 10 Hz. The support unit (van) is the mobile laboratory: during the tests it is parked on the edge of the field. A radio-modem system links the tractor PC to the van PC, for exchanging data and allowing the supervision of the behavior of critical parameters and the instrument's efficiency (Fanigliulo, 2004).

Figure 3. Tractor-machine assembly (left) and manual feeding of logs (right)

The work crew included three operators: a driver and two field workers. The driver controlled the operating parameters of the tractor-apparatus assembly from the cabin and also intervened on eventual jamming of the feeding mechanism. The ground workers fed the logs into the machine, moving trunks from the pile to the feeding funnel (figure 3).

The analysis of the work costs associated with the yard's organization was carried out according to some of the main analytical calculation methodologies proposed by various authors (Baraldi, 1973; Biondi, 1999; Miyata, 1980; Ribaudo, 1977).

RESULTS AND DISCUSSION The tests for establishing the performance of the cutting auger machine were conducted relating them to the two cutting typologies: short cut and long cut. The logs used in the tests were divided into two piles. For each log the weight, the height and the diameter were measured before the trials. The mean values of these three characteristic differ slightly between the two groups (figure 4).

The fragments were accumulated in two separate piles: the average length of the long pieces resulted in 137 mm, and the average length of the short pieces was 82 mm.

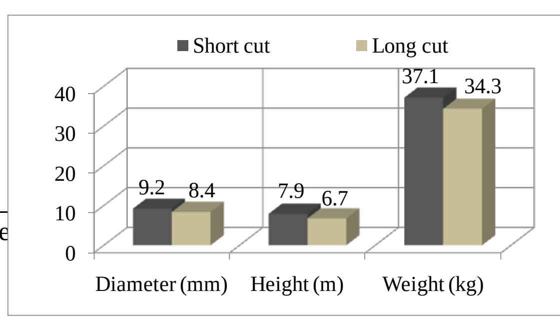

Figure 4. Characteristic of the logs used in the test

Total time needed for cutting the same mass of logs into short pieces is about threefold that needed for cutting into long pieces. Working time analysis, for the different phases of production of the wood fragments, was analyzed separately for each group of logs. In both cases, the cutting machine achieves a high working efficiency, since most of the time is employed in the cutting phase. The unproductive time, caused by stoppages due to feed jamming, was considerable for the long cut and negligible for the short cut. Also the time needed for loading the logs is higher when making long pieces. The explanation is that producing short pieces is slower and the workers have enough time for moving the logs from the pile to the machine (figure 5).

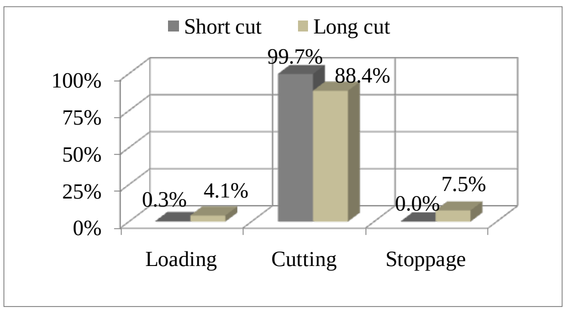

Figure 5. Working time for the different phases.

The gross productivity of the work yard increases when heavier logs are processed, this occurs for both cutting typologies, but it's more evident with the long cut (figure 6).

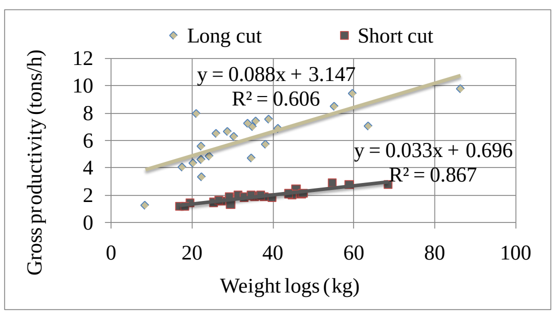

Fig. 6. Gross productivity for the two cutting typologies

The gross productivity for making long pieces is more than double that reached for making short cuts. Considering the weight range of the logs used in the tests, from 15 to 70 kg, the resulting mean productivity changes from 4.5 to 9.3 tons per hour for long pieces, and from 1.2 to 3.0 tons per hour for short pieces. The cost, referred per ton, needed for processing the logs with the two cutting typologies was determined on the basis of these two productivity relationships, compared to the hourly costs of the yard. The calculation of the yard's hourly cost was done considering the technical and economic elements in Table 1. The current value of the prototype was estimated because no price comparison is available the for similar machinery. The results of the economic analysis and the operating costs of the yard are shown in Table 2.

Table 1. Principal economic elements considered in the analysis

Description	Unity of measure	Tractor Gandini Legend 145	Cutting auger machine
Initial investment cost	Euros	70,000	17,000
Salvage value	Euros	7,516	1,825
Average life	years	10	10
Annual employment	hours	1,200	800
Power	kW	106	-
Interest rate	%	5.0	5.0
Consumption of fuel	Liters per hour	12.0	-
Consumption of lubrificants	Liters per hour	0.48	0.00
Space of repleicement	m^2	20.0	15.0
Labour cost	Euros per hour	16.0	16.0
Average price fuel	Euros per liter	0.77	-
Average price lubrificants	Euros per liter	9.0	9.0
Tires cost	Euros	10,800	1,200
Building replacement cost	Euros per m^2	300	300

Table 2. Hourly costs of the yard

Description	Unity of measure	Tractor Gandini Legend 145	Cutting auger machine	Total cost of the work yard
Fixed costs	Euros per year	9,042	2,095	11,137
Fixed costs (a)	Euros per hour	7.54	2.62	10.15
Variable costs (b)	Euros per hour	21.50	3.03	24.52
Labour costs (c)	Euros per hour	16.00	32.00	48.00
MACHINE COSTS (a+b)	Euros per hour	29.03	5.65	34.68
TOTAL COSTS (a+b+c)	Euros per hour	45.03	37.65	82.68

The total hourly cost for the yard amounts to 82.68 Euros. The labor cost, referred to three workers, is very high and counts up to 58% of the total cost. Comparing machine productivity with the associated hourly cost, the variation of the unitary production cost is obtained as a function of log weight, for both cutting typologies (figure 7).

Figure 7. Unitary costs for cutting different weight logs.

The torque values measured at the PTO are very different between the short and the long cut typologies. For growing log diameters, the increases in the torque values are much higher with the long cutting reaching, with the largest diameters of logs tested, about double the value reached with the short cutting method (figures 8 and 9).

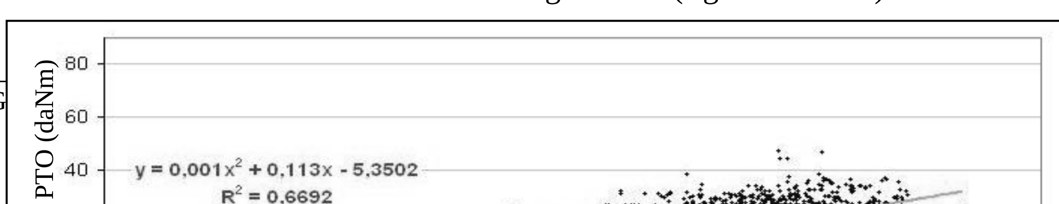

Figure 8. Torque values measured at the PTO for cutting short pieces.

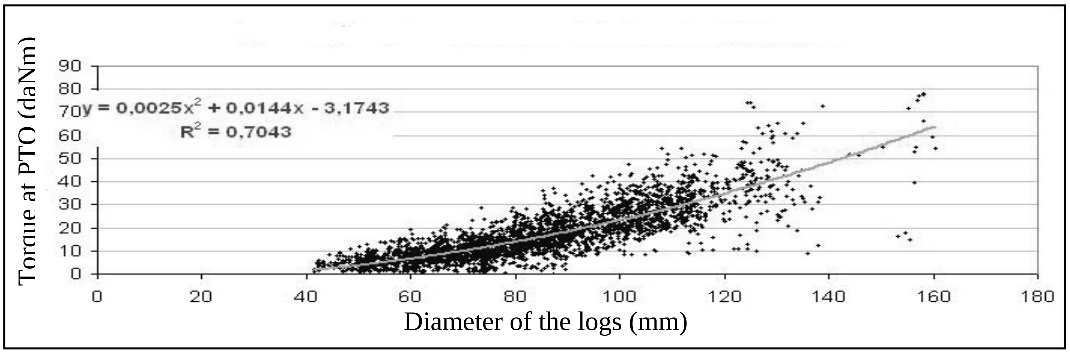

Figure 9. Torque values measured at the PTO for cutting long pieces.

The engine power requirements also behave in a similar manner. The power values associated with the long cut typology, for growing values of log diameters, increase very quickly, reaching about double the value reached with the short cutting method with the largest diameters of trunks (figures 10 and 11).

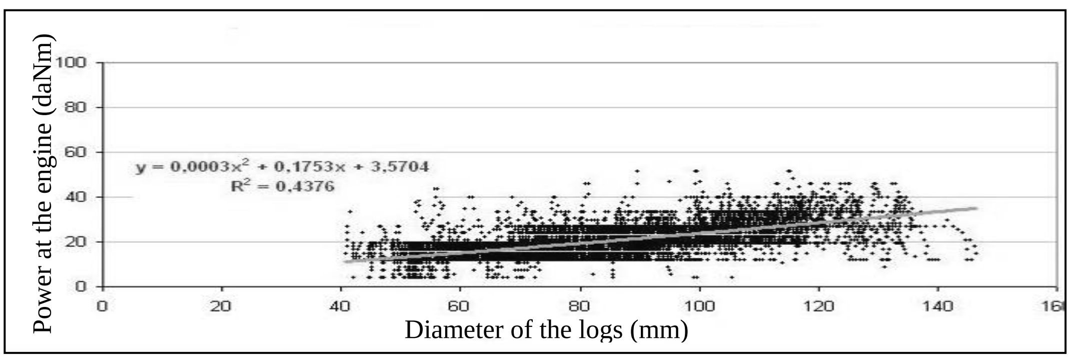

Figure 10. Power values measured at the engine for cutting short pieces.

The long cutting method, therefore, would seems less advantageous for the tractor power required. For cutting big logs (more than 150 mm diameter) the higher power request may be a limit because at least an 80 kW power class tractor is needed, while with the short cutting method 60 kW power class is sufficient.

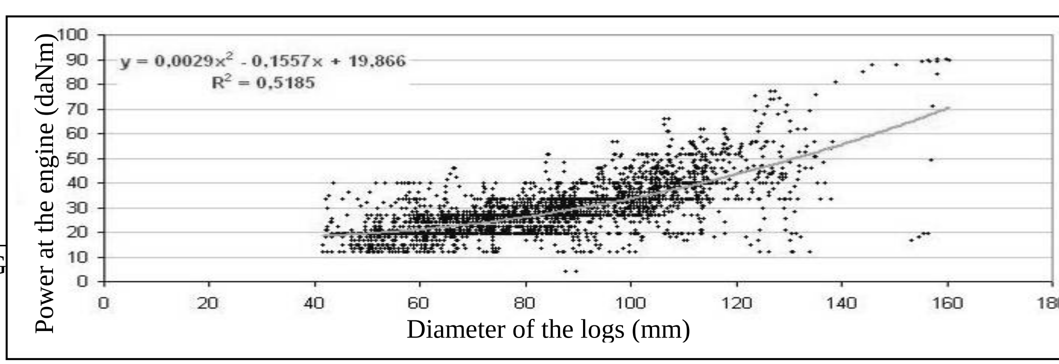

Figure 11. Power values measured at the engine for cutting long pieces.

CONCLUSIONS The chopping machinery cuts logs easily turning them into short pieces fit to be used in biomass boilers to produce thermal energy. The reduction in short pieces of wood, in comparison to the wood chips, makes the biomass less susceptible to the processes of fermentation. Consequently, there will be a lower loss of calorific power of the wood pieces than in the wood chips.

The decreasing course of the costs confirms that the machine is economically sustainable when the logs are heavier and the diameters bigger, although these must not exceed the operational limits, represented by maximum diameters of around 200 mm.

For weights of the logs between 10 and 80 kg (diameters between 40 and 180 mm), the long cut system gives production costs ranging from 20 to 8 Euros per ton. The costs of the short cut system, instead range from 81 to 25 Euros per ton. The long cut system is also economically sustainable for small dimension logs, while the short cut system becomes economically sustainable when the logs are heavier than 70 kg, and diameters are more than 130 mm, in this case the costs are less than 27 Euros per ton.

Currently the prototype works on a fixed station connected with tractor. It’s possible to foresee a development of the prototype through the design and construction of a system self propelled machine that will be able to move in field. It should be used in alternative to the other chopping machines used for harvesting short and medium rotation coppices, to produce biomass for energy.

The machine was conceived as alternative to the machines at present on the market used for the production of woodchips. The innovative cutting system is precise, relatively silent and it doesn't produce negative vibrations typical of other chipping machines.

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