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Predicting Delay Factors when Chipping Wood at Forest Roadside Landings

Corresponding author: Helmer Belbo

Affiliation: The Norwegian Institute of Bioeconomy Research

Postal address: Postboks 2609, 7734 Steinkjer

Email adress: beh@nibio.no

ORCiD: orcid.org/0000-0001-7060-1467

Co-Author:

Henriette Vivestad

The Norwegian Institute of Bioeconomy Research

Email address: henriette.vivestad@norgesvel.no.

Postal address: Postboks 115, 2026 Skjetten

Title: Predicting Delay Factors when Chipping Wood at Forest Roadside Landings

Highlights: This paper presents a method to predict organizational delays in wood chipping operations at forest roadside landings. The approach suggested here will improve supply planning and thereby reduce costs in wood-chip supply of virgin forest biomass resources. A method to predict delays caused by unfavorable working conditions is also suggested, but more work should be done to improve that method.

Abstract:

Chipping of bulky biomass assortments at roadside landings is a common and costly step in the biomass-to-energy supply chain. This operation normally involves one chipping unit and one or several transport trucks working together for simultaneous chipping and chip transport to terminal or end user. Reducing the delay factors in these operations is a relevant ambition for lowering supply costs. A method to estimate organizational delays based on 1) the capacity ratio between the transport and the chipper, 2) the use of buffer storage and 3) the number of transport units involved is suggested here. Other delays will also be present, and some of these may relate to the working conditions at the chipping site. A method to set a site functionality score based on characteristics of the work site is also suggested. Fourteen roadside chipping operations were assessed and the operators were interviewed to address the impact of machinery configuration and chipping site characteristics on machine utilization. At most sites, the chipper was the more productive part, and the chipper utilization was to a large extent limited by organizational delay. Still the utilization of the transport units varied between 37 and 97 %, of which some 36% of the variation was explained by the site functionality score. Knowledge from the work presented here should be a good starting point for improving biomass supply planning and supply chain configuration.

Keywords: Wood-chip supply; forest operations; machine utilization, chipping, woodchip transport.

Introduction

A forest landing is a location to which wood is yarded/forwarded for loading onto trucks (Stokes et al. 1989), or even also for processing trees . For voluminous biomass assortments such as logging residues and small whole trees, chipping at the forest landing followed by immediate truck transport of the chips is a common method (Asikainen and Pulkkinen 1998; Asikainen et al. 2008; Kärhä 2011; Röser Dominik et al. 2012; Eriksson et al. 2014b; Kons et al. 2014; Eliasson et al. 2015). The machines involved are mutually dependent in a so-called hot system, where significant queuing and waiting time is likely to occur(Asikainen 1998). Field trials of such operations indicate delay factors (i.e. the ratio of delay time to the productive machine time) for the chipping machines in the range 32 – 50 % in average, of which 11 – 19 percent points belonged to mechanical interruptions (maintenance, repair, etc.) and operator interruptions (rest, breaks, etc.), and 20 – 31 percent points were organizational or other delays (Spinelli and Visser 2009; Röser Dominiq 2012; Eliasson et al. 2014).

Both practitioners and researchers highlight the importance of careful organization of chipping and truck transport systems, and the importance of having adequate landing conditions for the operation, to minimize costly delays (Asikainen 1998; Spinelli and Visser 2009; Asikainen 2010; Eriksson et al. 2014a). The impact of varying trucking capacity and buffer storage to system performance has been highlighted in several simulation studies lately (Eriksson et al. 2014b; Eliasson et al. 2017). From the later study of a container system it was recommended to set up four container trucks and a buffer reception of six containers (Eliasson et al. 2017). However, limited flat area of sufficient bearing capacity may limit maneuver space and complicate positioning of the reception unit(s) by the chipper. In many cases the chip reception unit(s) must be backed to the chipper, and the “backing distance”, road width and straightness will affect terminal time for the chip transport. Also typically the turning point is at the inner part of the forest road, while the chipping site is closer to the outlet public road. If then only the forest road provides the maneuver space for both chipper, chip transport and perhaps also chip containers, the efforts to switch chip reception units may be substantial. A good understanding of how the work conditions at the roadside landing and supply chain configuration impact machine utilization is therefore an essential part of the supply planner's competence.

In this paper a method to predict delays in roadside wood-chipping operations is suggested. Organizational delays are determined on the basis of the capacity ratio between the chipping and the transport units, as well as the presence or absence of buffer storage and the number of transport units involved. Other delays are also predicted based on a simple quantitative method for evaluating landings for chipping operations. The method will allow supply planners to predict machine utilization and system performance at future work sites. The method is based on deduction to model the organizational delay factor, and a checklist survey approach to set the site functionality score. Then a study of twelve chipping operations in Norway was done as a first attempt to verify this approach of predicting delays and machine utilization in chipping operations.

Material and methods

Production capacity and delay factors in roadside chipping operations

The production capacity of a chipper or chip truck is here understood as the delay-free production rate (m3 or tonne h^{-1}). For chippers, the capacity can be estimated fairly well by the power of the chipper and the piece size (i.e. the average mass of the pieces to be chipped) (Spinelli and Hartsough 2001). The transport capacity is defined as the net payload (m3 or tonne) of the transport fleet divided by the time consumption of a delay-free roundtrip. The capacity ratio (CapRat) is the ratio between the capacity of the transport unit(s) and the chipper when both are running independently without any delays.

In forest operations studies it is common to separate the work place time (or scheduled time (Björheden and Thompson 1995)) into work time (productive and supportive work time) and non-work time (disturbance and delay times) (Samset 1990; Björheden and Thompson 1995; Magagnotti et al. 2012). In some recent studies the delay times are separated into mechanical delay, operator delay, and to organizational and other delay (Spinelli and Visser 2009). Delay times are normally related to the effective time as a delay time factor (Samset 1990; Spinelli and Visser 2008; Spinelli and Visser 2009). In our approach, the time consumption per production unit (truck load, fleet load, or m^3) was separated to productive time, organizational delay and other delay factors as illustrated in eq 1 and 2.

$$T_{tot} = T_{pmt} + T_{org\_dl} + T_{other\_dl} \tag{1}$$

$$T\_tot = T_{pmt} \times \left(1 + DF_{org\_dl} + DF_{other\_dl}\right) = T_{pmt} \times \left(1 + DF_{tot\_dl}\right) \tag{2}$$

where:

T_{tot} is the total time consumption per work cycle unit (m^3, load or fleet load).

T_{pmt} is the productive machine time required to complete one work cycle.

T_{org_dl} and DF_{org_dl} are the organizational delay time per work cycle and the corresponding delay factor.

T_{other_dl} and DF_{other_dl} are other delay time, and the corresponding delay factor.

The organizational delay factors is here defined as the minimum delay that could be expected in a chipping- and transport operation, according to the setup of production capacity of both tasks as well as the number of trucks engaged in the operation and the use of buffer storage. The approach to determine organizational delay factor is described in appendix 1. For the chipper, this delay is estimated by equation 3.

$$CH\_DF_{org\_dl} = \max \begin{cases} \dfrac{1}{CapRat} - \dfrac{Bffr\_m^3}{N\_trucks \times Truckload\_m^3} - \dfrac{\left(N\_trucks - 1\right)}{N\_trucks} \\ 0 \end{cases} \tag{3}$$

Where:

$CH\_DF_{org\_dl}$ is the organizational delay factor for the chipper

$CapRat$ is the capacity ratio between the transport unit(s) and the chipper when both are running independently without any delays.

$Bffr\_m^3$ is the buffer volume, limited to one truckload volume

N_trucks is the number of trucks involved in the transport

$Truckload\_m3$ is the volume of one truckload

The organizational delay factor for the chip transport unit is derived in the same manner. The deduction is presented in Appendix 1, and the final model for estimating the delay factor is provided in equation 4.

$$CT\_DF_{org\_dl} = \max\begin{cases} CapRat - 1 \\ N\_trucks \end{cases} - \min\begin{cases} \dfrac{CapRat \times Bffr\_m^3}{N\_trucks \times Truckload\_m^3} \\ \max\begin{cases} BufferDummy\left(1 - \dfrac{CapRat \times \left(N\_trucks - 1\right)}{N\_trucks}\right) \\ 0 \end{cases} \end{cases} \quad (4)$$

Where:

$CT\_DF_{org\_dl}$ is the organizational delay factor for the chip transport

CapRat has the same definition as for equation 3

BufferDummy has value 1 in case there is a buffer volume available, 0 if not

In our approach, delays beyond the estimated organizational delay are pooled to the “other delays” term (eq 1 and 2).

The utilization of each machine is defined as productive machine time versus total work time according to eq 5.

$$Machine\ Utilization(MU) \quad = \frac{T_{pmt}}{T_{tot}} = \frac{1}{(1 + DF_{tot\_dl})} \qquad (5)$$

[Figure 1 near here]

According to the definitions used here, there will be a strict relation between the capacity ratio and the organizational delay factor for both chipper and transport units. These relations are illustrated in figure 1. The figure illustrates that in cases where the capacity of the transport fleet and the chipper are equal (i.e. capacity ratio is 100%), the organizational delay will be zero only if there is a chip reception buffer equaling one truckload or more. If this capacity ratio is achieved with only one truck and without buffer, both the chipper and the transport unit will have an organizational delay equal to the productive machine time for each truckload. If this capacity ratio is achieved using several trucks, both the chipper and the trucks will experience a delay factor corresponding to each transport unit's fraction of the total transport capacity. If the chipper has a higher capacity than the transport fleet, the capacity ratio will be less than 100%, the delay factor of the chipper will increase and the delay factor of the transport units will decrease. Increased transport capacity will have the opposite effect, until the transport units start queuing for chipping capacity. At this situation, the chipper's organizational delay will be zero, and a buffer reception for chips will not affect the delay factor for neither the chipper nor the transport units.

For chippers, the productive time per production unit was estimated using time consumption models having chipper power and piece size as independent variables (Spinelli and Hartsough 2001). For roundwood logs and small whole trees the piece size was set to 100 kg, while for logging residues the piece size was set to 40 kg. In cases where the forwarder-based chippers were transporting chips from the chipping site to a truck or container loading site the speed was set to 2 km/h.

For chip transport, the productive time per round trip may be divided into loading time, driving time and unloading time (Ranta and Rinne 2006). The loading time may be further divided into direct and indirect loading time (Asikainen 1998). For fixed bin trucks the direct loading time depends on the productivity of the loading facility (e.g chipper or wheel loader), while trucks using interchangeable containers will have a loading time equaling the container swapping time (Asikainen 1998). The indirect loading time is the time needed to prepare the truck for loading, including parking, tarp covering and so on. The driving time is governed by distance and average velocity. The direct unloading time is the time needed for emptying the truckload, while the indirect unloading time will vary according to the conditions, routines (e.g. biomass quality and quantity measurements), and eventual queuing at the chip reception site. In this particular study, the capacity of the chip transport is set by the time consumption under ideal conditions. I.e. time needed for loading and maneuvering the chip receptacle at the landing beyond the time needed at ideal conditions are considered non-productive time for the transport unit. For container trucks the time consumption for exchanging filled and empty containers has been reported to 8 minutes per container on average (Liss and Johansson 2006). For fixed bin chip transport, the loading time may be very short if the truck is loaded by e.g. a front loader. The minimum time for filling the fixed bin transport was set to 10 minutes.

Study sites

Fourteen chipping locations were visited where both the chipper operator and the truck driver were interviewed about system performance and work environment. The location were identified by asking all forest woodchip suppliers that could be found if they had active chipping operations at forest roadside landings in the period June - September 2015. Locations were then selected to fit time schedules and travel options, and to get some variation in the machine configurations. Most of the sites were located in the south-eastern part of Norway (figure 2).

[figure 2 near here]

Chipping site characteristics

The physical dimensions (length, width) of the landing were measured (figure 3), as well as the distance to turning point and if relevant to bin exchange area. Also the relative position of these latter points, i.e. upstream towards the inner end of the forest road or downstream towards the public road, to the chipping site was recorded. For cases where it was possible to reach the public road in both directions from the landing these points were set to be downstream. The relative position was set to evaluate whether the chipper has to stop chipping and move from the chipping location to let the chip transport unit pass for turning, container positioning and so on.

[Figure 3 near here]

The chipping sites were given a “site functionality score”, a rating based on 1) distance to turning point, 2) adequate bearing capacity of area used for road-dependent equipment, 3) machines propensity to block each other because of limitations at the site, and 4) the site allows engagement of sufficient transport capacity (i.e. sufficient number of trucks, trailers, containers to allow the operation run smoothly). Each of these factors was set to one in case they were good (i.e. short distance to turning point, fair/good bearing capacity) and zero if they were poor. The actual points distinguishing good and poor conditions were set after all the sites had been visited. The site functionality score was simply set to the sum of these factors. The total score will be an integer value in the range 0 – 4, where the latter indicate the “best” working conditions.

Equipment characteristics

Chippers were categorized according to their dependency on road conditions, and the transport units were categorized according to their utilization of container swapping;

- Terrain chippers are chippers using a roundwood forwarder as base machine. Some of them have an on-board chip bin of ~20 m3 bulk volume, providing the option of physically separating the chipping location and loading (to truck or container) location.
- Road chippers are chippers mounted on a truck chassis or a tractor trailer.
- Container trucks are trucks swapping filled and empty bin containers at (or near) the chipping site.
- Fixed bin trucks are trucks filled directly by the chipper. Container trucks being filled directly by the chipper were also set in this category.
- We were not able to study other equipment categories in Norway. Other relevant technologies or machine configurations would include chipper-trucks (Eliasson 2010), container handling chipper trucks (Picchi and Eliasson 2015) and self-loading chip-trucks (Liss and Johansson 2006). These options are less dependent of having other machines simultaneously at the same site, and would therefore probably be less vulnerable for poor site characteristics.

Beside this, the power was recorded for chippers, and load volumes were recorded for chip transport units. Productivity figures and delay times for each machine at each site were estimated by the average truckload work cycle duration at each site. The chipper operators reported their time consumption for chipping and waiting for each truckload delivery. The transport operators reported the total work cycle time, total time at the landing, and waiting time at the landing for each truck load. From these figures the productive and non-productive time per production unit (m^3 bulk volume) was calculated both for the chipper and transport.

Results

Study sites, terminal characteristics and equipment combinations

[Table 1 near here]

The combinations of chipping units and transport units for the visited sites are listed in table 1. The road chippers were chipping directly to containers set on the ground or into the fixed bins on the truck/trailer. The terrain chippers co-working with container trucks were chipping directly to containers or to their on-board chip bin, with subsequent transport and unloading to containers on the ground. At three locations the terrain chipper had no on-board chip container, and was chipping directly to a fixed bin truck.

The work site width (including the road) was in the range 4 – 14 m, where the terrain chipper & fixed bed truck combination differed from the rest in having wider terminals (11-14 m) than the other combinations (4-9 m). According to the chipper operators, the work site width should be at least 4 m and preferably 15-20 m. According to the transport operators, the minimum width is 3.5-5 meters and ideal width 8 – 25 meters, where the operators co-working with terrain chippers preferred the wider options. Working sites having a width above 4 m were awarded one point on the site functionality score, while narrower sites got zero. The operators of the terrain chippers would accept an inclination up to 10% at the chipping site, while the operators of the road dependent chippers had more stringent requirements (0-6%). All truck operators indicated that a completely flat surface was necessary at the terminal. The limit to separate good sites (one point to the score) from poor sites was set at 5% inclination. The distance from the turning place to the terminal site varied between 0 and 2.5 km, and all operators indicated that this distance should be less than 1-2 km. For this variable, the limit for good sites was set to 2 km. For the container trucks, the distance from the swapping site to the terminal varied from 0 to 700 meters. The separation point between good sites and poor sites varied according to whether the truck had to back (drive reverse direction) the container from the swapping point to the chip loading point. If backing the entire distance was necessary, the maximum distance for getting a positive site score was set to 150 m, if not the limit was set to 300 m. In cases where the location of the chipping site, turning point and/or container swapping point caused mutual blocking of the chipper and transport, the mutual blocking variable was set to zero.

The site functionality score ranking working conditions at the chipping sites varied from zero (poor conditions) to four (good). Three terminals got a score below two, at all these sites the bearing capacity of the area intended for the terminal was the major challenge. The low bearing capacity either hindered the use of trailers, or an adequate positioning of the chipper next to the wood pile. The intermediate terminal scores were given where the distance to turning point or bin exchange area was rather long, or if the chipping operation was obstructed by traffic.

[Figure 4 near here]

Productivity and capacity utilization

The organizational delay factors for both the chipper and transport units at each study site are shown in figure 4. The transport capacity was lower than the chipper capacity at all but one site (figure 4 plot 1 and 2). The achieved productivity of chippers varied between 26 and 90 m^3 bulk volume per hour (figure 5 plot 1). For the chippers, the utilization varied between 32% and 58%, and the corresponding total delay factors was in the range 212 – 72%. The organizational delay factor was in the range 60-212% (figure 5 plot 2). The other delay's delay factor was in the range -6% to 105% (figure 5 plot 3), of which the site functionality score explained 60% of the variation (table 2).

[Figure 5 near here]

The productivity of the chip transport truck fleet is set by the total work cycle time and the total load capacity for all trucks involved (figure 6). The contractors apparently attempted to match the capacity of the chipper and the chip transport unit(s). For shorter transport cycles (in our case < 75 minutes) the load volumes were < 50 m^3, at these sites only one truck without trailer was involved in the operation (figure 6). For longer transport cycles, the load capacities were extended by either adding a trailer or another truck and trailer combination. The total chip transport productivity was in the range 30 – 90 $m^3 h^{-1}$ (figure 6).

[figure 6 near here]

For the chip transport, the utilization varied between 32% and 97% (Figure 7, plot 2), and the corresponding total delay factor was in the range 210 – 3%. The organizational delay factor was in the range 0 – 140%, where only supply chain configurations without a buffer volume got a value above zero. For transport configurations with a buffer volume equal to one truckload, the capacity ratio must exceed one (i.e. the transport capacity must exceed the chipping capacity) to get an organizational delay factor above zero (figure 4 plot 2).

[Figure 7 near here]

For the transport, the delay factor for other delays was in the range -6% to 83 % (figure 7, plot 3), in which the site functionality index could explain 36% of the variation (table 2). In some cases the poor work conditions had impacts that were not quantified. At site 12, low bearing capacity made the contractors terminate the entire operation prematurely. At site 14, the chipper was stuck in the soft mud prior to the site visit, but the operation continued after the machine was towed to better ground conditions. The capacity or time loss for these incidents were not recorded or speculated on, but the impact on total time consumption and thereby production costs was obviously more than what is presented here.

Discussion and conclusions

In this study organizational delays in “hot” woodchip supply chains were deducted on the basis of the production capacities of the units and buffer storages involved in the operations. This approach will enable supply planners and contractors to predict system productivity and machine utilization with less uncertainty. The impact of the supply chain configuration, in terms of capacity matching, truck configuration and buffer storage to the organizational delay is illustrated in figure 1. According to the figure, the only practical way to eliminate organizational delay for both the chipper and the transport is to have equal capacity in the two operations and buffer storage between the chipper and the transport.

At all but one sites visited in this study the capacity ratio was below 100% indicating that the chipper capacity was larger than the transport capacity in these cases. The organizational delay factor was therefore larger for the chipper than for the transport units in about all cases (figure 4). As the investment cost of the chipper is often larger than for a truck transport unit, one could question the priority done in the supply chain configurations studied here.

The terminal functionality score had a significant impact on the delay factor both for the chipper and the transport units. Poor terminal functionality was mostly related to limited flat area of sufficient bearing capacity on the terminal, but also excessive distances between the turning place and chipping site or the container swapping place and the chipping site (site 12, 14). In one case constraints at the terminal caused the operators to terminate the operation prematurely.

The minimum width of the chipping sites was 4 meters (excluding the width of the wood pile). At this width the chipper and chip transport unit or bins may be arranged back to back for chipping at the site, which is often a forest road. However, this arrangement obviously limits the reception capacity, as only one container, truck or trailer can be engaged with the chipper at a time, and the chipper will always need to wait when the reception unit is to be replaced. For terrain chippers having an on-board chip bin, a somewhat larger width is needed for the spot where the chipper is to unload to chip bins or a truck, as the chipper and the reception unit must stay next to each other. By increasing the width of the site from four to 5.5 - 6 m, the flexibility of the operation increases in several ways. Either in that the reception capacity by the chipper can be doubled or tripled, or in allowing traffic to pass the operation without interruption. A further widening of the site will further reduce the potential jam of other traffic and ease the swapping and positioning of containers.

The Norwegian standard for forest roads sets a normal road width of 4 m, and meeting spots for on-coming traffic of 7 m width and 25 m length every 500 m. It will therefore be possible to do chipping operations anywhere these roads are flat (which may be seldom in many areas). Wider parcels might be found every 500 m at the best. It will therefore often be a consideration whether the forwarders should bring the biomass to nearest landing candidate or to these meeting spots before piling the material. The low density of suitable landings is a likely explanation for the popularity of terrain chippers having an onboard chip bin in Norway. This is an expensive setup both regarding investment cost and machine transport between work sites, but increases the flexibility regarding the positioning of the pile of chipping material and the location for loading for road transport.

There are systems available that reduce the dependency between the chipper and the chip transport, but these are apparently of little use in Norway. Self-loading chip trucks (Liss and Johansson 2006) and chipper trucks (Eliasson 2010) are common options in Sweden and Finland. Another option is the container handling chipper trucks (Picchi and Eliasson 2015), where the chipper truck can do the container swapping. As with the terrain chippers having an on-board chip bin, this configuration provides an option for decoupling the positioning of the wood pile and the container handling area. In addition, this option relaxes the dependency between the chipper and the transport unit, as both the chipper or the truck can do the container swapping.

Poor planning of the chip supply was listed as a problem by a number of the operators interviewed. Besides the variables included in the site functionality score and observations done in this study, typical problems were that the wood pile was put to the “wrong” side of the road, or too close to or far from the road, making it troublesome to find adequate work positions for the chipper and the reception unit. Also, routines for covering the material, or cleaning the surface of shrub prior to pile establishment was frequently lacking.

The site functionality score should obviously be improved to better predict the extra time needed for the different tasks due to various constraints and shortcomings of the chipping site. In the approach presented here, each criterion yielded a binary score to separate “good” from “bad” conditions, and the site score was found by simply adding the results from all criterions. A more flexible (continuous) scale for some of the criteria and perhaps interaction terms between some of them could give a better prediction of time losses related to the work environment. For example, challenges with mutual blocking of the chipper and the transport unit are related to the width of the site, but also the relative positioning (upstream or downstream) of the turning point and the eventual container swapping site. But the impact of these factors will vary between different equipment configurations. A model predicting the time loss in each setting with a higher resolution and better accuracy would therefore be quite detailed and beyond what our data could support.

A future possible utilization of the site functionality score method presented here is making GIS algorithms characterizing optional chipping sites from road maps and high resolution terrain models. Methods to determine the suitability of landing sites for cable yarders have already been suggested (Søvde 2015). This approach used for roadside chipping operations would provide the ability to identify landing candidates, classify them, and predict the performance of different supply chain configuration alternatives in a certain geographical biomass catchment area even before machinery investments are made.

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References

Asikainen A. 1998. Chipping terminal logistics. Scandinavian Journal of Forest Research. 13(3):386-392.
Asikainen A. 2010. Simulation of stump crushing and truck transport of chips. Scandinavian Journal of Forest Research. 25(3):245-250.
Asikainen A, Liiri H, Peltola S, Karjalainen T, Laitila J. 2008. Forest energy potential in Europe (EU 27).
Asikainen A, Pulkkinen P. 1998. Comminution of Logging Residues with Evolution 910R chipper, MOHA chipper truck, and Morbark 1200 tub grinder. International Journal of Forest Engineering. 9(1):47-53.

Björheden R, Thompson MA. 1995. An international nomenclature for forest work study. Proceedings of IUFRO 1995 S304 Subject Area: 20th World Congress; Tampere, Finland.

Eliasson L. 2010. Chipper Trucks Increaingly Common. In: Thorsén Å, Björheden R, Eliasson L, editors. Efficient forest fuel supply systems. Uppsala: Skogforsk; p. 70-71.

Eliasson L, Eriksson A, Mohtashami S. 2017. Analysis of factors affecting productivity and costs for a high-performance chip supply system. Applied Energy. 185(Part 1):497-505.

Eliasson L, Lundström H, Granlund P. 2014. Bruks 806 STC - En studie av prestation och bränsleförbrukning vid flisning av bokgrot. Uppsala (Sweden): Skogforsk. nr. 833.

Eliasson L, Von Hofsten H, Johannesson T, Spinelli R, Thierfelder T. 2015. Effects of Sieve Size on Chipper Productivity, Fuel Consumption and Chip Size Distribution for Open Drum Chippers. Croat j for eng. 36(1):11-17.

Eriksson A, Eliasson L, Jirjis R. 2014a. Simulation-based evaluation of supply chains for stump fuel. International Journal of Forest Engineering. 25(1):23-36.

2017. Simulation and modeling of wood chip container logistics at forest landings. Bioenergy from Forest 2014; 2014b; Helsinki. Helsinki.

Kons K, Bergström D, Eriksson U, Athanassiadis D, Nordfjell T. 2014. Characteristics of Swedish forest biomass terminals for energy. International Journal of Forest Engineering. 25(3):238-246.

Kärhä K. 2011. Industrial supply chains and production machinery of forest chips in Finland. Biomass and Bioenergy. 35(8):3404-3413.

Liss J-E, Johansson J. 2006. Utvärdering av et nytt ekipage för vidaretransport av bränsleflis. Garpenberg: Institutionen för matematik, naturvetenskap och teknik. Högskolan i Dalarna. 3.

Magagnotti N, Spinelli R, Acuna M, Bigot M, Guerra S, Hartsough B, Kanzian C, Kärhä K, Lindroos O, Magagnotti N et al. 2012. Good practice guidelines for biomass production studies". Sesto Fiorentino, Italy: CNR IVALSA. http://www.forestenergy.org/pages/wg_2.

Picchi G, Eliasson L. 2015. Chip truck utilization for a container handling chipper truck when chipping logging residues and the effect of two grapple types on chipping efficiency. International Journal of Forest Engineering. 26(3):203-211.

Ranta T, Rinne S. 2006. The profitability of transporting uncomminuted raw materials in Finland. Biomass and Bioenergy. 30(3):231-237. English.

Röser D. 2012. Operational efficiency of forest energy supply chains in different operational environments. Joensuu: University of Esatern Finland.

Röser D, Mola-Yudego B, Prinz R, Emer B, Sikanen L. 2012. Chipping operations and efficiency in different operational environments. Silva Fennica. Silva Fennica. 46(2):275-286.

Samset I. 1990. Some observations on time and performance studies in forestry. Ås: Norsk institutt for skogforskning. 43.5.

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

Spinelli R, Visser R. 2008. Analyzing and Estimating Delays in Harvester Operations [Research-article]. International Journal of Forest Engineering. 19(1):36-41.

Spinelli R, Visser RJM. 2009. Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy. 33(3):429-433.

Stokes BJ, Ashmore C, Rawlins CL, Sirois DL. 1989. Glossary of Terms Used in Timber Harvesting and Forest Engineering. New Orleans, LA: U.S. Dept of Agriculture, Forest Service, Sourthern Forest Experiment Station. SO-73.

Søvde NE. 2015. Algorithms for estimating the suitability of potential landing sites [Peer-reviewed Optimization Papers]. Mathematical and Computational Forestry & Natural Resource Sciences. 7(1):1-8.

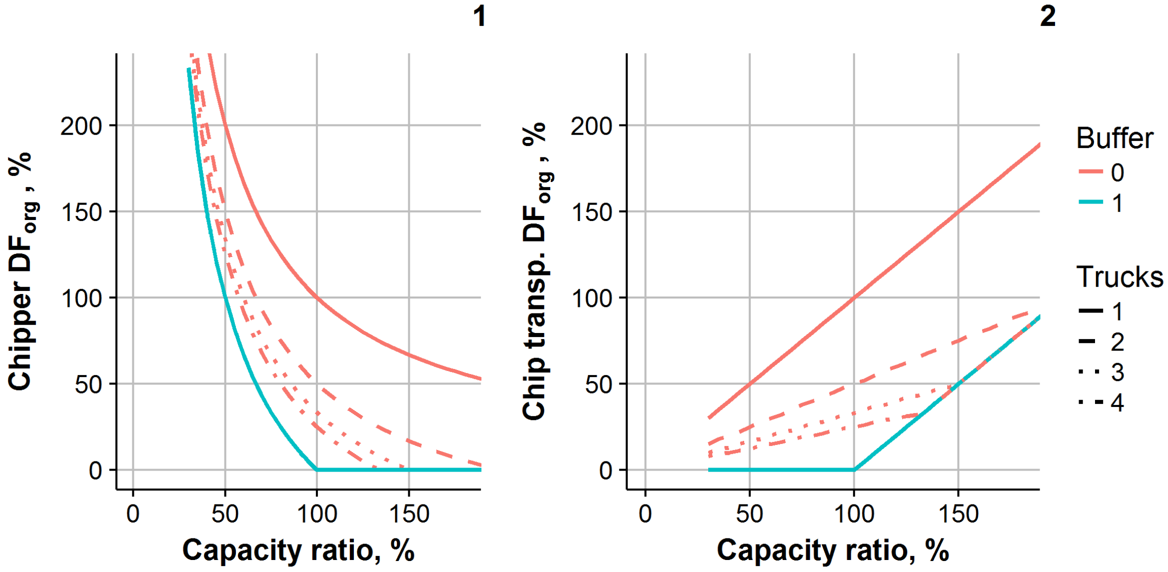

Figure 1. The left plot (1) shows the relation between capacity ratio and the organizational delay factor for the chipper. The right plot (2) shows the same relation between the capacity ratio and the chip transport.

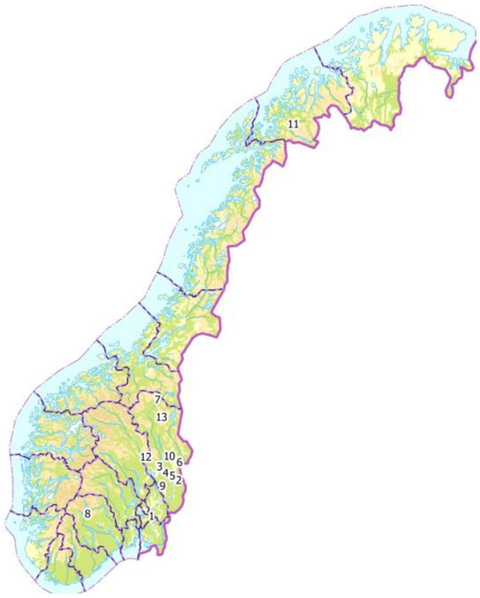

Figure 2. Location of the fourteen sites, the numbers in the map represent each consecutive site.

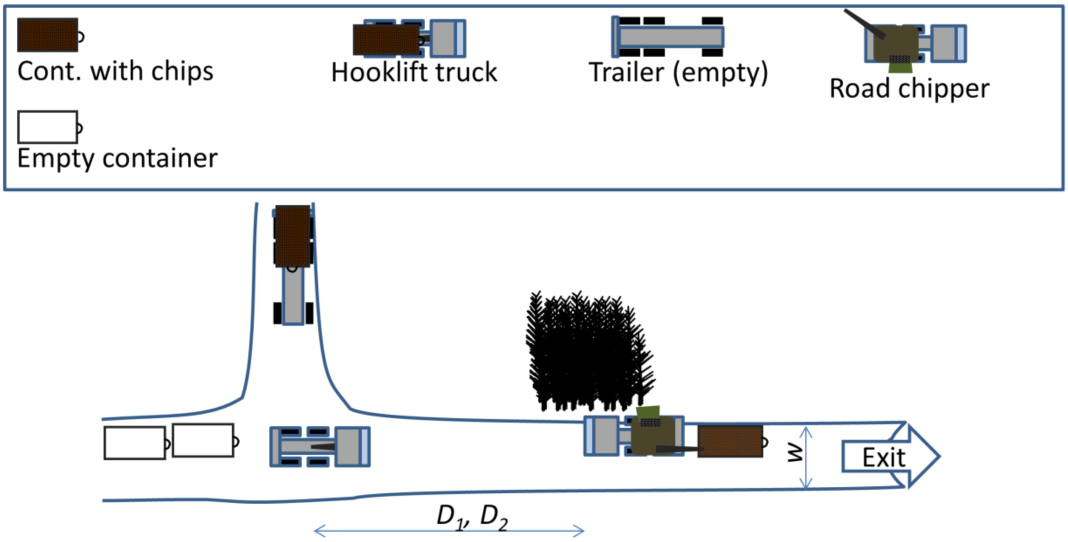

Figure 3. Illustration of a landing. The distance from the turning point and the container exchange point to the chipping point was measured (D1 and D2). Also the work site width was measured (w). Here the turning point and bin exchange point is located upstream to the landing, i.e. the chipper has to move to let the transport pass both for container exchange and load delivery.

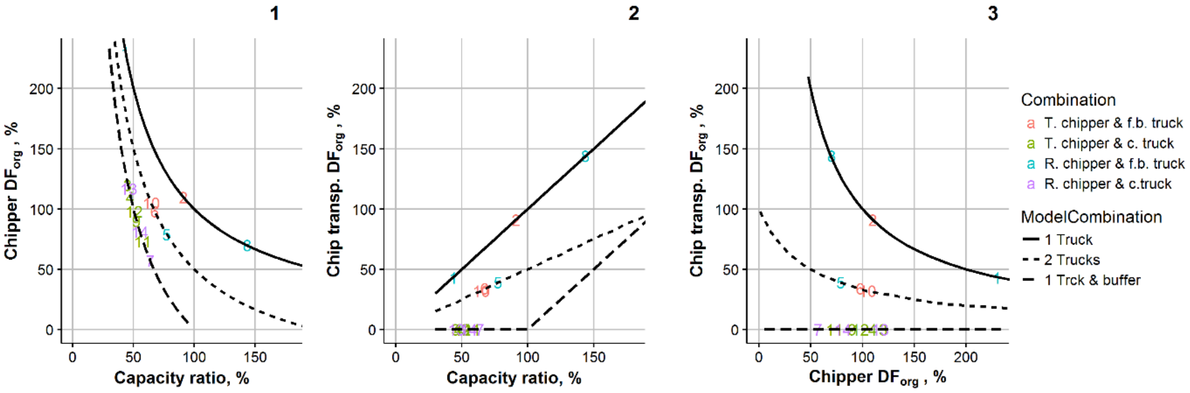

Figure 4. Plot 1 shows the organizational delay factor for the chippers versus the capacity ratio. The lines for "ModelCombinations" indicate their configuration. The supply chains using container trucks has a buffer volume of one truckload or more. This reduces the delay factor compared to configurations without any buffer storage, when comparing for equal capacity ratio. Comparing site 1 and 8, having one fixed bin truck, to site 5, 6 and 10, having two trucks, one can clearly see how the addition of transport units alleviate the chippers organizational delay factor at low capacity ratios. Plot 2 shows the same for the transport unit. The buffer storage used with the container trucks eliminated the organizational delay for the transport units at all sites. Plot 3 compares the delay factors of the chipper and the transport.

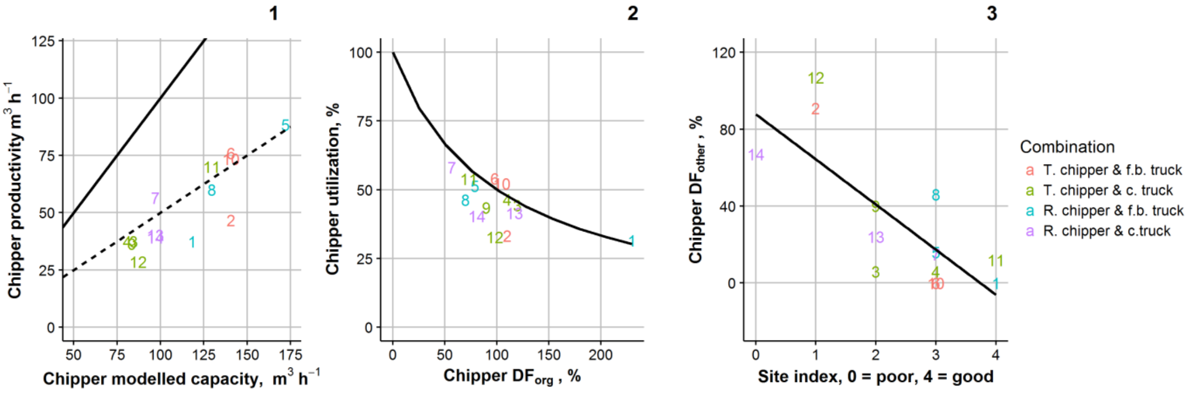

Figure 5. The first plot (1) shows the achieved productivity of the chipper versus estimated chipping capacity. The solid and the dotted line shows the productivity at 100 and 50 % utilization. Plot 2 shows the chipper utilization versus the organizational delay factor (DF) for the chipper. Here the solid line shows the maximum chipper utilization that would be achievable according to the organizational delay factor. Plot 3 shows the delay factor for other delays versus the terminal functionality score. The solid line is the regression line of all observations.

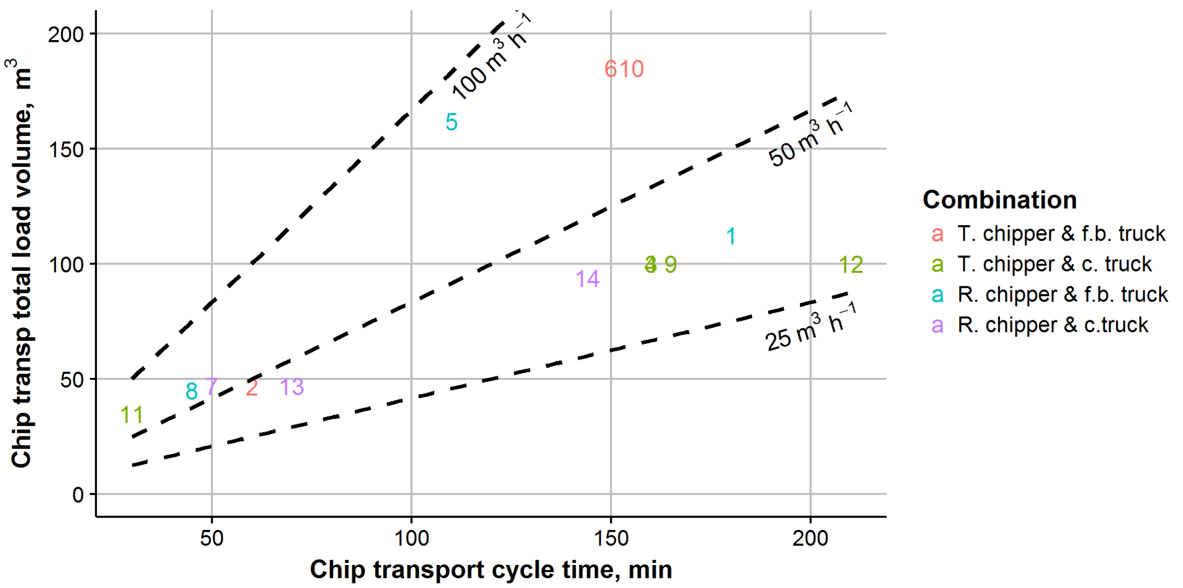

Figure 6. The figure shows the total (for all trucks involved) load volume and the corresponding delivery cycle time for the trucks and trailers used at each site. The lines indicate the productivity for combinations of load volume and cycle times.

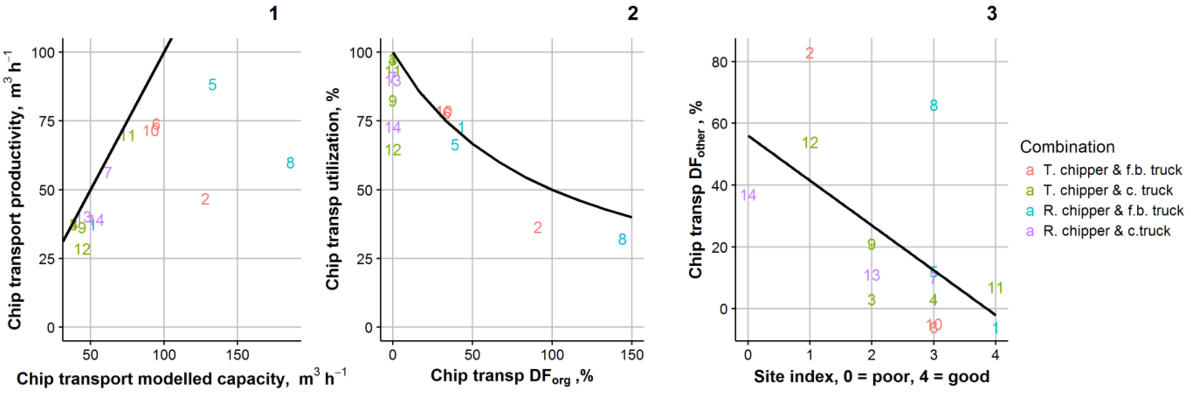

Figure 7. Plot 1 shows the actual productivity versus the theoretical maximum chip transport capacity. The straight line is indicating the productivity at 100% utilization of the capacity. In plot 2 the utilization of the transport capacity is plotted against the estimated delay factor for the chip transport. The solid line in plot 2 indicates what should be the maximum achievable utilization according to the delay factor. Observations close to the solid line indicates an operation with little other delay than the organizational delay caused by the machine configuration. Plot 3 shows the delay factor for other delays versus the terminal functionality. The solid line is the regression line for all observations.

Table 1. Numbers of chipping units and transport units observed at the studied sites.

	Road dependent chipper	Terrain chipper	Total
Container truck	3	5	**8**
Fixed bed truck	3	3	**6**
total	**6**	**8**	**14**

Table 2. Regression models relating DF_{other} to site score

Regression model: $DF_{other} = \alpha - \beta$ x SiteScore	
Chipping	Chip transport
$\alpha = 0.90 \pm 0.16$, $p < 0.001$	$\alpha = 0.56 \pm 0.16$, $p < 0.01$
$\beta = - 0.26 \pm 0.16$, $p < 0.01$	$\beta = - 0.15 \pm 0.06$, $p < 0.05$
Residual s.e. = 0.25, $R^2 = 0.6$	Residual s.e. = 0.24, $R^2 = 0.36$