Original scientific paper

Production of Wood Chips from Logging Residue under Space-Constrained Conditions

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Abstract

A study was conducted on chip production from logging residue left after a cable yarder operation. The logistics were managed with tractor and trailer units (shuttles). The study specifically dealt with a very difficult case of space constrained operations, further expanding the knowledge about chip supply in extreme work conditions. The focus of the investigation was also extended to the shuttles. The study tested a production chain, in which only 3 machines (1 chipper, 2 shuttles) were used to minimize operational costs. The use of 2 shuttles was decisive, reducing shuttle delays. The chips produced had an average moisture content of 40.2 ±3.1%. Particle size distribution shows an unfavorable composition. The content of accepts is as low as 72%, while oversized particles get up to 5.4% and fines rise to a maximum of 24%. The estimated net productivity of the whole system was 11.5 t PMH^{-1}, corresponding to a gross productivity of 11.1 t SMH^{-1}. The cost of the whole operation amounted to 21.2 €t^{-1}.

Keywords: Biomass; forestry; logistics; mountain; harvesting

1. Introduction

Recent years have witnessed a global drive for sustainable energy. In European policy, measures have been adopted aiming to increase the use of renewable resources (Lindstad et al. 2015). The industry and markets have adapted to these new demands (Mihelič et al. 2015, Stupak et al. 2007). That explains the renewed interest for the recovery of logging residues as a renewable energy medium. The downside of logging residue is the fact that they are scattered on very large areas (Karpachev et al. 2017), which makes collection very expensive, especially given the low market value of the end product.

Logging residues left after whole tree extraction with cable yarders are a good option for wood biomass production, as the residues are pre-concentrated by the cable yarder (Spinelli et al. 2007). Here the problem is the terrain and the condition of forest roads in the alpine region. Poor road standards (steep gradient, narrow width, small turning radius) pose a serious challenge to the economy of the logistic operation. Trucks with trailers are often unable to reach the worksite, or there is not enough space on the road for parking a chipper and a truck with trailer. An option would be to use trucks with containers, but that is not a very popular option with contractors, as the tare weight of the truck is increased (Spinelli et al. 2014a). Theoretically, the most efficient solution is to upgrade the road network, but that incurs significant costs and must be assessed very carefully due to its potential for environmental impact (Petković and Potočnik 2017). That is especially true for hydro-geological impacts, because larger roads mean steeper banks, which are the origin point of much sediment production (Hernández-Díaz et al. 2015, Pičman et al. 2007).

There is one more option, however, which is popular with private contractors in Southern Europe, namely: using a farm tractor and a trailer for the intermediate transportation of chips from the chipping pad to the roadside landing. Once there, chips are dumped onto the ground and loaded onto truck and trailer units with a separate loader, or with a front-end loader mounted on a tractor. The advantage of this system is flexibility, as tractors with trailers are very maneuverable and can easily navigate steep and narrow roads. Furthermore, tractors with trailers are not special machinery and they are widely available at local farms. The system is also less dependent on the arrival of trucks because the chip pile built at the roadside landing serves as a buffer, so when the truck arrives it can be readily loaded (Marchi et al. 2011).

However, this system also has its drawbacks, and namely: additional persons have to be present; there is a need to store the piles of chips; additional work phases are included (load transfer, i.e. dumping and reloading). Furthermore, product losses occur almost inevitably, because the landings are usually unpaved and the front end loaders are incapable of retrieving all of the chips dumped onto the terrain, without incurring severe product contamination. In fact, some level of product contamination is most likely to occur, especially if the ground on the landing is rough.

At any rate, this system is often used, but the studies about it are still relatively rare. Therefore, the productivity and the cost of such operation were investigated, including all main processes, from chipping to loading on road trucks. The study also included an analysis of the quality of chips (moisture content, particle size distribution and bulk density) derived from logging residues from a spruce-dominated stand. The final objective was to provide recommendations to operation managers, for deciding if and when this operational mode is economically feasible in their specific working conditions.

Table 1 Description of the site

Height above sea level, m	1350
Latitude (WGS84)	46°43'42"
Longitude (WGS84)	14°26'24"
Species	Spruce, beech, maple, larch
Average inclination, %	89
Association	Rhodothamno-Rhododendretum hirsuti
Rockiness, %	45
Total study time, SMH	4
Productive time, PMH	2
Loads produced, n°	5
Volume produced, m^3	126
Chips produced, t	47.5
Bulk density, kg m^{-3}	377.5±20.93
Feedstock type	Top & lop, slash
Moisture content, %	40.2±3.11
Site organization	Large pile, very limited space

Notes:
m^3 – cubic meters of loose chips
t – fresh tones
PMH – productive machine hours excluding all delay time
SMH – scheduled machine hours, including all delay time

2. Materials

2.1 Study area

The study consists of a case study in the Northern Slovenia. The attributes of terrain, landing characteristics and feedstock type were considered representative for the conditions commonly encountered by wood chipping contractors working with forest residue chipping in mountainous conditions. The characteristics of worksite and feedstock are shown in Table 1. The chipper used the same work settings during the entire study. In particular, cut length and screen size remained the same (Eliasson et al. 2015, Facello et al. 2013).

2.2 Supply process

Piles of forest residue located at cable yarder landing were used for the production of green chips. The piles of slash were piled using hydraulic crane of the cable yarder, following a whole tree cable yarder operation. The operation was a cold deck operation, meaning that residue recovery occurred after the yarder had completed its work and had been dismantled, in order to minimize interruptions and delays of yarding and chipping operations. The truck-mounted chipper was located next to the side of the pile. Two tractor and trailer units acted as shuttles, which were directly fed by the chipper and the chips where transported to the roadside landing. The tractor and trailer units are referred to as shuttles. When chipping was finished, one tractor remained on the road side landing waiting for the trucks to arrive, and then proceeding to load them with a front-end loader attachment. All tests were conducted in early December 2011.

Three workers were on-site during the trial, because the extreme conditions of the site required one driver to be available for each machine. Too much maneuvering was involved for one single tractor driver to manage both shuttles. The chipper operator was also the machine owner and contracting firm manager. He was a trained and well experienced professional, who was very proficient with his job and equipment. The drivers of the shuttles were also experienced professionals, well used to work in such conditions.

Slash piles were located below the forest road next to the landing site. The residues consisted of slash, tops, broken or otherwise damaged parts of logs and branches. Residues had been stacked randomly, as trees were brought to the forest road and processed. The topping diameter was 10 cm.

2.3 Machines used and machine configurations

The chipper used in the operation was a truck-mounted Starchl MK74 600. The machine was a standard model, but had been adapted for work with residue piles, as the contractor's primary business was chipping the logging residue left at the side of forest roads after cable extraction (Fig. 1). The machine was new, and it had just been acquired by the contractor at the time of the study, featuring a detached cab (Poje et al. 2018). Adaptation consisted in the fitting of a loader with the maximum possible reach for the available truck size. The loader mounted a FG31R grapple, designed for handling contaminated logging residue, with open tines. The chipper was mounted on a truck and powered by its own independent engine with total power of 242 kW, which categorized the machine into the larger family of industrial chippers (Spinelli and Hartsough 2001). Main chipper characteristics are presented in Table 2.

The truck chassis was supported by 3 axles. The power was transmitted to rear two axles of the chassis, with locking differentials. The machine was quite heavy and axle weight was close to the maximum Slovenian legal limit for road traffic. However, the 3 axle configuration was deliberately chosen by the contractor, as it maximized maneuverability. The minimum turning radius was 9.9 m, which allowed negotiating winding mountain roads. A 4-axle configuration would have been limited by a much larger turning radius.

Traction power was delivered to both rear axles. The 6×4 configuration is better than the 6×2 option, because driving on steep and often unpaved mountain roads requires higher traction capacity than a single-axle drive configuration is able to provide. On the other hand 8×8, or 6×6 drive options may result too heavy and expensive for producing a low-value assortment. Therefore, the contractor deemed that a 6×4 configuration offered the right trade-off between mobility and maneuverability in such conditions.

Fig. 1 The Starchl MK74 600 mounted on a truck chassis

Table 2 Main chipper characteristics

Truck manufacturer	Mercedes-Benz
Truck model	Actros 2640
Truck engine type	Mercedes Benz V6, OM 501 LA II/3
Truck engine power	298kW at 1800 rpm
Chipper manufacturer	Fa. Helmut Starchl Hackmaschinenbau
Chipper model	Starchl MK 74 600
Chipper – engine type	CAT C9 inline 6-cylinder, 4 stroke diesel
Chipper – engine power	242 kW, 1450 Nm
Weight	24,500 kg
Length	9.5 m
Width	2.55 m
Height (transport position)	4.0 m
Crane	Epsilon Palfinger M110L
Crane reach	10.7 m
Grapple	Epsilon FG31R
Cabin for machine operator	Epsilon Epscab CAM/CAE
Chipping Closed drum with 12 chipping knives	
In-feed size	740×450 mm
Screen size	100×100 mm
Drum diameter	610 mm
Drum turning speed	Up to 500 revolutions min^{-1}

Note: Data provided by the manufacturer and contractor

The blower enabled discharging chips to three machine sides: front, rear and port side. The starboard side was unavailable for chip discharge because it carried the chipper in-feed and it always faced the wood piles, which made it impossible to park a container on that side (Spinelli et al. 2015).

When the study started, the truck had 4500 work hours and the chipper 400 h on its meter.

2.4 Supply chain and logistics layout

The route from the main public asphalt road to the cable yarder was gravel road, 550 m long, with no place for trucks to turn. The landing for chips was a widening of the main asphalt road and usually served as a parking lot; therefore, the distance from the slash pile to the landing site was the same as the distance between the slash pile and the main road. The logistics of roundwood transportation were extremely strained, as the road was steep, narrow and several hairpins had to be navigated. Therefore, log trucks had to detach their trailers, back up all the way up to the yarder pad, load the logs and return to the roadside, where the logs were transferred onto the trailers. The lessons learned in the transport of roundwood made it clear that the logistics of chip production could not be based on truck and trailer units. Instead, lighter and more agile tractor-trailer units became the contractor's vehicle of choice for managing the supply chain logistics (Table 3). The shuttle units were representative of two standard types often used in this type of operations. Configuration 1 (Lindner-Stetzl) was smaller and lighter than configuration 2 (Deutz-Fleigl). The trailer in configuration 2 was a new generation push-off model, with built-in hydraulics that substantially shortened unloading time. There were several advantages to the push-off trailer over a conventional tipper trailer, and namely: better stability and capacity to unload in buildings with low ceilings. Such trailers can also compact the load to increase payload when dealing with low-density material, but this option was not used in the study. The drawbacks of the push-off trailer were its higher price and heavier tare weight.

The propulsion of both tractors was in 4×4 configuration, while trailers were without propulsion. The narrow width of the shuttle units and their short turning radius combined to achieve better maneuverability than any truck and trailer convoy could. Chips were blown into the shuttle units, which shuttled them to the roadside landing, for dumping onto a large pile built on the ground. Chips were then re-loaded onto road convoys using a Quicke Q75 front-end loader attachment installed on one of the tractors. In the case of the study, both chip contamination and losses were minimal, as the roadside landing was asphalt.

Table 3 Main tractor and trailer characteristics

Machine	Configuration 1	Configuration 2
Tractor manufacturer	Lindner G.m.b.H	Deutz Fahr
Tractor – model	GeoTrac 103	6160
Tractor – engine type	Perkins	Deutz TCD 4.1
Tractor – engine power	74,5kW at 2200 rpm	120 kW at 2100 rpm
Trailer manufacturer	Stetzl	Fliegl
Trailer – model	TK13	Gigant ASW 160
Weight tractor + trailer empty	3720+2950	5670+4200
Permitted total weight of trailer	13,000 kg	16,000 kg
Length tractor + trailer	4550+3437	5600+4772
Width (maximum)	2150	2380
Height (maximum)	2453	3050
Type of discharge	Tipper	Push off
Volume of trailer	25 m^3	27 m^3

3. Methods

A typical time study (Magagnotti and Spinelli 2012) was performed using a handheld computer, running the dedicated Laubrass UMT Plus time study software. One researcher has timed the chipper and the other the shuttles. The snap-back timing method was used. The study was designed to evaluate chipper and shuttle productivity and identify the variables that were most likely to affect it. Timing operations can be seen in Table 4.

Timing sessions lasted the entire workday. The purpose was to obtain a good representation of the structure of a typical workday, subdivided into different productive and non-productive activities (Bjorheden and Thompson 2000). Productive time was separated from delay time. All delays were included in the study, and not only the delays that were below a set duration threshold. Such practice could misinterpret the incidence of downtime, especially on comparatively long observation periods (Spinelli and Visser 2008). Delays caused by the study itself were separated and excluded from the data set. The filling of one trailer was considered as one work cycle. Study time was divided into defined time elements, according

Table 4 Operations of time studies, their short description and classification

Operation	Description of operation	Classification of time according to Bjorheden and Thompson (2000)
Chipping	Chipping of material	WP, WT, PW, MW
Feeding	Adding material on the conveyer	WP, WT, PW, MW
Positioning	Placing the machine	WP, WT, PW, CW
Sorting	Organizing the pile and picking up leftover material	WP, WT, PW, CW
Meal break	Main (meal) break	WP, NT, WD, ME
Personell delay	Delays because of worker	WP, NT, WD, RP
Operational delay	Delays because of organization	WP, NT, WD, IT
Mechanical delay	Delays because of the machine	WP, NT, SW, ST
Preparation time	Time it takes to set the machine up and take down time	WP, WT, SW, PT, CO
Driving on road	Driving on road	WP, WT, SW, PT, RL
Driving on landing	Driving on skid trail/landing	WP, WT, SW, PT, OP

to the IUFRO classification (Bjorheden and Thompson 2000) and following the harmonized European guidelines (Magagnotti and Spinelli 2012). The operator performance was not normalized by means of productivity rating. All observed cycles were included into the master database.

Mass output was determined by taking loads to a certified weighbridge. Volume output was estimated by measuring the internal volume of trailers, and visually assessing the volume of mounds or voids on trailer tops. Two 500 g samples were collected from each trailer in order to determine particle size distribution and moisture content. Each sample was composed by mixing subsamples collected at different points from the container top. Sample size for determination of particle size distribution was determined according to standard (EN15149-1:2010). Moisture content was determined with the gravimetric method, according to European standards (EN14774-2, 2010). Fresh sample weight was determined immediately after sample collection with a portable scale, to avoid the bias caused by moisture loss during storage and transport to the laboratory. Particle size distribution was determined with the oscillating screen method, according to European standards (EN15149-1, 2011).

Fuel input was estimated by measuring the quantity of fuel used after the machine was refueled. This was the total fuel consumption for the mix of productive work, delays and relocation occurred during the study.

Machine costs were calculated with the method developed within the scope of COST Action FP0902 (Ackerman et al. 2014). It was assumed that the machine worked 2000 scheduled machine hours (SMH) per year, over a depreciation period of 5 years (amounting to a service life of 10,000 scheduled machine hours). Labor cost was calculated at 20€ SMH^{-1}, inclusive of indirect salary costs. The costs of insurance, repair and service were obtained from the contractor. The investment price includes 22% VAT. The calculated operational costs were increased by 25% in order to include relocation, overheads and administration costs (Table 5).

Study data were analyzed with MS Excel in order to extract descriptive statistics and check for the statistical significance. Because of the interdependent nature of particle size distributions, basic approaches of compositional data analysis were used (Aitchison 1986). Compositional data were transformed using Isometric Log

Table 5 Estimated cost of machines involved in the operation

	Chipper	Configuration 1	Configuration 2	Loader
Investment – base machine, EUR	260,000	80,000	92,449	92,449
Investment – attachment EUR	–	16,000	24,278	–
Resale value (20%), EUR	52,000	19,200	23,345.4	18,489.8
Number of working days, Days per year	200	200	200	200
Service life, Years	5	5	5	5
Utilization, SMH/year	1600	1600	1600	1600
Interest rate, %	4	4	4	4
Depreciation, EUR/year	32,640	8693.15	11,707.08	9221,02
Interests, EUR/year	6888	2247.42	3032.13	2399.74
Insurance, EUR/year	5772	1400	1500	1500
Diesel, EUR/year	34,560	12,288	13,824	13,824
Lube, EUR/year	6912	2457.60	2764.80	2764.80
Maintenance, EUR/year	20,800	5535.62	7470.53	5916.74
Total, EUR/year	107,572	32,621.78	40,298.55	35,626.29
Total, EUR/SMH	67,23	20,38	25,18	22,27
Crew, n	1	1	1	1
Labor, EUR/SMH	20	20	20	20
Overheads (25%), EUR/SMH	23,05	11,34	12,54	11,81
Machine rate, EUR/SMH	115,29	56,73	62,73	59,07

Ratio transformation in the CODAPAC software (Comas-Cufí M. and Thio-Henestrosa S. 2011), and the ternary diagram was plotted in R (Team 2008).

4. Results

The mechanical availability (i.e. total worksite time minus mechanical delays, divided by total worksite time) of the chipper was very high and amounted to 99.6 . Utilization (the ratio between productive time and total worksite time) of the chipper was 50.4%, which corresponded to a 74% delay factor (Spinelli and Visser 2009).

A detailed overview of worksite time (Fig. 2) shows that waiting accounted for 46% of the total time on site. Waiting generally occurred because no shuttles were available on site, or they were being maneuvered into place. Apparently, two shuttles were not enough to keep the chipper busy, despite the relatively short extraction distance. However, constrained space and the absence of any space for exchanging would have made it very difficult to introduce a third shuttle.

Chipping time represented 33% of total worksite time. The average chipping time was 37.5 ±3.45 s m^{-3} (loose volume). Feeding time represented 16% of total worksite time, or 17.8 ±5.61 s m^{-3} (loose volume).

Pure chipping productivity, defined as productivity achieved during the time of chipping, varied between 87 and 106 m^3 of loose chips per hour and was the highest in the last cycle (Table 6). Differences were leveled out by inclusion of supportive (positioning and sorting) and non-productive time (delays), which were an integral part of worktime.

Calculating productivity on the basis of fresh weight did not change the general picture of productivity. Pure chipping productivity ranged from 31 to 41 t h^{-1}.

Fuel consumption varied between 0.4 and 0.62 l m^{-3} loose volume, or between 0.8 and 1.9 liter per ton of chips.

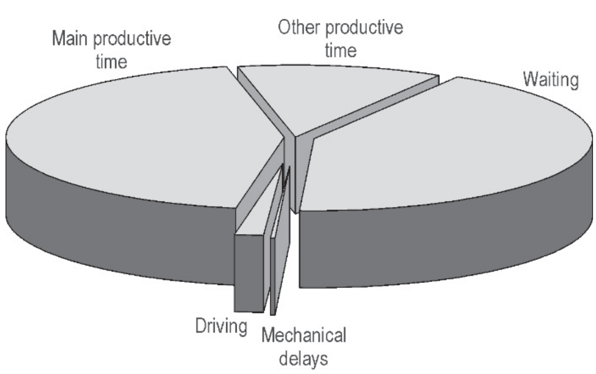

Fig. 2 Breakdown of worksite time for chipper

Shuttle utilization amounted to 76%, with very little interaction delays. This included driving and unloading. The utilization of shuttle 1 was 4.6% lower than that of shuttle 2, due to a different unloading system.

Loading of chips, dumped on the ground (asphalt landing) by shuttles, into container trucks required moving chips over an average distance of 7.5 m, or a maximum distance of 15 m. The distance depends on the distribution of dumped chips on the landing. Loading productivity was very high and averaged 112.9 t PMH^{-1}, or 89.9 t SMH^{-1}. The time it took to clean the roadside landing is included in this figure.

Table 6 Productivity, fuel use and cost

Chipper		
Pure chipping productivity – chipping only	$m^3 h^{-1}$ chipping	96.3
Net chipping productivity – excl. delays	m^3 PMH^{-1}	65.1
Gross chipping productivity – incl. delays	m^3 SMH^{-1}	36.9
Fuel use	l m^{-3}	0.51
Chipping unit cost	EUR m^{-3}	3.5
Shuttle 1		
Net productivity – excl. delays	m^3 PMH^{-1}	57.4
Gross productivity – incl. delays	m^3 SMH^{-1}	18.0
Unit cost	EUR m^{-3}	3.0
Shuttle 2		
Net productivity – excl. delays	m^3 PMH^{-1}	59.5
Gross productivity – incl. delays	m^3 SMH^{-1}	16.7
Unit cost	EUR m^{-3}	3.5
Loader		
Net productivity – excl. delays	m^3 PMH^{-1}	274.5
Gross productivity – incl. delays	m^3 SMH^{-1}	218.3
Unit cost	EUR m^{-3}	0.2
Whole system		
Net productivity – excl. delays	m^3 PMH^{-1}	30.8
Gross productivity – incl. delays	m^3 SMH^{-1}	29.4
Unit cost	EUR m^{-3}	10.7

Notes:
m^3 – cubic meters of loose chips
Net productivity is calculated on the basis of net time, excluding preparation and delays
Gross productivity is calculated on the basis of total time, including preparation and delays

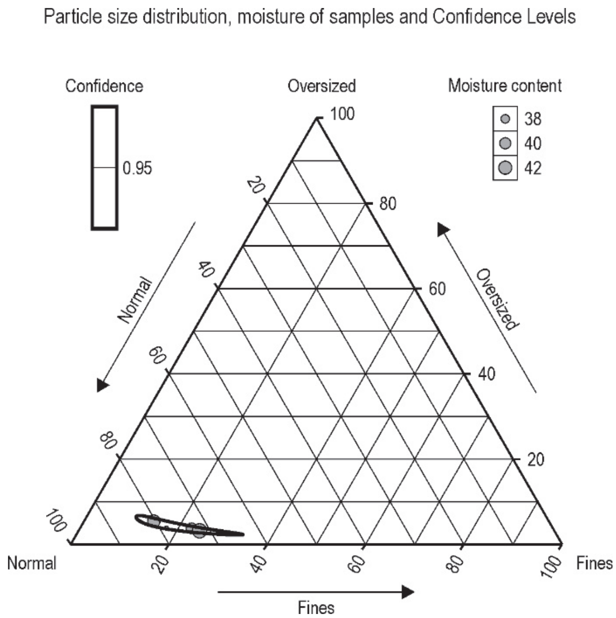

Fig. 3 Ternary diagram of particle size distribution and moisture content of samples

The estimated chipping cost was 3.5 € m^{-3} for loose chips, or 8.8 € t^{-1} for fresh chips. The cost of chip shuttling was 3.0 € m^{-3} or 7.8 € t^{-1} for shuttle 1, and 3.5 € m^{-3} or 9.5 € t^{-1} for shuttle 2. Therefore, shuttling with the push off trailer was 1.7 € t^{-1} more expensive than with the tipper trailer. The cost of re-loading on road convoys amounted to 0.6 € t^{-1}. These figures include transfer to the site, which was accounted for in the overheads. The estimated net productivity of the whole system (one truck-mounted chipper and two shuttles) was 11.6 t PMH^{-1}. Corresponding gross productivity was 11.1 t SMH^{-1}. The estimated cost for the whole operation amounted to 26.7 €t^{-1}.

Wood chip moisture content was different between cycles and ranged from 36.2 to 43.6 percent.

The ternary diagram in Fig. 3 shows that the largest proportion of the chip mass was represented by accepts (particles of size between 100 and 3.15 mm), which averaged 76.2% of the total, with a minimum of 72.2% and a maximum of 80.4%. The average incidence of oversize particles (above 100 mm) was 4.1% (maximum 5.4% and minimum 3.18%). Fines (particles smaller than 3.15 mm) accounted for 19.8% of the total mass as an average, with a minimum at 14.2% and a maximum at 24.5%.

5. Discussion

Other studies have already explored the subject of chipping operation in space-constrained mountain areas (Spinelli et al. 2007), but this study deals specifically with a very difficult case, where very limited space is available for maneuvering. Therefore, it further expands the knowledge about chip supply in extreme work conditions, and offers a glimpse of an operation caught in an awkward but not uncommon situation. Furthermore, the study enlarges the focus of the investigation to the shuttles, which previous studies kept in background (Spinelli et al. 2015). Unfortunately, inference is based on a very limited number of observations, due to the second typical limitation of mountain operations, after poor road standards, and namely: small lot size. Nevertheless, the small number of observations obtained from the study is still large enough for the proficient application of statistical analysis, which has allowed checking the quality of our data with scientific methods.

Transportation is a main component of chip supply cost, and requires careful planning, especially in mountainous areas (Kühmaier and Stampfer 2012). Furthermore, interaction between the chipper and the transport fleet generally results in low chipper utilization (Spinelli et al. 2014a). The alpine work conditions push the economics one step further, as conventional road trucks are often unable to reach the worksite. That can occur because of a number of reasons, all related to the poor quality of the road infrastructure (e.g. narrow width, steep gradient, small turning radius). When road trucks are unable to reach the worksite, operators are forced to consider alternative transport options. One of them is chipping on site and shuttling the chips with tractor and trailer units to a location suitable for trucks. This additional step will naturally incur additional costs, potentially causing a negative economical outcome for the contractor. However, transportation distance is not the only limiting factor. Chip quality also plays an important role, as it has a major effect on the price of the end product. The study operation produced green residue chips, with high moisture content and a high proportion of leaves and needles, which qualified the chips into the lowest grade and negatively impacted the price. Taken together, transportation and quality constraints contributed to push the economics of this operation quite close to the limits of financial viability.

On the other hand, the study has tested a production chain in which only 3 machines (chipper, 2 tractors and trailers) were used, in order to minimize operational costs (Rawlings et al. 2004). In that regard, the use of 2 shuttles was decisive, because it allowed reducing shuttle delays.

Such conditions are especially detrimental for chipper efficiency, as shown by a very high delay factor, which exceeded the already high 50% benchmark reported for truck-mounted chippers (Spinelli and Visser 2009). For the same reason, the incidence of pure chipping time was much lower than in previous studies (Spinelli and Hartsough 2001). Fortunately, feeding was relatively fast, due to the good cooperation between the yarding team and the chipping team. The chipper operator was confident that there were no stones or metal in the pile of residue. Therefore, the chipper operator never checked the grapple for contaminants and always collected full grapple loads. The operator took care to keep the road clean and free of residue, and to make sure that the position of the truck was as near to the edge of the road as possible. This way the length of the crane was fully exploited and the pile of feedstock easily reached.

The machine takes a lot of time to re-position, so it is not ideal for poorly organized sites, which require several positioning maneuvers (Spinelli and Hartsough 2001). Each time the chipper is re-positioned, the operator has to lower the crane and cabin, exit, retract the stabilizers, climb into the truck cabin, move the truck and repeat the whole process in reverse. Fortunately, frequent re-positioning was not a problem in this trial, as all feedstock was easily available in one large pile.

The utilization of the shuttles was high, compared with the figures reported in other studies (Spinelli et al. 2014a). The reason for that was that the distance from the landing to the chipping site was relatively short, and the number of shuttles involved in the system was well-balanced. It is still debatable whether adding a third shuttle would have increased chipper utilization. The forest road had very few enlargements, which prevented the easy exchange between incoming and outgoing shuttles. Therefore, the incoming shuttle had to wait at the nearest enlargement and let the outgoing trailer drive past, before it could drive to the turning point (up the road and past the chipper), turn and return back to the chipper for loading. Under such conditions, a third trailer would only add to the overall waiting time of the system, as it would hinder traffic and add to the interaction delays.

The moisture content of chips obtained from logging residue is usually very high. The reason for that is that branches and tops normally have higher moisture content than stem wood. Residue chips also have a high content of bark and needles (Spinelli et al. 2011a), which detracts from quality. Average moisture contents of fresh coniferous forest residue reported so far are 38% (Rawlings et al. 2004), 35.4 ±3.9% (Spinelli et al. 2014a), and 34.9% (Spinelli et al. 2011a). The chips produced in our study have the highest average moisture content with 40.2 ±3.1%. Some reduction of moisture content may have been achieved by leaving the residue sit for a longer time at the landing, so that natural drying may occur. However, that is not always possible, because residues left at the edge of the forest may represent a source of infestation by insect, and forest managers often prescribe rapid removal.

The particle size distribution is also unfavorable. The content of oversized particles gets as high as 5.4%, while fines rise to a maximum of 24%. These figures are worse than reported in other studies for the same feedstock type, especially for what concerns the presence of fine particles (Spinelli et al. 2011b). A high incidence of fine particles is typical of chips produced from softwood branches, and derives from the abundant presence of needles (Spinelli et al. 2011b). However, the amounts of fines in the study samples are close to the maximum values recorded in all previous studies, which may hint at some problems with machine settings – possibly excessive knife wear (Spinelli et al. 2014b) and/or an excessively small screen size (Nati et al. 2010). Adjusting machine settings and replacing knives more frequently is likely to lead to an improvement in chip quality, although the unfavorable characteristics of the original feedstock will still have their effect. Replacing the blower with a belt conveyor may lead to a further reduction in the incidence of fines, but it would increase machine size and weight and it would be very impractical for a machine used in space-constrained work environments (Spinelli and Magagnotti 2012).

Fortunately, chipping and extraction cost is within the 20–27 € t^{-1} range found in previous studies (Spinelli et al. 2014a), despite the extreme access constraints. In that regard, the short shuttling distance certainly helped: it is doubtful whether the same results could have been achieved on substantially longer distances, exceeding one or two kilometers.

6. Conclusions

Comminution of forest residues is not just an economic activity, but also an important forest tending measure. Unfortunately, the effects of climate change include increased natural disturbances and drought (Dale et al. 2001), which result in a higher risk for forest fires and insect infestations. That calls for stricter fire mitigation measures, including a reduction of forest fuel build ups (Hartsough et al. 2008). Slash piles must be removed whenever possible because they represent a substantial fuel accumulation, and an ideal breeding place for noxious insects (Kacprzyk and Bednarz 2015).

Chipping seems an ideal solution, but the question arises whether there is another, more cost-effective option for biomass chipping than that presented in this study. Recent simulation studies show that extracting chipped biomass is often more efficient than extracting uncomminuted residues and chipping them at the main landing (Spinelli et al. 2014a). While it lacks the comparative element of previous simulation experiments, the present study shows that chipping before extraction is still a viable option even when road network conditions are extremely poor, and may reassert the benefits of chipping as close to the source as possible (Björheden 2008).

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