forests

Article

The Effect of Knife Wear and Sharpening Mode on Chipper Productivity and Delays

Matevž Mihelič [1], Dinko Vusić [2,*], Branko Ursić [2], Antonio Zadro [3] and Raffaele Spinelli [4]

[1] Department of Forestry and Renewable Forest Resources, Biotechnical Faculty, University of Ljubljana, Jamnikarjeva ul. 101, 1000 Ljubljana, Slovenia; matevz.mihelic@bf.uni-lj.si
[2] Faculty of Forestry and Wood Technology, University of Zagreb, Svetošimunska cesta 23, 10000 Zagreb, Croatia; bursic@sumfak.unizg.hr
[3] Matije Gupca Odvojak 2 7, 32254 Vrbanja, Croatia; azadro94@gmail.com
[4] CNR IBE, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Italy; spinelli@ivalsa.cnr.it
* Correspondence: dvusic@sumfak.unizg.hr

Abstract: The production of wood chips can be achieved using different types of wood chippers whose productivity can be influenced by many factors including proper knife management. Research was conducted to determine the productivity of the new Diamant chipper in chipping air-dried tops stacked at a roadside landing and to compare the efficiency of dry sharpening and wet sharpening in restoring chipper productivity, the time required by dry sharpening with that of knife replacement, and the cost of dry sharpening to knife change in real-life conditions. To clearly define the influence of knife management, a model of the effect of knife wear on chipper productivity was produced. Analysis of variance was used to check the significance of any differences in chipping and total time consumption per cycle. Multiple regression was used to express the relationship between chipping time consumption per cycle and the cumulated mass processed by a set of knives—the latter taken as an indicator of knife wear. The study lasted 10 full workdays, included a total of 136 truckloads or 3560 t of fresh wood chips (or green tons = gt), and resulted in the average productivity of 59.0 gt per productive chipping hour (excluding all delays) or 39.4 gt per machine scheduled hour (including all delays). Delays represented 37% of total worksite time. Knife management (dry sharpening or change) accounted for 30% of the total delay time due to raw material contamination. Dry sharpening took 30% less time than a full knife change. As wear accumulated and knives lost their edge, the chipping time per cycle increased from 25 in the first cycle (full truck load) to 38 min in the third cycle. The presented study offers robust productivity figures, together with a reliable estimate of the productivity losses caused by knife wear, and could help improve knife management in order to increase chipper productivity as well as reduce unnecessary delays.

Keywords: dry sharpening; wet sharpening; delay time

Citation: Mihelič, M.; Vusić, D.; Ursić, B.; Zadro, A.; Spinelli, R. The Effect of Knife Wear and Sharpening Mode on Chipper Productivity and Delays. *Forests* **2024**, *15*, 1101. https://doi.org/10.3390/f15071101

Academic Editor: Junwei Ma

Received: 14 May 2024
Revised: 20 June 2024
Accepted: 22 June 2024
Published: 26 June 2024

1. Introduction

In order to reduce greenhouse gas emissions in the atmosphere, the European Union has set ambitious targets in its strategies, a part of which is biomass use. In the European Union, forestry accounts for more than 60% of domestic biomass supplied for energy purposes [1]. The rising trend of energy use from renewable energy sources has boosted the demand for wood fuel [2], although wood fuel prices remain relatively low, which makes biomass supply a risky business, where production costs can easily exceed market prices [3]. To mitigate such risk, there is a constant need to optimize wood fuel supply chains. Therein, the most expensive production step in terms of energy and cost is wood comminution [4]. That is why a considerable amount of research is devoted to improving logistics [5,6], chipper selection [6,7], and machine configuration [8,9]. It is uneconomical to modify the overall chipper characteristics like engine power; therefore, the choice of the appropriate machine for the extent of operations and logistics is paramount; however, it has been demonstrated that it is possible to maximize the efficiency of comminution equipment. When chippers are used, knife maintenance and overall conditions are paramount [10,11] and can tip the balance of the economy of operations with higher productivity and better product quality [12] and thus higher product value. Therefore, knife wear has a dominant effect on fuel consumption, chipper productivity, and product quality [12–16], and this effect is generally stronger than the effect of tree species or chipper configuration [14].

Chipper knife wear is the result of a complex combination of mechanical, thermal, electrical, and chemical processes [17], which leads to an increase in the blade front angle and a consequent loss of efficiency in its shearing action [18]. Chipper knives are generally made of high-grade cold working alloy steel of different types and are normally hardened to between 55 and 60 HRC (Rockwell scale) [10]; thus, wear is slow but still inevitable. The only remedy to knives becoming blunt is to restore their blade angle through periodic sharpening. This requires removing part of the knife through abrasion, which leads to progressive material loss until the integrity and functionality of the knife can no longer be guaranteed, and replacement takes place. Normal wear caused by contact with wood can be compounded by accelerated wear due to the presence of contaminants in the feedstock, such as dirt, stones, or metal. Chipper knives are designed to cut wood—not minerals—and the presence of the latter generally results in fast wear or sudden damage. Decision on the optimal time for knife change or sharpening is usually based on the subjective feeling of the machine operator [19].

The problem of blade wear can be tackled with two different approaches. One is to use cheap disposable knives, which removes the need for sharpening and reduces the cost of a premature write-off [20]. The other is to use conventional re-usable knives, which are regularly sharpened when they become dull. This latter approach is the dominant one and is adopted by most operators. In that case, blunt knives are removed from the chipper and replaced with a set of new knives, for later sharpening with a wet sharpener. A sharpener is a precision tool that grinds the blade surface at a set angle to restore proper shape. Water is poured over the blade during sharpening to prevent heating damage to the metal. Wet sharpening is very effective but requires a dedicated piece of equipment and can only be performed after removing the knives from the chipper—generally at a workshop. Otherwise, knives can be honed manually on the fly with portable electric grinders, without removing them from the chipper (dry sharpening). The result is not as good as with a wet sharpener because manual grinding is not accurate enough and it cannot restore a proper front angle; thus, dry sharpening is not intended to replace wet sharpening, but rather to complement it [10], making use of the time available during interaction delays in the field and extending the time between wet sharpening sessions. Regardless of the approach adopted in each case, all operators are faced with the opposing needs of extending the time between knife replacement (and eventual resharpening) and minimizing the efficiency losses derived from gradual knife blunting.

Therefore, the goals of this study were:

(1) To determine the productivity of the new Diamant chipper;
(2) To model the effect of knife wear on chipper productivity;
(3) To compare the efficiency of dry sharpening and wet sharpening in restoring chipper productivity;
(4) To compare the time required by dry sharpening with that of knife replacement (for taking the knives to the workshop and wet sharpening them);
(5) To compare the cost of dry sharpening and wet sharpening.

2. Materials and Methods

2.1. Materials

Research was conducted at two chipping sites, both located in the lowland forests of the Spačva basin, east Croatia (Table 1). In the period of chipping, the average temperature was 22.5 °C, average monthly precipitation was 71 mm, and average humidity was 70%. At both chipping sites, the raw material consisted of air-dried tops stacked at a roadside landing as a result of a common practice in Croatian lowland forests in which forwarders are used for primary transport [21,22] and a management method in which logging residue is completely removed from the regeneration stand after felling [23] to be chipped after seasoning at the roadside, as is common in most supply chains in European countries [24] and stated as the most cost-efficient [25]. The tops had been forwarded to the roadside after roundwood transport in two preparatory cuts conducted in hardwood stands in the last quarter of 2018 (chipping site B) and between the end of 2018 and the first quarter of 2019 (chipping site A). Visual observation indicated that the stacked tops had been contaminated with dirt during handling and transport and that contamination seemed more severe at chipping site A.

Table 1. Chipping sites data.

Chipping Site	A	B
Forest office	Strošinci	Vrbanja
Management unit	Debrinja	Vrbanjske šume
Coordinates	44°57′08.6″ N 19°06′15.0″ E	45°00′36.4″ N 18°58′04.2″ E
Raw material	Tops	Tops
Species	65% hedge maple (*Acer campestre* L.) 35% narrow-leaved ash (*Fraxinus angustifolia* Vahl), European hornbeam (*Carpinus betulus* L.), pedunculate oak (*Quercus robur* L.), and other hard broadleaves	40% European hornbeam 31% narrow-leaved ash 14% hedge maple 15% other hard broadleaves, common linden (*Tilia cordata* Mill.), pedunculate oak, and white poplar (*Populus alba* L.)
Moisture content	39.5 ± 3.4%	28.7 ± 3.7%

At both sites (Figure 1), chipping was conducted with the same Albach Diamant 2000 (ALBACH Maschinenbau AG, D-85088 Menning, Germany) self-propelled industrial chipper, which discharged the chips directly into chip vans (semitrailer trucks) (Table 2). Chipping site B offered better work conditions than chipping site A, since the landing was located along the main forest road and offered enough space for the trucks to maneuver. In contrast, the landing at chipping site A was placed along a secondary forest road that did not offer enough space for maneuvering. Therefore, empty chip trucks had to drive to a suitable space some 750 m further ahead in order to turn around and come back to the landing facing the way out. In this case, each truck change required the chipper to travel to the nearest suitable passing area.

(**a**) (**b**)

Figure 1. (**a**) Chipping site A; (**b**) chipping site B.

Table 2. Chipper specifications.

Make and Model	Albach Diamant 2000
Power, kW	565
Length, m	10.34
Width, m	2.55
Height (lifted cabin), m	3.95 (4.80)
Weight, t	32
Tires	650/65R 42
Intake width, mm	1230
Intake height, mm	980
Rotor speed, r/min	420
Number of blades	6, 8, 12
Crane type	Forwarder crane Epsilon, S110F
Crane max. range, m	10.1
Crane max. load at 10.1 m, t	1

The chipper featured the new, seventh-generation drum, with 6 staggered knives (Figure 2). Seventh-generation drums have an open design and carry replaceable knife mounts and brackets, which enable the fine-tuning of cut length to the target chip size. In particular, chip length can be changed from 15 to 60 mm. However, the unit used for the experiment was equipped with short knives (200 mm) and small brackets that did not enable significant knife adjustments. Therefore, the same cut length (38 mm) and screen (80 mm × 80 mm mesh size) were used for the entire duration of the experiment.

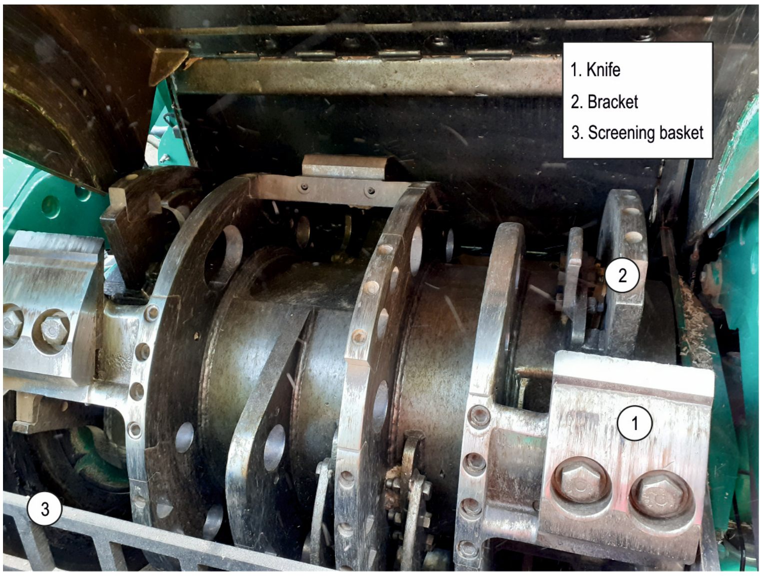

Figure 2. The seventh-generation open drum with 6 knives.

In the trial, both wet and dry sharpening were used—the former for knives that were severely degraded, the latter for a quick refresh of knives on the fly. Wet sharpening required taking the worn-out knives off of their brackets and replacing them with sharp knives, while dry sharpening was applied to slightly worn knives and was performed manually with a portable electric grinder, without removing the knives from the chipper. This task was entirely manual, without the metal bevel guides designed for this purpose. Therefore, the quality of dry sharpening was heavily dependent on variable operator competence, experience, and care. However, dry sharpening was an established practice within the company, and one would expect it to be performed with sufficient competence. The producer of the knives used during the test uses 1.2360 steel for the production of knives. The steel has a hardness of 56 to 59 HRC (Rockwell scale). The same type of knives are still regularly used by the contractor. The cutting edge was wet sharpened to a 30° angle. Wet sharpening was performed by Winter Hobelmesser Schleifmaschine Grinder 1700 Auto Magnetic machine (Henrik WINTER, HOLZTECHNIK GmbH, D-04159 Leipzig-Stahmeln, Germany) using the standard method. The thickness of the removed material depended on the severity of knife damage, but on normally damaged knives, the grinder was set to remove 2 mm of the knife edge.

2.2. Methods

Time studies were conducted to determine chipping time and delays at both chipping sites [26]. When recording the delays, the reason for each event was recorded along with its duration. Later on, the delays were grouped into functional categories. All recorded delays were included in the productivity model. A single chipping cycle was represented by the truckload, and all recorded time consumption (in minutes) was associated with the truckload mass, as determined at the factory weighbridge. Chip moisture content (m.c.) was determined with a Schaller BLL humimeter randomly sampling 3 to 4 truckloads per day.

Cycles during which knife sharpening or change took place (at the end of the cycles) were highlighted in the original database. The total mass of chips processed by a set of knives before change (or dry sharpening) was obtained by summing the mass of all trucks between two change or sharpening events.

Statistical analyses were performed with the Statistica TIBCO Software Inc. (2020) Data Science Workbench, version 14. Analysis of variance was performed to check the significance of any differences in chipping and total time consumption per cycle, as well as truckload mass between the chipping sites. Multiple regression was used to express the relationship between chipping time consumption per cycle and the cumulated mass processed by a set of knives—the latter taken as an indicator of knife wear. Non-parametric tests (Mann–Whitney and chi-square) were used to compare sample means, as the tests are robust and widely used in the literature. Significant differences in the intensity and duration of the knife sharpening/change between the chipping sites were tested using the non-parametric Kolmogorov–Smirnov test, as normality of data is not required. Statistical significance was accepted for $\alpha < 0.05$.

All figures reported in this study refer to fresh hardwood chips, with a water mass fraction between 28% and 40%.

3. Results

The study lasted 10 full workdays and included a total of 136 truckloads, or 3560 t of fresh wood chips (or green tons = gt). A total of 71 cycles were recorded at chipping site A over five workdays (1844 gt) and 65 cycles were recorded at chipping site B, also over five workdays (1716 gt). On average, 27.4 ± 4.0 min/cycle of chipping time (43.7 ± 11.9 min/cycle of total time) was needed for the production of 26.0 ± 1.7 gt/cycle at chipping site A. At chipping site B, the corresponding figures were: 26.9 ± 4.5 min/cycle chipping time (42.2 ± 12.5 min/cycle of total time) and 26.4 ± 1.8 gt/cycle. The grand average for productivity was 59.0 gt per productive chipping hour (excluding all delays) or 39.4 gt per machine scheduled hour (including all delays).

The analysis of variance found no statistically significant differences between work sites in terms of chipping time per cycle ($F = 0.385$, $p = 0.535$), total time per cycle ($F = 0.497$, $p = 0.482$), and truckload mass ($F = 1.998$, $p = 0.159$). Therefore, the data from the two sites were amalgamated and used as a single database.

Delays represented 37% of total worksite time, for a delay factor (delay time/productive time) of 0.58. Detailed analysis of the delays recorded at the different chipping sites (Table 3) indicated that the more favorable conditions encountered at site B did result in a reduction of those delays that were associated with truck swapping, to the benefit of shorter turnout time. However, that benefit was eroded by a longer transportation distance and the inadequate availability of trucks; eventually, shorter truck changing times were offset by longer waiting times, compared with site A.

Table 3. Structure of recorded time (worksite time).

Chipping Site	A	B	Total
Total worksite time, min	3104	2746	5850
Productive (chipping) time, min	1944	1750	3694
Delays, min	1160	996	2156
Knife sharpening, min (%)	166 (14.3)	136 (13.7)	302 (14.0)
Knife change, min (%)	215 (18.5)	129 (13.0)	344 (16.0)
Other mechanical delays, min (%)	115 (9.9)	84 (8.4)	199 (9.2)
Truck change, min (%)	531 (45.8)	329 (33.0)	860 (39.9)
Truck waiting, min (%)	14 (1.2)	183 (18.4)	197 (9.1)
Moving and bunching, min (%)	9 (0.8)	15 (1.5)	24 (1.1)
Break, min (%)	60 (5.2)	65 (6.5)	125 (5.8)
Talk, min (%)	50 (4.3)	55 (5.5)	105 (4.9)

Knife management (dry sharpening or change) accounted for 30% of the total delay time due to raw material contamination. Knife management amounted to 12.3% and 9.7% of the total time at site A and site B, respectively. The average knife management time per cycle was 5.4 ± 10.9 min and 4.1 ± 8.9 min respectively for site A and site B, without any significant differences according to the Kolmogorov–Smirnov test ($p > 0.1$). Therefore, a single average knife management delay time was estimated for each of the two sharpening modes.

As wear accumulated and the knives lost their edge, chipping time per cycle increased from 25.0 min to 25.6 min between the first and the second cycle, up to 38.0 min after chipping 79 t in the third cycle. After that, the knives were dry sharpened or changed. Despite the low coefficient of determination (R^2 = 0.2298), productivity clearly decreased with the cumulated mass processed by a set of knives (Figure 3) with a slightly steeper trend for dry-sharpened knives. Statistical significance was demonstrated through multiple regression analysis. The results of the analysis are shown in Table 4, which proves the highly significant and inverse relationship between productivity and the amount of chips processed by a set of knives. Although highly significant, this function has a relatively low explanatory value (23% of the overall variability) due to the expected large background noise derived from the erratic presence of contaminants in the chipped material. A few small stones can cause instant damage to the blades, thus dramatically impairing their performance. The same wood pile can contain material with variable levels of contamination, and therefore, knives may need to be changed after 2, 3, or more than 6 loads, depending on chance. When a pocket of particularly contaminated material is engaged, performance will drop more rapidly than for the rest of the pile. The same regression analysis showed no significant differences between wet- and dry-sharpened knives.

Table 4. Results of the multiple regression analysis for the effect of knife wear on productivity.

Chipping Productivity gt PMH^{-1} = a + b sum gt + c Wet + d Wet sum gt R^2 adj. = 0.239, n = 136, RMS = 7.484				
	Coeff	**SE**	**T-Value**	***p*-Value**
a	68.572	2.477	27.685	<0.0001
b	−0.136	0.036	−3.731	0.0003
c	−2.011	3.096	−0.650	0.5171
d	0.012	0.044	0.270	0.7879

Notes: gt = green tons; PMH = productive machine hours, excluding all delays; sum gt = total mass (gt) chipped by a set of knives since they were sharpened (i.e., indicator of wear); Wet = indicator variable for the wet sharpening treatment: 0 = dry-sharpened knives; 1 = wet-sharpened knives; n = number of observations; RMS = root mean square; SE = standard error.

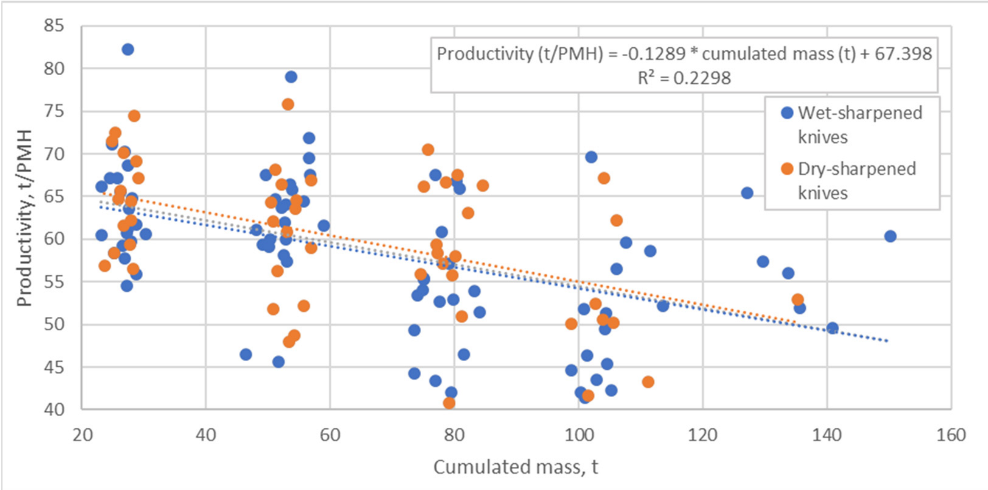

Figure 3. Chipping productivity as a function of the mass of chips processed by a set of knives, for wet- and dry-sharpened knives.

Furthermore, decompositional analysis of the time series indicated a substantial decline in productivity after the second cycle regardless of knife maintenance mode (dry sharpening of the older knives or replacement with new wet-sharpened knives). For the first cycle, median chipping productivity after dry sharpening was not significantly ($p = 0.3087$) higher than median productivity immediately after wet sharpening, with 65.6 t/h vs. 63.5 t/h.

The maximum number of loads chipped with a set of knives was six for wet-sharpened knives and five for dry-sharpened knives. Excluding the data of the last knife set (that was probably not fully used up), the average number of loads per knife set was 4, regardless of the sharpening treatment. The median mass of chips produced before a fresh set of knives needed new sharpening was 104.5 gt for wet-sharpened knives and 105.4 gt for dry-sharpened knives. The actual difference was therefore small and had no statistical significance ($p = 0.71$), possibly because the number of samples was too small to dampen the large variability caused by the erratic presence of contaminants in the chipped wood.

Finally, the study offered conclusive evidence that dry sharpening took much less time (−30%) than a full knife change (i.e., removing the worn-out knives and installing new ones). In this study, the average dry sharpening session took about 20 min (SD = 13 min), while the average full knife change took 29 min (SD = 29 min). The difference was not just large but also highly significant ($p = 0.00163$). Furthermore, one should not forget that knife change does not only carry the cost and the time of the change but also that of wet sharpening in the workshop. The price requested by the local workshop for sharpening a set of knives amounted to EUR 15. Therefore, the average knife change costs EUR 15 plus 29 min of chipper operator time. If the latter is costed at 50 EUR/h, then the total cost of wet sharpening is EUR 39. In contrast, dry sharpening only takes 20 min of operator time or EUR 17. Wet sharpening is then 2.3 times more expensive than dry sharpening. If one also spreads that cost over the larger amount of chips processed after dry sharpening (i.e., 105.4 gt vs. 104.5 gt), the impact of dry sharpening over the produced ton of chips is 0.16 EUR/gt, while that of wet sharpening is 0.37 EUR/gt, which is quite a dramatic difference.

4. Discussion

The present study offers valuable insights into the chipping process, and the information it has produced can be considered quite robust, thanks to the extended observation time (two entire weeks) and the large amount of work performed during that time (136 truckloads). On the other hand, the observational character of the study makes that information lacking in some details, which suggests caution when drawing conclusions from it.

In general, the results of the study are plausible, and they are corroborated by the figures reported in the existing literature. The productivity levels reported herein are comparable with those obtained for the previous models of the same chipper [27] or for similar chipper models that have recently appeared on the market [28]. More in general, those figures are fully within the ranges reported by Bergström and Di Fulvio [29] for a larger array of industrial chippers. The same corroboration is obtained for delay time: the ~40% delay factor reported in this study matches the figures presented by Spinelli and Visser [30], Belbo and Vivestad [31], and Mihelič et al. [32] quite well—with the latter two studies specifically addressing the case of roadside landings with various degrees of accessibility.

The good representation of delay time is not surprising for a study that extended over two full weeks. This time span was likely long enough to catch most of the delay occurrences and to offer a balanced perspective, where the impact of erratic events was suitably dampened. Concerning delays, it is interesting to see how different categories tend to balance each other; if the truck changing time is shortened, then the truck waiting time increases, eventually denying the benefit of better landing accessibility. This seems to reflect the apparent general rule of delay compensation, already observed by Spinelli and Magagnotti [14] who described how a reduction in waiting time was offset by an increase in rest time. In fact, no general rule covers compensation for delays; if such compensation is often observed, that is because opportunities for improvement are missed with alarming frequency. Essentially, if the truck terminal time is reduced, then one should integrate an additional truck into the transportation task and profit from the longer time available to the chipper for filling up trucks. Otherwise, it is inevitable that the time saved through quicker maneuvering will be occupied by an increase in waiting time. It is just that simple. Most rationalization efforts covering just one step in a chain are doomed to fail, and that is indeed a general rule.

Eventually, what the study says with a strong voice is that the Diamant 2000 is a very productive machine but that its large potential is limited by organizational factors that expand delay time. The data show that quite clearly, and we believe there can be very few objections to that statement. The same could be said for its corollary, namely, if you have a very productive machine, you need to create the conditions for that machine to unleash its full potential. But therein, the issue becomes somewhat more complex. Several operators have found out that it is easier to use very productive machines to compensate for the difficulty of precision management. Besides being expedient, compensation through exuberant productivity is the only rational solution when management is fragmented between different contractors—typically one for chipping and the other for transportation. In that case, precision management of the entire chain becomes a real challenge, and deploying extra capacity is the only alternative.

Despite the large variability observed for the effect of knife wear, the study also offers plausible figures for performance reduction consequent to knife wear and the overall duration of the knives. It indicates that productivity decreased between 15% and 28% after chipping between 100 and 115 gt of wood, which would match the 15% decrease reported by Nati et al. 2010 [11] after processing between 115 and 280 gt of chips or the 32% decrease reported by Spinelli and Magagnotti [14] after processing 120 gt of chips. The figures are all quite close, even if those studies were conducted under different conditions and with different machines. However, all machines were industrial drum chippers in the >300 kW class, working at landings and fed with hardwood material.

What is missing from this study is an assessment of fuel consumption and chip particle size and of their variation with blade wear. This is a consequence of its observational character, which does not deny the fundamental validity of the study but advises against trying to infer too much from it. In particular, the absence of fuel use data makes it difficult to develop a minimum cost curve for the frequency of knife change. Such a curve would represent only part of the reality because it would be based on productivity alone, and it would disregard the important contribution of varying fuel efficiency. Similarly, the absence of particle size data denies information about the criteria used by the operator for deciding when to sharpen the chipper knives. Anecdotal evidence indicates that most operators make the decision based on the excessive decay in chip quality [19], but the absence of any such figures from this study makes it difficult to determine how consistent the operator was with his knife-sharpening decisions. In fact, the inherently subjective knife sharpening criteria adopted by all operators make it inevitable that observational blade wear studies are confounded by very large variability. Nevertheless, most have returned comparable results, which bear a clear witness to the important role of operator competence and experience.

Finally, some interesting inferences can be drawn from the knife sharpening vs. knife change time study. The knife change time reported in this study is aligned with that indicated by other chipper delay studies [30] but almost twice as long as reported by Spinelli and Magagnotti [14]. The latter study indicated a mean knife change time between 13 and 16 min, depending on whether a power wrench was available or not. In the worst case, the knife change time required a maximum of 26 min. The shorter time reported in that study may depend on better work conditions (a workshop) and/or better operator worker and competence. However, another highly suggestive explanation is that the chipper in that study used two full-length knives, whereas that in the present study was equipped with six knives. It stands to reason that it would take less time to replace two knives instead of six, however longer and heavier the two full-length knives are. Therefore, one possible inference from that result is that dry sharpening may represent a faster knife-restoring option compared to changing, especially with those chippers that are equipped with many staggered knives and less so with those chippers that are equipped with fewer conventional full-length knives.

5. Conclusions

The study presented in this paper produces a wealth of interesting new information about chipping performance: it offers robust productivity figures, together with a reliable estimate of the productivity losses caused by knife wear; it generates useful suggestions for delay time control; and it raises a number of interesting questions and yields many good insights about chipper knife management. The productivity of the new Albach Diamant 2000 wood chipper ranged from 26.9 $\pm$ 4.5 min/cycle (site B) to 27.4 $\pm$ 4.0 min/cycle (site A) chipping time. The used model of the effect of knife wear on chipper productivity showed a significant impact of total chipped mass per set of knives on chipper productivity. Regarding the fact that wet-sharpened knives lasted a maximum of six loads and dry-sharpened knives lasted a maximum of five loads, it may be concluded that the edge of wet-sharpened knives can last longer. Considering the costs of knife management (dry sharpening and wet sharpening), dry sharpening required less time and equipment which resulted in 2.3 times lower expenses than wet sharpening, which can have a significant influence on the economy of the operation. On one side, frequent downtime of the chipper can be utilized for knife sharpening, thus increasing the efficiency of the operation, and on the other side, savings could occur due to less time spent in the workshop wet sharpening the knives. Future research should include the quality determination of produced wood chips, e.g., particle size distribution, which can provide more information to make more concise conclusions and find the best chipper settings in order to improve productivity without negatively influencing wood chips parameters. All things considered, the study is a witness to the fact that a properly planned and conducted observational study still offers considerable benefits, even when it lacks the advantages and the power of a controlled experiment.

Author Contributions: Conceptualization, M.M. and D.V.; methodology, D.V.; validation, R.S., M.M. and D.V.; formal analysis, R.S., D.V., M.M. and B.U.; investigation, A.Z.; writing—original draft preparation, D.V. and M.M.; writing—review and editing, R.S., D.V., M.M. and B.U.; visualization, D.V., B.U. and M.M.; supervision, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original data set is not publicly available, but it can be requested from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Brief on Biomass for Energy in the European Union. Available online: https://op.europa.eu/en/publication-detail/-/publication/7931acc2-1ec5-11e9-8d04-01aa75ed71a1/language-en (accessed on 18 April 2024).
2. Krausmann, F.; Erb, K.H.; Gingrich, S.; Lauk, C.; Haberl, H. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecol. Econ.* **2008**, *65*, 471–487. [CrossRef]
3. Palander, T.; Voutilainen, J. Modelling fuel terminals for supplying a combined heat and power (CHP) plant with forest biomass in Finland. *Biosyst. Eng.* **2013**, *114*, 135–145. [CrossRef]
4. Talbot, B.; Suadicani, K. Analysis of two simulated in-field chipping and extraction systems in spruce thinnings. *Biosyst. Eng.* **2005**, *91*, 283–292. [CrossRef]
5. Volk, T.A.; Eisenbies, M.H.; Hallen, K. The development of harvesting systems in woody biomass supply chains: A case study of short rotation woody crops. In *Sustainable Biorefining of Woody Biomass to Biofuels and Biochemicals*; Kumar, D., Kumar, S., Rajendran, K., Ray, R.C., Eds.; Woodhead Publishing: Cambridge, UK, 2024; pp. 43–63.
6. Piqueiro, H.; Gomes, R.; Santos, R.; de Sousa, J.P. Managing Disruptions in a Biomass Supply Chain: A Decision Support System Based on Simulation/Optimisation. *Sustainability* **2023**, *15*, 7650. [CrossRef]
7. Stolarski, J.; Wierzbicki, S.; Nitkiewicz, S.; Stolarski, M.J. Wood Chip Production Efficiency Depending on Chipper Type. *Energies* **2023**, *16*, 4894. [CrossRef]
8. Nogueira, D.F.B.; Fiedler, N.C.; Vidaurre, G.B.; Lopes, E.D.; Pelissari, C.K.R.; Ramalho, A.H.C.; Robert, R.C.G.; Maffioletti, F.D. Quality of eucalyptus wood chips for bioenergy as a function of drying time and horizontal chipper settings. *Heliyon* **2024**, *10*, e25991. [CrossRef] [PubMed]
9. Fiorineschi, L.; Cascini, G.; Rotini, F.; Tonarelli, A. Versatile grinder technology for the production of wood biofuels. *Fuel Process. Technol.* **2020**, *197*, 106217. [CrossRef]
10. Spinelli, R.; Marchi, E. Trends and Perspectives in the Design of Mobile Wood Chippers. *Croat. J. For. Eng.* **2021**, *42*, 25–38. [CrossRef]
11. Nati, C.; Spinelli, R.; Fabbri, P.G. Wood chips size distribution in relation to blade wear and screen use. *Biomass Bioenergy* **2010**, *34*, 583–587. [CrossRef]
12. Kuptz, D.; Hartmann, H. Influence of tree species and machine settings on chip quality and specific energy consumption of a stationary drum chipper. *Biomass Bioenergy* **2021**, *155*, 106305. [CrossRef]
13. Krilek, J.; Čabalová, I.; Výbohová, E.; Mamoňová, M.; Ťavodová, M.; Melicherčík, J.; Gendek, A.; Aniszewska, M.; Todaro, L.; Giudice, V.L. Assessment of the chipping process of beech (*Fagus sylvatica* L.) wood: Knives wear, chemical and microscopic analysis of wood. *Wood Mater. Sci. Eng.* **2024**, *19*, 473–484. [CrossRef]
14. Spinelli, R.; Magagnotti, N. The effect of raw material, cut length, and chip discharge on the performance of an industrial chipper. *For. Prod. J.* **2012**, *62*, 584–589. [CrossRef]
15. Kuptz, D.; Hartmann, H. The effect of raw material and machine setting on chipping performance and fuel quality—A German case study. *Int. J. For. Eng.* **2015**, *26*, 60–70. [CrossRef]
16. Kuptz, D.; Hartmann, H. Evaluation of Fuel Quality, Throughput Rate and Energy Consumption During Non-Industrial Wood Chip Production with Three PTO Driven Chippers. *Croat. J. For. Eng.* **2022**, *43*, 109–122. [CrossRef]
17. Moiseev, A. Wear resistance of wood cutting tools. *Lesn. Promyshlennost* **1981**, 110.
18. Obreshkov, P. *Wood Processing Machines*; Wood Research Institute: Sofia, Bulgaria, 1996; p. 192.
19. Spinelli, R.; Hartsough, B. A survey of Italian chipping operations. *Biomass Bioenergy* **2001**, *21*, 433–444. [CrossRef]
20. Spinelli, R.; Magagnotti, N. Using disposable chipper knives to decrease wood fuel processing cost. *Fuel Process. Technol.* **2014**, *126*, 415–419. [CrossRef]
21. Mederski, P.S.; Borz, S.A.; Đuka, A.; Lazdiņš, A. Challenges in Forestry and Forest Engineering–Case Studies from Four Countries in East Europe. *Croat. J. For. Eng.* **2021**, *42*, 117–134. [CrossRef]
22. Bumber, Z.; Đuka, A.; Popović, M.; Poršinsky, T. Soil Characteristics in Oak Lowland Stand—A Case Study of a 6 Wheeled Forwarder's Impact on Forest Soil. *Croat. J. For. Eng.* **2024**, *45*, 85–95. [CrossRef]

23. Vucelja, M.; Borz, S.A.; Bjedov, L.; Tomljanović, K.; Kranjec Orlović, J.; Boljfetić, M.; Matijević, M.; Margaletić, J. Forest Residue Management Impact on Rodent (Rodentia: Murinae, Arvicolinae) Damage in Pedunculate Oak (*Quercus robur* L.) Forests in Croatia. *Croat. J. For. Eng.* **2023**, *44*, 121–135. [CrossRef]
24. Moskalik, T.; Gendek, A. Production of Chips from Logging Residues and Their Quality for Energy: A Review of European Literature. *Forests* **2019**, *10*, 262. [CrossRef]
25. Belbo, H.; Talbot, B. Systems Analysis of Ten Supply Chains for Whole Tree Chips. *Forests* **2014**, *5*, 2084–2105. [CrossRef]
26. Björheden, R.; Thompson, M.; Rickards, J. *Forest Work Study Nomenclature, WP 3.04.02. Test Edition Valid 1995–2000*; International Union of Forestry Research Organisations (IUFRO), Department of Operational Efficiency, Swedish University of Agricultural Sciences: Garpenberg, Sweden, 1995; 16p.
27. Mihelič, M.; Spinelli, R.; Magagnotti, N.; Poje, A. Performance of a new industrial chipper for rural contractors. *Biomass Bioenergy* **2015**, *83*, 152–158. [CrossRef]
28. Magagnotti, N.; Spinelli, R.; De Francesco, F.; Lombardini, C. A Versatile Terrain and Roadside Chipper for Energy Wood Production in Plantation Forestry. *Balt. For.* **2016**, *22*, 107–115.
29. Bergström, D.; Di Fulvio, F. Review of efficiencies in comminuting forest fuels. *Int. J. For. Eng.* **2019**, *30*, 45–55. [CrossRef]
30. Spinelli, R.; Visser, R. Analyzing and estimating delays in wood chipping operations. *Biomass Bioenergy* **2009**, *33*, 429–433. [CrossRef]
31. Belbo, H.; Vivestad, H. Predicting delay factors when chipping wood at forest roadside landings. *Int. J. For. Eng.* **2018**, *29*, 128–137. [CrossRef]
32. Mihelič, M.; Spinelli, R.; Poje, A. Production of wood chips from logging residue under space-constrained conditions. *Croat. J. For. Eng.* **2018**, *39*, 223–232.