# Determining the effect of feedstock type on chipping productivity, fuel consumption and quality output

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***Abstract:****Current chipping productivity models do not include any specific references to the quality of the raw material being chipped, so that they return the same estimates regardless of feedstock type. Hence, chain level comparisons do not integrate such effects and may produce inaccurate results. Therefore, CNR set out to determine with statistical methods what is the effect of feedstock type on 1) chipping productivity, 2) fuel consumption and 3) chip quality, as reflected by particle size distribution. A controlled study was organized, using the same industrial chipper to process 8 different feedstock types, deriving from the intersection of the following factors: tree species (beech or larch), tree portion (stem or branches) and moisture content (fresh or dry). Five replications were conducted for each treatment, and each replication consisted of a grapple load of material. The reason for using just one grapple load was the intention of containing the effect of blade wear, which would become a significant confounding factor with larger quantities. For the same reason, replications were randomized. All the chips produced during each replication were weighed and sampled for moisture content and particle size distribution. A flow meter was installed on the chipper, so as to read the exact fuel consumption for each replication. Statistical analysis highlighted the significant differences between treatments, which should be included in any comparison of alternative layouts for the chip production chain.*

**Keywords:** chipping, fuel consumption, productivity, biomass

## 1 Introduction

The current rapid development of the energy biomass market has generated a growing interest in the recovery of forest residues, such as tops, branches and other tree parts previously without commercial value. Recovery generally requires some form of processing aimed at increasing the bulk density and the homogeneity of the biomass, which is crucial to its effective handling. Such process must be performed as early as possible, in order to accrue its benefits all along the supply chain. Chipping is one of the most popular biomass processing techniques, and offers the advantage of improving bulk density and handling quality (Pottie and Guimier 1985).

Since bulky raw materials should be comminuted as early as possible (Björheden 2008), mobile chippers are used directly in the forest or at the roadside landing, before transportation (Asikainen and Pulkkinen 1998). Until present, most comparisons of wood energy supply chains account for chipper productivity and fuel consumption with fixed assumptions (Gustavsson et al. 2011, Eriksson 2008) or generic models (Forsberg 2000, Wihersaari 2005). However, the conditions of chipping change with the specific work system considered and operation performance could be influenced by species, size and moisture content. While specific models for chipper productivity are already available to the international scientific community (Spinelli and Hartsough 2001), much less information exists on chipper fuel consumption and most data are currently derived from local studies, published in the national languages (Andersson and Nordén 2000, Liss 2003).

Some of these studies indicate a strong relationship between fuel consumption and wood characteristics, which would contradict the use of standardized average figures (Liss 1987). Furthermore, wood characteristics may have a significant effect on particle size distribution, which is crucial to fuel handling efficiency (Jensen et al. 2004), to its drying and reaction rate (Lu et al. 2010), to the energy required for conversion into ethanol (Hosseini and Shah 2009).

Therefore, the goal of this experiment was to determine the effect of wood characteristics on the performance and product quality offered by a mobile industrial chipper, of the type commonly used for roadside chipping. In particular, the study aimed at finding if tree species (softwood or hardwood), tree portion (stem or branches) and wood moisture content (fresh or dry) could be associated with statistical significance to any eventual differences in machine productivity, fuel consumption and particle size distribution. Such information is crucial to obtaining accurate estimates of chipper fuel consumption and GHG emissions, and will therefore allow for a more realistic comparison between energy wood supply chain options.

## 2 Material and methods

The machine utilized for the study was a drum chipper. model Pezzolato PTH 900/660 mounted on a trailer. The machine was powered by a 260 kW Fiat-Iveco C87 Ent diesel engine. The drum carried two large blades and had a diameter of 660 mm and a width of 950mm.

At the beginning of the experiment, a new set of knifes and a 50mm vertical bar screen (typical for industrial operations) were installed. The material to be chipped was brought to the infeed system by an integral knuckle boom loader, mounted on the chipper itself.

For the test, the chipper was fed with 8 different raw material types, deriving from the combination of tree portion (stem or branches), tree species (softwood or hardwood) and wood moisture content (fresh or dry). European larch (Larix decidua *Mill.*) and common beech (Fagus sylvatica *L.*) were used to represent softwood and hardwood species, respectively The choice of the species was influenced by the availability of trees in the area. The experiment included 5 replications per treatment and each replication consisting of a single grapple load. Two treatments were replicated 6 times in order to use up all the material (table 1).

The amount of material used for each replication was small, in order to avoid the effect of blade wear. A study by Nati et al. (2010) did find that the blade wear had a significant impact on chipper productivity and fuel consumption. The latter increased with the amount of wood processed by the same set of blades and could be predicted with specific equations. These equations were used to estimate the productivity drop and the fuel consumption increase occurred between the beginning and the end of the study, as a consequence of blade wear. The total amount of wood processed for the study was 8.17 fresh tonnes, and the resulting figures were 1.9 % and 0.6 %, respectively for fuel consumption and productivity.

**Table 1: Test description: experimental design**

| Treatment Code | Tree species | Tree part | Moisture content | Replications n° | Piece size kg (fresh) | Batch size kg (fresh) | m.c. % |
|---|---|---|---|---|---|---|---|
| SSF | Softwood | Stem | Fresh | 5 | 34.8[b] | 326.6[a] | 38.8[bc] |
| SBF | Softwood | Branches | Fresh | 5 | 3.8[a] | 141.0[b] | 41.7[c] |
| SSS | Softwood | Stem | Stored | 6 | 24.2[b] | 174.3[b] | 41.4[c] |
| SBD | Softwood | Branches | Dry | 5 | 2.7[a] | 125.6[b] | 21.5[a] |
| HSF | Hardwood | Stem | Fresh | 5 | 23.5[b] | 243.6[a] | 37.4[bc] |
| HBF | Hardwood | Branches | Fresh | 5 | 3.6[a] | 119.0[b] | 34.9[b] |
| HSD | Hardwood | Stem | Dry | 5 | 40.5[c] | 271.4[a] | 20.8[a] |
| HBD | Hardwood | Branches | Dry | 6 | 2.4[a] | 126.3[b] | 19.5[a] |

Note: different letters on the average values in the same column indicate statistical significance at the 5% level; m.c.= moisture content as % of total weight

To measure fuel consumption a mechanical-electromagnetic flow meter was installed on the injection pump lines. Before starting the experiment, the flow meter was calibrated and the engine was run for about 30 minutes in order to reach a stable temperature. Instantaneous fuel consumption readings were recorded at one second intervals. Each measurement lasted between 17 and 90 seconds, with an average of 40 seconds.

Chips produced within each replication were weighted with a portable scale for determining the production. The material was blown onto a tarpaulin, which was then folded, tied and lifted with a separate hydraulic loader. The portable scale, with an accuracy of 200g, was placed between the loader hook and the tarpaulin, whose weight was recorded separately and subtracted from the individual readings.

To determinate moisture content and particle size distribution, two one-kg samples were collected from each replication. The moisture content was obtained with the gravimetric method, according to European standard CEN/TS 14774-2, while particle size with the oscillating screen method, according to European Standard CEN/TS 15149-1.

Effective time consumption was determined on the fuel consumption graphs, rather then by a stopwatch during actual work. When the chipper is processing such small batches, it is very difficult to determine with accuracy when the machine is actually working and when it is running idle. After the drum has finished its job, the machine evacuation system will keep spitting small quantity of chips for some seconds and the engine regime is dropping again. Under real work conditions, a new load would be engaging the drum at this stage, and the engine regime would not be decreasing so sharply and for so long. To determine the start and the end of process time, all graphs were analyzed in order to estimate a basal fuel consumption figure, taken as a reference for the running machine before its drum actually engages the wood. This figure was found at the 15 l $h^{-1}$ level, which was then adopted as the threshold for defining actual chipping time. All test time when fuel consumption was above this level was counted as chipping time and used for calculating net chipping productivity, whereas all the other test time was excluded from calculations (Figure 1). Average fuel consumption when chipping was calculated on the records above the 15 l $h^{-1}$ threshold.

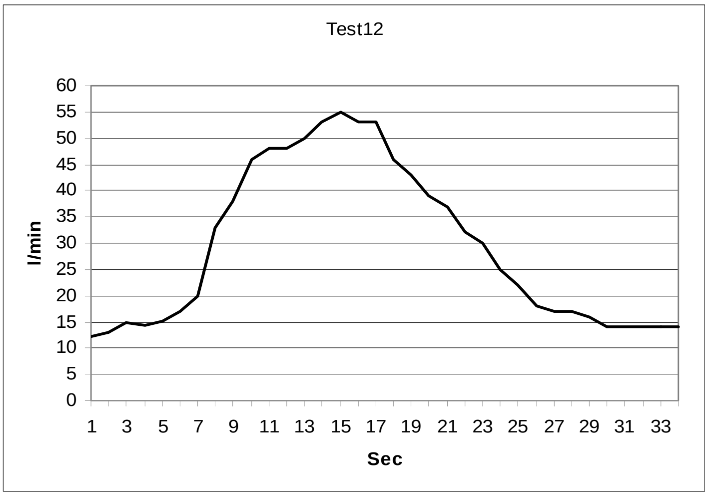


**Figure 1: Fuel consumption graph obtained from test n. 12**

To check the statistical significance of the eventual differences between treatments, data were analyzed with Statview advanced statistics software. Data satisfying the normality assumption were analyzed with Scheffe's post-hoc test, which is considered most conservative and robust (SAS 1999). When the normality assumption was not verified, the Kruskal-Wallis non-parametric test was used.

## 3 Results

As showed in table 1, a important distinction can be made between tree parts and their substantially different piece size. Stem treatments offered 10 times the piece size of branch treatments. Hence, any "tree part" treatment incorporated a possibly dominant piece size effect. A further consequence was that batch size (grapple load) was proportionally larger for stem material than for branch material. In any case, piece size was relatively small, since large logs were not chipped, but processed into more valuable structural assortments. As expected, fresh material was heavier than dry material.

Table 1 also shows that there was no difference in the moisture content of dry softwood stems and fresh softwood stems. Although the first batch was harvested 18 months before the test, it had undergone a minimal moisture content loss, no greater than that obtained by the second batch after just one month in the open air. That effectively eliminated the "dry softwood stem" treatment from the comparison, and the treatment was renamed "stored softwood stems".

The results in table 2 show that tree part had a dominant effect on net chipping productivity: tests conducted on stem wood returned significantly higher productivity figures than tests on branch wood. As an average, the productivity recorded when chipping stem wood was 50 to 60 % higher than that obtained when chipping branch wood. That held true when productivity was expressed in fresh tons, and in oven dry tons (odt). For the same tree part, tree species and moisture content had no significant effect on net chipping productivity.

A similar grouping was obtained for hourly fuel consumption. The chipping of branch wood required about 30 $l\ h^{-1}$ and that of stem wood 42 $l\ h^{-1}$. The results for unit fuel consumption were somewhat more articulated, and data stratified in three different groups. The lowest consumption levels (in the range of 1.7 $l\ t^{-1}$) were recorded on fresh stem wood: this allowed high chipping productivity, and did not prove too hard to hack. On the other hand, the highest consumption levels (in the range of 2.8 $l\ t^{-1}$) were recorded for dry hardwood stems and dry softwood branches, the former probably hardest to hack, the latter offering such a low productivity that unit consumption grew highest. Fresh softwood branches and hardwood branches were associated to intermediate unit consumption levels. However, when the effect of moisture content was removed and unit consumption was referred to dry matter output, then most differences evened out, and only two material types stuck out from an otherwise rather homogenous picture, with consumption levels in the range of 3.2 l $odt^{-1}$. These were dry hardwood branches and fresh softwood branches, respectively associated to a fuel consumption of 2.6 and 3.8 l $odt^{-1}$.

**Table 2: Net chipping productivity and fuel consumption**

| Treatment code | Tree species | Tree part | Moisture content | Productivity t $h^{-1}$ | Productivity odt $h^{-1}$ | Consumption l $h^{-1}$ | Consumption l $t^{-1}$ | Consumption l $odt^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| SSF | Softwood | Stem | Fresh | $27.4^{b}$ | $16.7^{d}$ | $45.7^{b}$ | $1.68^{b}$ | $2.74^{ab}$ |
| SBF | Softwood | Branches | Fresh | $12.9^{a}$ | $7.5^{ac}$ | $28.1^{a}$ | $2.20^{ab}$ | $3.79^{b}$ |
| SSS | Softwood | Stem | Stored | $21.3^{b}$ | $12.4^{b}$ | $37.7^{ab}$ | $1.78^{b}$ | $3.04^{ab}$ |
| SBD | Softwood | Branches | Dry | $11.2^{a}$ | $8.9^{ab}$ | $30.8^{a}$ | $2.86^{a}$ | $3.66^{ab}$ |
| HSF | Hardwood | Stem | Fresh | $22.9^{b}$ | $14.3^{bd}$ | $41.4^{b}$ | $1.84^{b}$ | $2.94^{ab}$ |
| HBF | Hardwood | Branches | Fresh | $14.8^{a}$ | $9.6^{abc}$ | $31.8^{a}$ | $2.17^{ab}$ | $3.32^{ab}$ |
| HSD | Hardwood | Stem | Dry | $16.4^{ab}$ | $13.0^{bcd}$ | $44.0^{b}$ | $2.70^{a}$ | $3.42^{ab}$ |
| HBD | Hardwood | Branches | Dry | $14.8^{a}$ | $11.9^{b}$ | $31.0^{a}$ | $2.11^{ab}$ | $2.63^{a}$ |

Note: different letters on the average values in the same column indicate statistical significance at the 5 % level; odt = oven-dry ton

ANOVA tests confirmed the dominant effect of tree part on net productivity. When productivity is expressed in dry weight, then tree part and moisture content have no effect on productivity, except when interacting with tree part. Tree part is the only factor with a significant effect on hourly fuel consumption. The situation is more complex when considering fuel consumption per unit product, because interactions also have their specific effects.

Table 3 shows the main results for particle size distribution. Chips from fresh softwood branches emerged for the significantly higher proportion of oversize particles compared to the other chips. On the contrary, fresh hardwood branches produced a significantly larger proportion of fines, compared to all other raw material types. This was probably related to beech leaves, which, once into the chipper, pulverized, generating a significant amount of dust material. Overall, fresh branches produced the lowest proportion of acceptable chips, in the range of 90%. They also showed a visible tendency to produce chips in the larger size classes, although this difference was not statistically significant. On the contrary, chips produced from dry branches presented about the same proportion of accept particles as chips produced from stem wood.

**Table 3: Particle size distribution of the chips produced during the experiment**

| Treatment code | Tree species | Tree part | Moisture content | Oversize % weight | Large % weight | Medium % weight | Small % weight | Fines % weight | Accepts % weight |
|---|---|---|---|---|---|---|---|---|---|
| SSF | Softwood | Stem | Fresh | 0.0[a] | 2.1[a] | 63.0[a] | 30.6[b] | 4.3[ab] | 95.7[a] |
| SBF | Softwood | Branches | Fresh | 6.4[b] | 17.7[b] | 61.1[a] | 11.7[a] | 3.1[ab] | 90.5[b] |
| SSS | Softwood | Stem | Stored | 0.2[a] | 4.8[a] | 56.4[a] | 35.9[b] | 2.7[a] | 97.1[a] |
| SBD | Softwood | Branches | Dry | 0.0[a] | 5.0[a] | 44.8[a] | 46.8[b] | 3.4[ab] | 96.6[a] |
| HSF | Hardwood | Stem | Fresh | 0.2[a] | 1.2[a] | 47.9[a] | 48.0[b] | 2.7[a] | 97.1[a] |
| HBF | Hardwood | Branches | Fresh | 1.8[a] | 6.6[a] | 60.6[a] | 24.1[a] | 6.9[b] | 91.3[b] |
| HSD | Hardwood | Stem | Dry | 0.0[a] | 1.3[a] | 28.2[a] | 68.0[c] | 2.5[a] | 97.5[a] |
| HBD | Hardwood | Branches | Dry | 1.0[a] | 4.3[a] | 50.4[a] | 41.0[b] | 3.3[ab] | 95.7[a] |

Note: different letters on the average values in the same column indicate statistical significance at the 5 % level; "Accepts" represent the sum of chips. In all classes (i.e. Large, Medium and Small), excluding oversize particles and fines.

## 4 Discussion

The experiment confirms previous studies about the dominant effect of piece size on power requirement (Liss 1986), productivity (Spinelli and Magagnotti 2010), and fuel consumption (Van Belle 2006). Tree species and moisture content seem not to influence machine productivity and fuel consumption. Concerning tree species, one may question if European larch can represent the softwood family, although it would be problematic to find any single species capable of representing such a large group. As to moisture content, one may notice that Liss (1987) did find a significant relationship between wood moisture content and chipper power requirements. However, he worked on a smaller chipper than that used for our test, and it is possible that machine sensitivity to external factors is inversely proportional to engine power. This lead to the obvious affirmation that the results of this study were valid for the specific machine or similar and tree species used to conduct it.

Net chipping productivity and fuel consumption are calculated for chipping time only, excluding all accessory work time and all delays (Björheden et al. 1995). In actual operations, the effect of delays, that may occupy up to 50% of the total work site time (Spinelli and Visser 2009), will not only reduce machine productivity and decrease hourly fuel consumption, but may also blur the eventual differences related to wood characteristics. On the other hand, focusing the study on the actual chipping phase allowed minimizing operator effect, because the machine was totally independent from operator control in this phase. Operator effect is a main source of variability (Purfürst and Erler 2006), and may account for productivity differences up to 77 % (Harstela 1988). In fact, it is not certain that using the same operator for different tests or in the same test will categorically exclude operator effect (Lindroos 2010). Hence, limiting the observation to a totally "robotic" phase guarantees the exclusion of operator effect.

Fuel consumption per dry unit is rather constant, and the only significant difference is between fresh softwood branches and dry hardwood branches. Such difference could be because fresh softwood branches are bulk and resilient so the feeding is slow while dry hardwood branches are brittle and compact, thus allowing rapid feeding with minimum effort. For the rest, it appears that the higher productivity obtained when processing larger pieces can offset the higher fuel consumption per hour. This seems to indicate that adopting an average fuel consumption per dry mass unit is a reasonable way to account for the energy inputs and the GHG emissions associated to chipping operations, when analysing chip supply chains (Yoshioka et al. 2006).

Another separate study conducted by the same authors (Spinelli et al. 2010) did find that the percent weight of accept particles was lowest in fresh softwood branches. This was true regardless of chipper type, despite its significant effect on particle size distribution (Spinelli et al. 2005). Hence, the result obtained in the current study confirms a primary effect of wood characteristics on particle size distribution.

## 5 Conclusion

Productivity and fuel consumption are influenced primarily by piece size of the material to be chipped while wood characteristics such as species and moisture content seem to have a secondary effect. Tree part and moisture content may have a strong effect on the particle size distribution of the chips. Moisture content could be managed to manipulate particle size distribution. These results were verified for the species used in the test and are valid for industrial chippers only. Different results might be obtained if substantially different species or machines are used. Nevertheless, the indications of the study seem rather clear, and may reflect a more general trend.

## 6 References

Andersson G., Nordén B. (2000) - Fiberpac 370. Systemstudie komprimering avverkningsrester. Skogforsk, Uppsala, Sweden. 39 p. (in Swedish).

Asikainen A. and Pulkkinen P. (1998) - Comminution of Logging Residues with Evolution 910R chipper, MOHA chipper truck, and Morbark 1200 tub grinder. Journal of Forest Engineering 9: 47-53.

Björheden R. (2008) - Optimal point of comminution in the biomass supply chain. Proceedings of the Nordic-Baltic Conference on Forest Operations, Copenhagen 23-25 September 2008. Danish Forest and Lanscape, Copenhagen, Denmark.

Björheden R., Apel K., Shiba M., Thompson M.A. (1995) - IUFRO Forest work study nomenclature. Swedish University of Agricultural Science, Dept. of Operational Efficiency, Garpenberg. 16 p.

Eriksson L. (2008) – Comparative analyses of forest fuel in a life cycle perspective with a focus on transport systems. Resource conservation and Recycling 52: 1190-1197.

Forsberg G. (2000) – Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. Biomass and Bioenergy 19: 17-30.

Gustavsson L., Eriksson L., Sathre R. (2011) – Costs and $CO_2$ benefits of recovering, refining and transporting logging residues for fossil fuel replacement. Applied Energy 88: 192-197.

Harstela P. (1988) – Principle of comparative time studies in mechanized forest work. Scandinavian Journal of Forest Research 3: 253-257.

Hosseini S., Shah N. (2009) - Multiscale modelling of hydrothermal biomass pretreatment for chip size optimization. Bioresource Technology 100: 2621–2628

Jensen P., Mattsson J., Kofman P., Klausner A. (2004) - Tendency of wood fuels from whole trees, logging residues and roundwood to bridge over openings. Biomass and Bioenergy 26: 107-113.

Lindroos O. (2010) – Scrutinizing the theory of comparative time studies with operator as a block effect. International Journal of Forest Engineering 21: 20-30

Liss J. (1986) – Drivningsmetoder för självverksamma skogsägare vid tillvaratagande av bränsleflis. SLU, Garpenberg, Sweden. 66 p. (in Swedish).

Liss J. (1987) – Effektbehov och energiförbrukning vid produktion av bränsleflis med lantbrukstraktormonterade huggar. SLU, Garpenberg, Sweden. 88 p. (in Swedish).

Liss J. (2003) – Kostnadsjämförelse mellan buntsystem och traditionella flissystem vid uttag av skogsbränsle. Dept. of Mathematics, Natural Sciences and Engineering, Dalarna Univerity, Garpenberg, Sweden. 22 p. (in Swedish).

Lu H., Ip E., Scott J., Foster P., Vickers M., Baxter L. (2010) - Effects of particle shape and size on devolatilization of biomass particle. Fuel 89: 1156-1168.

Nati C., Spinelli R., Fabbri P. (2010) - Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 34: 583-587.

Pottie M., Guimier D. (1985) – Preparation of forest biomass for optimal conversion. FERIC Special Report SR-32, Pointe Claire, Canada. 112 p.

Purfürst T., Erler J. (2006) - The precision of productivity models for the harvester: do we forget the human factor? In proceedings of "**Precision Forestry in plantations, semi-natural and natural forests". International Precision Forestry Symposium, Ackerman PA, Längin DW & Antonides MC: 451-463. Stellenbosch University, South Africa. 5-9 March.**

SAS Institute Inc. (1999) - StatView Reference. SAS Publishing, Cary, NC. p. 84-93. ISBN-1-58025-162-5

Spinelli R., Hartsough B.R. (2001) - A survey of Italian chipping operations. Biomass and Bioenergy 21 : 433-444.

Spinelli R., Visser R. (2009) - Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy 33: 429-433.

Spinelli R., Magagnotti N. (2010) -. A tool for productivity and cost forecasting of decentralised wood chipping. Forest Policy and Economics 12: 194-198.

Spinelli R., Nati C., Sozzi L., Magagnotti N., Picchi G. (2010) – Physical characterization of commercial woodchips on the Italian energy market. Fuel 90: 2198-2202.

Van Belle J. (2006) – A model to estimate fossil $CO_2$ emissions during the harvesting of forest residues for energy – with an application on the case of chipping. Biomass and Bioenergy 30: 1067-1075.

Wihersaari M. (2005) – Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass and Bioenergy 28: 435-443.

Yoshioka T., Aruga K., Nitami T., Sakai H., Kobayashi H. (2006) – A case study on the cost and the fuel consumption of harvesting, transporting, and chipping chains for logging residues in Japan. Biomass and Bioenergy 30: 342-348.