Forest Biomass Terminal Properties and Activities

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Energy wood chipping at a terminal of Sveaskog in the North of Sweden with the enhanced graphics from Sveaskog Gällivare and U.S. Small Business Administration.

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Abstract

Primary residual forest biomass is an important source of energy in Sweden. The fuel quality of this biomass depends on several factors including its moisture content, ash content, and particle size distribution. Forest biomass terminals provide diverse services to the forest industry, including buffer storage, transfers of material between different modes of transport, and raw material upgrading. To design efficient terminals, it will be essential to understand the current state of forest terminals and the activities that occur within them.

The overall objective of the work presented herein was to obtain a general overview of the current state of forest biomass terminals in Sweden and to determine fuel quality parameters for five different assortments. Terminals were characterized in terms of their area, volume of material handled, equipment, inventory methods and age. The information required for this characterization was acquired by sending a questionnaire out to companies operating forest terminals that handle energy assortments in Sweden.

The properties of the 246 terminals varied widely. In general, the most pronounced differences were observed between terminals with areas of <5 ha and those with areas of >5 ha. Terminals of <5 ha accounted for 65% of the country's total terminal area, and more than half of the country's total forest biomass output was handled at terminals of <2 ha. Comminution was performed at 90% of all terminals.

The chip quality measurements showed that chipped logging residues (tops and branches) contain a high proportion of fine particles (<3.15 mm), amounting to around 17% of the chips' oven dry (OD) weight. Fines accounted for only 5.3-5.8% of the oven-dry mass of the other assortments, such as bundled tree-parts and roundwood. By screening these fine particles, it was possible to reduce the assortments' average ash content (AC) to 0.66-2.17% (corresponding to a 20-31% reduction of total AC). Screening could thus be used to divide a chipped material into a number of quality classes for different applications and with different prices.

This thesis provides a detailed overview of Sweden's forest terminals and fuel quality improvements that could be achieved by biomass screening at terminals.

Keywords: Assortment, equipment, inventory, storage, forest fuels, supply chain, particle size distribution, ash content, screening, sieving

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Характеристика и деятельность терминалов по производству лесной биомассы

Аннотация

В Швеции лесная биомасса является важным энергоресурсом. Качество щепы в производстве энергоресурсов зависит от многих факторов kak влажность, одержание золы, размер щепы. Терминалы производства лесной биомассы обеспечивают услуги лесной индустрии, учитывая объемы амортизации, разгрузку, перегрузку в разные виды транспорта и сохранение качество биомассы. Чтобы проектировать успешные терминалы необходимо фактически понять их состояние и активность на данный момент.

Цель данной работы – общий обзор состояния терминалов производства биомассы в Швеции для определения пяти особенностей ассортимента качества щепы. Терминалы характеризуются по площадь, объем биомассы, оборудование, метод инвентаризации и возраст.

Для получения этой информации был проведен опрос компаний, которые используют лесные терминалы в Швеции. В опросе участвовали 246 терминалов широкого объема деятельности.

Наибольшее различие наблюдается между терминалами площадью <5га. и теми, чья площадь >5га. Терминалы <5га. занимают 65% от общей площади терминалов в стране и больше чем половину от общей биомассы терминалов в стране обслуживается терминалами <2га. И з всех терминалов 90% производят щепу.

Квалификационные измерения щепы показали высокий остаток мелких частиц (<3,15 мм) на вырубках, достигая до 17% от веса сухой щепы. В других ассортиментах (как пачки частей дерева так и в бревнах) вес мелких частиц к общему весу составлял в пределах 5.3-5.8 % от сухой массы. Просеивая мелкие частицы среднего содержания золы в щепе можно сократить от 0.66-2.17% (это 20-30% уменьшения от общего содержания золы). Просеивание можно использовать для определения качества и цены щепы для разного уровня потребителей.

Эта диссертация дает детализированное представление о лесных терминалах Швеции и возможность улучшения качества щепы в результате просеивания.

Ключевые слова: ассортимент, оборудование, инвентаризация, хранение, поставки, распределение по размерам щепы, просеивание.

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Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Kons, K., Bergström, D., Eriksson, U., Athanassiadis, D., Nordfjell, T. (2014). Characteristics of Swedish Forest Biomass Terminals for Energy. *International Journal of Forest Engineering* vol 25(03), 238-246.

II Kons, K., Bergström, D., Di Fulvio, F. (2015). Effect of Sieve Size and Assortment on the Fuel Quality at Chipping Operations (submitted manuscript)

The contribution of Kalvis Kons to the papers included in this thesis was as follows:

I Kons took part in formulating the study's objectives, performed part of the complementary survey, analyzed all of the data, and wrote the manuscript. Bergström and Nordfjell formulated the study's initial aim, helped draw conclusions and contributed to the manuscript's revision. Athanassiadis also formulated the study's initial aim, helped draw conclusions, contributed to the manuscript's revision and helped with the GIS analyses. Eriksson gathered the initial data.

II Kons helped to plan the study's design and the formulation of its objectives, prepared the gathered samples for further analysis, analyzed all of the data, and wrote the manuscript. Bergström formulated the study's initial aim, helped draw conclusions, and contributed to the manuscript's revision. Di Fulvio helped to formulate the study's aim and to plan its design, contributed the initial gathering of material and data, helped with the statistical analyses and drawing of conclusions, and participated in the manuscript's revision.

Abbreviations

SDC	Swedish Forest Industry's IT Company
CHP	combined heat and power plant
OD	oven dry
t	metric tonne
g	gram
m	meter
m^3	cubic meter
cm	centimeter
s.u.b.	solid under bark
s.o.b.	solid over bark
l	loose
h	hour
MW	megawatt
GW	gigawatt
kW	kilowatt
GIS	geographic information system
ha	hectare
g	gram
k	kilo
PMH_0	productive machine hour, excluding delay time
MC	moisture content, wet basis
PSD	particle size distribution
AC	ash content, dry basis
ANOVA	analysis of variance
GLM	general linear model
VMF	Swedish Timber Measurement Association (Virkesmätningsföreningen)

1 Introduction

1.1 Terminal role in supply chain

Traditionally, forest biomass terminals serve as storage and transition points for roundwood deliveries within forest industry supply chains. However, the demands placed upon terminals have been changing over time. In the 1970s and 1980s, there was considerable interest in evaluating the capacity of forest biomass terminals to handle biomass for energy generating industries (Lönner et al., 1983; Hillring, 1995). However, at present forest terminals primarily exist to facilitate the distribution of roundwood supplies (Figure 1a).

(a) *(b)*

Figure 1: (a) Roundwood terminal in the central Sweden after the storm Gudrun in 2005, (b) Stockarydsterminalen AB, an energy industry biomass terminal (Photo (b): Tomas Nordfjell).

Unpredictable factors such as the weather affect energy demand, the progress of harvesting operations, and the supply of raw materials (Quayle and Diaz, 1980; Williamson et al., 2009). Because of this variation in supply and demand, terminals are becoming increasingly important as storage and buffer points for the delivery of biomass to heating and CHP facilities. In addition, Kärhä (2011) has reported that it became increasingly common for chipping operations to be performed at terminals between 2006 and 2010 in Finland. The emergence of biorefineries will introduce a further degree of uncertainty into the forest raw material supply chain because different biorefining techniques require different types and grades of raw materials (Joelsson and Tuuttila, 2012). The economic arguments presented by Bailey and Friedlaender (1982) and others suggest that industrial demand e.g. from biorefineries may prompt the forest industry to produce a wider range of assortments in order to meet these varied requirements.

1.2 Terminal characteristics

The ability of forest biomass terminals to deliver a wide range of products will be increasingly important in future because it will reduce the number of suppliers that are required to meet demand and thereby minimize the coordination and transaction costs incurred by the final customer (Daniel and Klimis, 1999). Palander and Voutilainen (2013) showed that the use of biomass terminals in forest biomass procurement chains could potentially reduce the total supply costs of CHP plants by 18.3% due to the centralization of procurement procedures. To reduce terminal inventory costs, terminals can be used as consolidating points for the assembly of larger shipments containing a wider range of assortments, avoiding the need to store material for extended periods of time (Kisperska-Moron, 1999; Kärkkäinen et al., 2003; Routa et al., 2013).

In addition, CHP plants in densely populated areas may require satellite terminals in the periphery of settlements because they may not have enough on-site storage space to meet their operational requirements, and to avoid disrupting residential areas with heavy traffic or sound and air pollution created by chipping operations (Wolfsmayr and Rauch, 2014). The ability to increase profits by exploiting economies of scale has driven increases in the size of biorefineries and CHP plants. These larger facilities must in turn source their raw materials from larger areas than would be required for smaller plants. To reduce the costs associated with long distance transportation, biomass can be densified, compacted, or pre-dried at forest terminals (Uslu et al., 2008).

However, increasing the number of assortments and the size of the inventories held at terminals increases the costs incurred by suppliers (Putsis and Bayus, 2001; Kärkkäinen et al., 2003). These cost increases may be aggravated by inefficient terminal design and internal logistics management at the receiving, transitioning and delivering terminals. Frosch and Thorén (2010) found a difference of over 60% in forest raw material handling costs between rail/road transition and receiving terminals in Sweden.

This clearly indicates that efficient terminal designs can have direct impacts on costs.

1.3 Terminal operations

1.3.1 Terminal operations in the past

Terminal operations involve a series of major steps (Grammel, 1978) (Figure 2). In addition, there are invariably various material handling and relocation processes that must take place between these main operations.

Traditional centralized terminals often consisted of large stationary systems and were designed to optimize the value achieved from single trees or the handling of tree sections in bulk (Hakkila, 1984). Terminal usage patterns of this sort were particularly common in the Soviet Union and China during the 1980s. Remarkably, in the Soviet Union, around 90% of all wood processing was conducted at terminals (Abol, 1984).

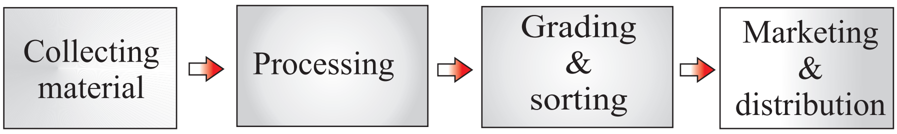
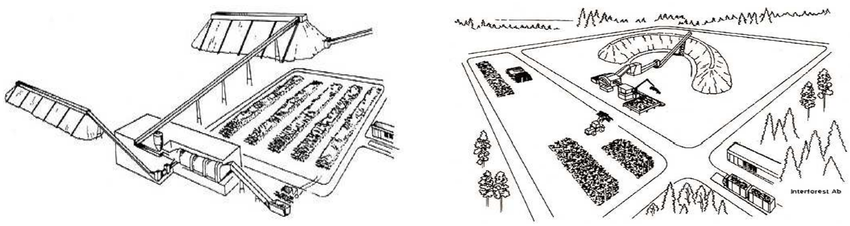


Figure 2: Operations at the forest biomass terminal according to Grammel (1978).

In the 1970s and 1980s, the utilization of small diameter timber in Sweden was primarily driven by the demands of the paper industry (Hakkila, 1984). However, the oil crisis of 1973 prompted a strong interest in using byproducts from the pulp and paper industry for energy production. This led to the introduction of new techniques for pulpwood and energy wood handling (Figure 3). With state support, many forest biomass terminals were established to secure resource deliveries for both the paper and energy industries, causing the annual production of forest fuels at terminals to rise dramatically to a peak in 1987 (Hillring, 1996).

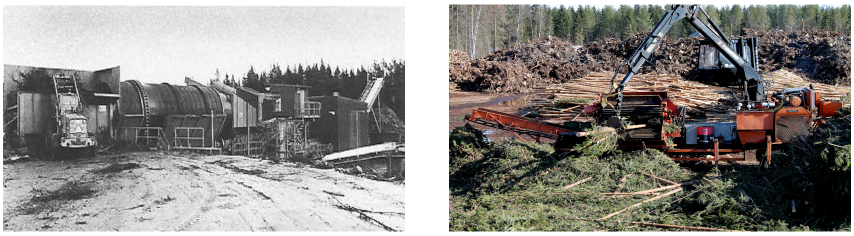
However, the production of forest fuel at terminals has since declined (Hillring, 1996); terminals accounted for only around half of Sweden's total forest fuel production from tree sections in 1989-1990, which is much lower than the proportion reported for the Soviet Union in 1980 (Brunberg, 1991; Abol, 1984). The growing demand for high quality raw material, the introduction of improved CHP combustion technologies, and the rapid development of cut-to-length technologies for harvesters ultimately led to the demise of tree section processing at forest terminals (Hillring, 1996).



(a) *(b)*

Figure 3: (a) Stand alone tree section terminal for processing unlimbed pulpwood and fuel wood (b) Stay alone biomass terminal for producing fresh fuel chips. (Lönner, 1985).

Aside from the chipping of the raw material, one of the most common processing operations conducted at terminals was the delimbing of tree sections. The two main delimbing technologies were: (1) modified debarking drums, which were often integrated into the systems used in the pulp industry; and (2) specially constructed standalone delimbing drums, which were used at more remote terminals (Figure 4a) (Hillring, 1996). In addition, chain flail debarkers offered a more mobile solution for upgrading tree sections (Hakkila, 1984). These machines use a set of chains attached to a drum, which rotates around a central axle. Tree parts are fed into the machine and beaten by the chains, causing the separation of branches and bark from the stem wood (Figure 4b). The main advantage of chain flail debarkers was that they could be relocated relatively cheaply.



(a) *(b)*

Figure 4: (a) A delibing drum at the forest biomass terminal (Photo: Jonas Palm) (b) Chain flail delimbing at the terminal operations.

The main purpose of terminals was usually to provide a secure supply of material for pulp and paper mills. However, they were also required to perform sorting and screening in order to improve the quality of the chips produced from tree parts and whole trees.

A number of wood chip screening methods were therefore introduced based on knowledge from the sawmill and paper industries. These methods use vibration, shaking, drums, and disc screens to sort chips based on their physical properties by exploiting differences in their responses to gravity, air flows, compression, and flotation (Hakkila, 1984). It should be noted that all screening methods are inevitably associated with at least some level of biomass loss (Hakkila, 1979).

In contrast, North American forest terminals were mainly used for merchandising or bucking and storing of saw logs in order to increase product value. In general, they were referred to as log sort yards (Sinclair and Wellburn, 1984). Log sorting was often performed on water, dry land, or booming grounds, and facilities were established on either water or land to store logs prior to further transportation (Sinclair and Wellburn, 1984). Merchandising at log sort yards is still practiced today in North America.

1.3.2 Terminal operations at present

One of the main problems in the logistics of primary forest fuels is that most assortments have low bulk densities, which makes it difficult to utilize the entire payload capacity of the vehicles used for their transportation and thus increases transportation costs. Consequently, the amount of material that can be transported in a given vehicle is determined by the material's volume rather than its mass. Payload underutilization is estimated to increase the cost of transporting loose logging residues by 0.35 €/MWh per 10 km on average (Ranta and Rinne, 2006). To increase payload capacity utilization, bulky assortments can be compressed and bundled on site (Pettersson and Nordfjell, 2007). Comminution (chipping/grinding) can also be used to increase payloads. It is typically performed at landings and has recently become the main operation performed at terminals (Angus-Hankin et al., 1995; Ranta and Rinne, 2006; Routa et al., 2013).

Comminution is mainly done by chipping or grinding (Figure 5). Chipping involves cutting the wood with sharp knives while grinding involves crushing with blunt knives (Eriksson et al., 2013).

Chipping is preferred to grinding when the material is free of contaminants (e.g. stones and soil) that could damage the knives. Compared to grinding, chipping produces a more homogenous material and consumes less energy (Spinelli et al., 2011). The properties of wood chips and ground materials are determined by the initial composition of the biomass (e.g. the tree species and tree parts from which it is derived), the nature of the comminution process (e.g. chipping or grinding), the settings and properties of the machine used for comminution (e.g. the lengths and angles of the knives, and the cutting speed), and the handling of the biomass (i.e. the configuration and location of its storage) (Eriksson et al., 2013). The properties of the biomass that have the greatest impact on its commminution are

(a)

(b)

Figure 5: (a) Energy wood loaded by truck mounted crane into Petersson chipper (b) Stumps loaded by grapple and front end loader into CBI Magnum Force crusher.

its density, moisture content, storage time and conditions, assortment of origin, and temperature (frozen biomass behaves differently to non-frozen material) (Kivimaa and Murto, 1949; Papworth and Erickson, 1966; Liss, 1991; Nati et al., 2010; Eriksson et al., 2013). When chipping, the machine settings can significantly affect the wood chip quality, so it is important to pay attention to the number of knives used, their sharpness, and their cutting angles (Hartler, 1986; Uhmeier, 1995; Hellström et al., 2008, 2009; Abdallah et al., 2011; Nati et al., 2014). Abdallah et al. (2011) has shown that the size of the produced wood chips is reduced by increasing the feed per tooth, cutting angle, and knife sharpness; the opposite effect is achieved by increasing the cutting speed. The chip size has a direct impact on the productivity and energy consumption of the comminution operation and is proportional to the size of the pieces of wood being comminuted (Liss, 1987, 1991; Van Belle, 2006; Ghaffariyan et al., 2013). The energy required for comminution can be reduced by producing larger chips (Nurmi, 1986). For example, increasing the chip length from 2.5 to 50 mm can reduce the energy required to produce a tonne of chips by around 88% (Kivimaa and Murto, 1949). The growing demand for fuel wood and the ongoing up-scaling of heat and power plants means that there is an increasing need for greater efficiency in the forest fuel supply chain to ensure that the cost of fuel wood remains competitive with that of alternative fuels (Björheden, 2011).

1.4 Material quality

1.4.1 Biomass for energy production

Bioenergy generation from woody biomass is important in Sweden and Finland (IEA, 2012). In Sweden, the forest industry has a close relationship with the energy industry because a significant portion of the waste material produced by forest industries (specifically, secondary forest fuels such as bark, sawdust, and residues from pulp production) is traded as fuel wood (Hillring, 2006). Primary forest fuels are assortments that are supplied directly from the forest and used for fuel production, such as logging residues and stumps from clear cuts, energy wood (low quality roundwood), and small diameter trees from early thinnings (Ranta, 2005; Routa et al., 2013). Other assortments used for fuel production (albeit to a lesser extent) include tree parts from marginal lands such as trees cut during power-line cleaning, trees harvested from reforested agricultural land, and trees cut during roadside clearances. The combustion of biofuels, peat and waste accounted for 140 TWh of Sweden's energy consumption in 2012 (Swedish Forest Agency, 2014).

Residual woody biomass from the forest industry (i.e. secondary forest fuels such as black liquor, bark, and saw dust) represent 42% of all bioenergy deliveries and these sources of material are currently fully utilized (Swedish Forest Agency, 2014).

Therefore, any increase in energy production from forest fuel-burning plants will have to be supported by increased procurement of primary forest fuels. Consequently, sales of energy wood, logging residues and forest chips increased by 41%, from 8.5 to 14.3 TWh, between 2007 and 2011 (Swedish Forest Agency, 2014; IEA, 2012). The quality of fuel chips is normally determined by their MC, heating value, AC, type and PSD (Jirjis, 1996). Other important quality parameters are the contents of fine particles (i.e. particles with diameters of less than around 3 mm), impurities (e.g. soil particles), and oversized particles (i.e. particles of >100 mm) (Jensen et al., 2004; Nuutinen et al., 2014). The main causes of problems with feeding systems and combustion processes in wood chip burning plants are large fluctuations in particle size and moisture content (Hakkila, 1984; Mattsson, 1990; Jirjis, 1995, 1996; Jensen et al., 2004). The particle size distribution of wood chips also affects their storage and drying properties (Kristensen, 2000; Garstang et al., 2002).

1.4.2 Biomass for bio-refineries

At present, the largest and most important forestry assortments aside from traditional forest products such as saw logs and pulpwood are energy assortments for heat and electricity production. While the distinction between traditional forestry products and energy assortments such as logging residues (which are often regarded as forestry byproducts) is important, there are many finer distinctions to be drawn and it is important to understand how assortments differ in terms of their energy value and biochemical properties (Söderholm and Lundmark, 2009).

The main chemical components of wood are cellulose, hemicellulose, lignin, and extractives. The chemical and physical properties of the woody biomass are heavily dependent on the tree species from which the wood was taken, the age of the tree, the part of the tree, seasonal factors, the handling and processing of the harvested material, and the conditions under which the trees are grown (Bergström and Matisons, 2014; Nurmi, 1993).

Stems and stumps have relatively similar properties (if the bark is disregarded), although the latter have a somewhat higher content of extractives (Bergström and Matisons, 2014; Hakkila, 1984). However, stump biomass often includes a relatively high content of soil-derived contaminants, which may adversely affect some refining processes. Stem wood is therefore the preferred raw material for many refining processes; it has been extensively studied and is relatively easy to handle (Bergström and Matisons, 2014). Consequently, most existing supply systems are well equipped for its processing.

Saw milling and the pulp and paper industries are the largest forest industries in the Nordic countries. Their operations produce vast quantities of bark as an unwanted byproduct. Bark is a potentially important source of green chemicals, although at present it is mainly burned for energy generation (Gandini et al., 2006; Miranda et al., 2012). The bark content of birch logs is about 11.4% by mass, around 3.4% of which is outer bark (Pinto et al., 2009; Holmbom, 2011). The bark content in the branches and in their vicinity is even higher; for tree species such as the southern pine, the bark content of branches is around 2.5 times higher than that of the main stem (Hakkila, 1984). The outer bark of the silver birch has an extractive content of around 40%, including a diverse range of fairly rare compounds (Holmbom, 2011; Miranda et al., 2013).

Compared to stem wood, tree crown parts have a much higher content of extractives and other compounds (Hakkila, 1984; Nurmi, 1993). The assortment with the highest content of crown and foliage mass is fresh logging residues (FLR). However, FLR are usually seasoned to reduce their moisture content before combustion. Because the extractives that are useful for bio-refining are either volatile or chemically unstable, their abundance in FLR starts to decrease immediately after harvesting (Alén, 2000; Ekman, 2000). According to Lappi et al. (2014), the extractive content of crown and bark mass obtained by chain-flail debarking decreased significantly within the first four weeks of storage and no detectable lignans remained in material that had been stored for 24 weeks. Comminution makes the decline in extractive content even more rapid (Alén, 2000). This could may introduce new handling and logistical constraints into the forest bio-fuel supply chain because extractive-rich material for biorefineries must be delivered much more quickly after harvesting than is the case for energy assortments.

2 Objectives

The overall objectives of the studies presented in this thesis were to acquire general knowledge about forest biomass terminals in Sweden and to determine fuel quality parameters for five different assortments.

The aim of Paper I was to characterize existing Swedish forest biomass terminals for energy assortments in terms of their location, size, type and number of assortments handled, infrastructure and basic management routines. Only terminals that handled biomass for energy production (either exclusively or in part) were examined.

The aim of Paper II was to compare the qualities of wood chips obtained from five different fuel wood assortments using two different chipper sieve settings. The productivity and energy consumption of the chipping process was also investigated.

3 Materials and methods

3.1 Paper I: Terminal characteristics

3.1.1 Data gathering

Data were gathered using a quantitative questionnaire that was sent out in 2012 by the Swedish Forest Industry's IT Company (SDC) to all major forest companies and owner associations that deal with forest biomass fuels. In total, 16 out of 18 forest companies and owners' associations provided information on their forest terminals for 2010 and 2011. Only terminals that had been in use for at least two years before the survey was conducted and which were expected to remain active throughout the year of the survey were included in the study. A follow-up survey was subsequently conducted to gather data from the two forest companies that did not participate in the first survey; data for these two companies were gathered in the winter of 2013. Data were collected on how long (in years) the terminals had been in use, the size (ha) of the terminal area in permanent use, the nature of the ground surface at the terminal (e.g. gravel or paved), the type of machines in operation at the terminal, the measuring equipment used to estimate truckload weights, the volumes of stored assortments, the frequency of stock inventories, and the number of customers served by the terminal. Information on the nature of the ground surface at the terminal was collected in order to estimate the risk of soil contamination in stored assortments.

3.1.2 Unit conversion

Different assortments are measured in different units. For example, quantities of energy wood (roundwood, often of low quality) are measured in solid cubic meters under bark (m^3s.u.b.) while stumps are measured in fresh metric tonnes (t). All assortment volumes were converted to oven dry tonnes (OD t) using the Wood Energy Calculations tool (WeCalc, 2012) in order to facilitate comparative analysis. The conversion coefficients for each original unit are shown in Table 1. Assortments such as bark, saw dust, dry sawmill chips, shavings, cut offs and recycled wood primarily consist of forest industry by-products, while energy wood, logging residues, stem wood chips, tree parts, and stumps (comminuted or loose) are primary energy assortments delivered directly to terminals from forest operations. Peat is commonly used in heating and CHP plants, and may also be stored or transferred at forest biomass terminals. To convert measurements from one unit to another, it is necessary to know what type of assortment is under consideration and its moisture content.

Table 1: *Conversion coefficients derived from WeCalc for different units of delivered biomass. s.u.b.=solid under bark, s.o.b.=solid over bark, l=loose, OD=oven-dry, MWh=megawatt hour, t=metric tonne*

Assortment	Units	Conversion coefficient[a]	Moisture content, wet basis (%)
Stem Wood	t → m^3 s.u.b.	1.20	-
	m^3s. → m^3s.u.b.	1.10	-
	MWh → m^3s.u.b.	2.30	-
	m^3s.o.b. → m^3s.u.b.	1.14	-
	t → OD t	0.40	60
Logging Residues	m^3s → m^3l	2.65	-
	m^3s → OD t	0.46	-
	m^3l → OD t	0.17	-
	MWh → OD t	0.20	-
	t → OD t	0.59	41
Bark	MWh → m^3l	0.60	-
	MWh → t	1.85	-
	t → OD t	0.38	62
Dry Chips	t → OD t	0.88	12
Tree Parts	m^3l → MWh	0.74	-
	MWh → OD t	0.20	-
	m^3s.u.b. → OD t	0.46	-
	m^3l → OD t	0.15	-
	t → OD t	0.44	56
Recycle Wood	t → OD t	0.70	30
Stumps	t → OD t	0.62	38

[a] The original unit is multiplied by the corresponding coefficient to obtain the new unit.

3.1.3 Grouping of terminals

The total number of terminals surveyed was 270. However, area data were only provided for 246 terminals, and only these terminals were considered in subsequent analyses (Table 2). In addition, certain analyses were only performed using data on those terminals for which specific information on variables such as the volume of stored material, number of customers, or the equipment present at the site was available. Therefore, the number of terminals considered when performing specific calculations ranged from 112-246 (Table 2).

Table 2: *Number of terminals included when calculating various terminal properties that depend on the area of the terminal*

Terminal properties	No. of terminals
Total area	246
Mass of yearly inventory turn over	207
Number of assortments	207
Measuring, loading and other equipment	203
Number of customers	203
Annual inventory frequency	180
Inventory method	170
Inventory maker	168
Terminal age from the year of establishment	149
Terminal geographical locations	112

Terminals were divided into four classes based on their area; <2 ha, 2-5 ha, >5-10 ha and ≥10 ha. Average, minimum (min), maximum (max) and standard deviation (sd) values were calculated for terminal area, yearly biomass inventory turnover, number of assortments and number of customers. Terminals were also grouped according to the number of inventories conducted per year, the method used to conduct inventories, the equipment present at the terminal, and their age.

3.1.4 Terminal geographical data

Geographical information that could be related to the surface areas of the terminals was provided for only 112 terminals (Figure 6). The locations of nearby heating and CHP plants were collected from the Swedish District Heating Association. Information on the locations of pulp mills and sawmills was gathered from the Swedish Forest Industries Federation. Road and rail road data were obtained from the Swedish Land Survey Authority. The shortest distances from the terminals to nearby CHP plants (≥100 GWh annually), pulp mills, and saw mills were calculated based on the local road network using ArcGIS Network Analyst. Distances between a terminal and the nearest neighboring terminal or the nearest point on a railroad were calculated as Euclidean distances, i.e. the distance “as the crow flies.” The same approach was used to compute the distance between adjacent terminals to establish their catchment areas. A winding coefficient of 1.4 can be used to convert Euclidean distances into distances by road (Berglund and Börjesson, 2003; Ranta, 2005).

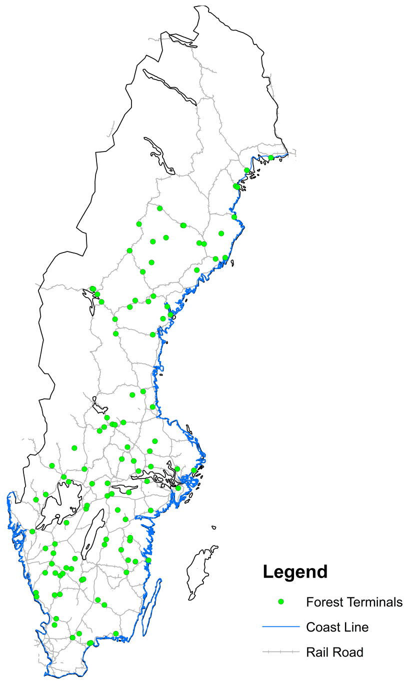


Figure 6: Forest terminal locations in relation to the railroad network and coastline.

Most of Sweden's energy demand is concentrated in the country's central and southern regions. However, the largest amounts of surplus forest biomass suitable for energy production are found in northern Sweden. Therefore it is essential to have adequate buffer storage capacity to support just-in-time deliveries to CHP plants producing more than 100 GWh in the more densely populated areas. The distance between each terminal and the nearest large CHP plant was calculated to assess the scope for providing such storage and delivery capabilities.

3.2 Paper II: Chipping at terminal

The chipping study was carried out at a terminal belonging to Domsjö Fabriker AB (WGS84 - 63°15′57.6″N 18°42′20.9″E) and managed by Domsjö Fiber AB, on the second and third of June 2014. Five different biomass assortments were chipped: energy wood, bundled tree parts, fresh and stored logging residues and fresh tree parts from marginal lands (Figure 7).

The energy wood consisted of mixed coniferous (Scots pine and Norway spruce) and deciduous (birch, aspen and grey alder) tree logs with stem diameters of 5-30 cm and lengths of 6 m that had been stored for one year.

Figure 7: Assortments used in the study (a) Energy wood (b) Bundles (c) Fresh logging residues (d) Stored logging residues (e) Tree parts.

The bundles were produced around three months before the trials were conducted using the Fixteri bundler system (www.fixteri.fi) from Scots pine tree parts harvested during early thinnings. The mean diameter, length, and dry density of the bundles were 0.7 m, 2.6 m, and 248 Oven Dry (OD) kg/m^3, respectively. The two different logging residue assortments consisted of fresh and stored branches and tops of Norway spruce from clear cuttings. The stored logging residues had been stored at a roadside landing for six months after being cut and were directly delivered to the study site. The tree parts from marginal lands were 6 m long sections of undelimbed mixed deciduous trees (birch, aspen and grey alder) with butt diameters of 5-20 cm. The material was randomly collected from the fuel wood delivering companies and delivered to the study site where it was stacked in separate piles. Each of the five assortments was divided in two equal piles, each containing an amount of material that could be chipped in 1-1.5 hours. The time consumption for the chipping work was recorded with a time study computer (Allegro Field PC®) running the SDI (Haglöfs Sweden AB) software package. The work time was divided into the following work elements in prioritized order, from first to last: chipping, loading the chipper, miscellaneous (moving the chipper, cleaning working space, etc.) and delays. The productivity was recorded in units of Productive Machine Hours of work excluding delays (PMH_0).

3.2.1 Machine system

The chipper used in this work was a Doppstadt DH 910 unit with a 450 kW engine and five 219 mm chipping knives (Figure 8). The dimensions of the chipper drum were 1,000×1,300 mm. Material was fed into the chipper using a truck-mounted Epsilon Q170 crane and a Hultdins SuperGrip II 360A grapple with a grabbing area of 0.36 m^2. Two different sieve sizes were used: "normal" (100×100 mm) and "large" (100×200 mm).

Figure 8: Truck based chipper system used in the study.

All five assortments were chipped using both sieve sizes, giving a total of 10 treatments (Figure 7). The first set of trials was conducted using the "large" sieve. Each run (treatment combination) took ca. one hour of effective chipping time. The chipping knives were checked after chipping each assortment and replaced with fresh sharp ones if necessary. The "large" sieve was replaced with the "normal" one after the first set of assortments had been chipped. The fuel consumption of the chipper was read from the machine gauge after each run and measured by top filling when replacing the large sieve with the normal one.

3.2.2 Sampling and sample preparation

Chips were blown onto the ground and then loaded into a 55 m^3 container using a front-end loader. Samples were collected systematically for each run by filling five 10-liter buckets with chips while the container was being loaded. These samples were used to estimate the chips' moisture content (MC, %, wet basis), AC (dry basis) and PSD (%, wet basis). For each container, the filled bulk volume and mass of loaded chips was determined at the terminal's measuring station, which was operated by VMF Nord (an accredited third part measuring agency).

The chips' MC and PSD were estimated according to Swedish standards SIS-CEN/TS 14774-3:2004 and SS-EN 14918. Each bucket was dried independently to estimate the MC of its chips, which were then sieved to measure the dry weight of each particle size class in the sample. Sieves with opening sizes of 0, 3.15, 8, 16, 31.5, 45 and 63 mm were used for this purpose. After measuring the dry weight of each particle size class, samples of the size-fractionated material were milled to estimate the AC of the different particle size groups according to Swedish standard SS-EN 14775 (Figure 9).

(a) *(b)*

Figure 9: Milled and sealed samples for analysis of ash content (a) Energy wood (b) Stored logging residues.

In cases where the volume of material in a given size fraction was relatively large, a subsample of around 20 cm^3 was set aside of grinded material. AC determination was performed in duplicate for each particle size fraction from each treatment, using samples of ground material weighing approximately 2 g each.

3.3 Statistical analyses

In Paper I, the significance of differences between terminals of different sizes was evaluated using analysis of variance (ANOVA) as well as the Chi-Square test and Fisher's exact test. A significance threshold of 5% was applied in all of these statistical tests.

In Paper II, statistical comparisons of the treatments with respect to key fuel quality measurements (AC and PSD) were performed using a General Linear Model (GLM) after logit transforming the share (S) value for each particle size class. The S value for the PSD is the mass of the particle size class of interest as a percentage of the total mass of the chip sample, and the S value for the AC is the dry mass of ash originating from the particle size class of interest as a percentage of the total dry mass of ash originating from the chip sample as a whole. The factors included in the model were Assortment (bundles, energy wood, fresh logging residues, stored logging residues, tree parts), $Sieve\_size$ (normal, large) and $Size\_class$ ($< 3.15, 3.15 < 8, 8 < 16, 16 < 31.5, 31.5 < 45, 45 < 63, 63 <$). The logit transformation was necessary to transform the primary range of the share values from $S \in [0,1]$ into $S \in [-\infty, \infty]$. The model used can be expressed as:

$$
\begin{aligned}
Logit\,S = Assortment + Sieve\_size + Size\_class + \ldots \\
Assortment \times Size\_class + Sieve\_size \times Size\_class + \epsilon.
\end{aligned}
$$

The interactions of the *Size_class* with the Assortment (*Assortment* × *Size_class*) and the *Size_class* with the *Sieve_size* (*Sieve_class* × *Size_class*) were included in the model. However, the *Assortment* × *Sieve_size* and *Assortment* × *Sieve_size* × *Size_class* interactions were excluded because they could not be readily interpreted. Differences associated with p-values < 0.05 were considered to be statistically significant. Because only one experimental run was performed for each treatment, the only way to compare the chipper productivity and fuel consumption when using the large and standard sieves was to perform two-sample t-tests based on all of the assortment types together. All statistical analyses were performed using Minitab 16 Statistical Software (Minitab® Inc.).

4 Results

4.1 Paper I

4.1.1 Terminal characteristics

The average paved area at terminals of different sizes ranged from 28% for terminals with areas of 5-10 ha to 60% for those covering 2-5 ha (Table 3). However, while the average paved area of terminals covering <2 ha was 47%, this size class also had the greatest proportion of unpaved terminals (36%). Overall, 13% of 2-5 ha terminals, 22% of 5-10 ha terminals, and 25% of terminals ≥10 ha had no paved surfaces.

Table 3: *Annual terminal characteristics. Values quoted are averages for all terminals of the indicated size class that provided relevant data, with standard deviations in brackets*

Terminal characteristics	Size class, ha				
	<2	2≤5	5≤10	≥10	All terminals
Area (ha)	0.9 (0.48)	3 (0.81)	6.3 (1.31)	14.3 (4.02)	1.9 (2.74)
Paved area (% of total area)	47 (43)	60 (38)	28 (39)	38 (39)	48 (42)
Biomass turnover per terminal (OD t)	6307 (10029)	10454 (8335)	29490 (40521)	24012 (21593)	8661 (14289)
Space utilization (OD t/m^2)	0.78 (1.26)	0.37 (0.32)	0.54 (0.79)	0.19 (0.2)	1.00 (1.12)
Biomass concentration per assortment (OD t)	3039 (5384)	4155 (2814)	5596 (4595)	5949 (3533)	3446 (4997)
Supply from terminal (OD t/customer)	3004 (8374)	3333 (3644)	5223 (4308)	4020 (2349)	3198 (7444)
No. of assortments (n)	2.4 (1.14)	2.7 (1.11)	4.0 (2.26)	3.4 (1.84)	2.5 (1.3)

In total, 14 different biomass assortments were handled at the 208 forest terminals. Energy wood accounted for 1.1 million OD t, or 63% of the total biomass (Table 4). Aside from energy wood, the three most important assortments by mass were logging residue chips, loose logging residues and bark. All 14 assortments were handled by at least one terminal covering <2 ha whereas terminals in other size classes only handled 10 different assortments. The average number of assortments handled at a given terminal tended to increase with the terminal's size class for terminals in the 2≤5 ha and 5≤10 ha size classes. The opposite trend was observed for terminals covering ≥10 ha, which handled fewer assortments than terminals of the 5≤10 ha class (Table 3). A similar trend was seen with respect to the average number of deliveries per customer: terminals of <2 ha had the fewest customers per terminal while all other terminal size classes had 4-5 customers per terminal on average.

Table 4: *Total mass handled (OD t) per year by terminals of different size classes*

Assortment	Size class, ha			
	<2 (n=154)	2≤5 (n=37)	5≤10 (n=9)	≥10 (n=7)
Energy Wood[a]	605 267	268 041	156 800	96 000
Logging Residue Chips	139 156	42 677	7 123	30 000
Logging Residues	61 418	22 855	31 585	15 930
Bark	65769	29556	6300	5000
Saw Dust	30 800	3 696	10 400	12 400
Stem Wood Chips	19 076	10 200	23 600	-
Tree Part Chips	17 660	3 471	176	1 371
Stumps	14 098	8 248	17 980	3 720
Tree Parts	14 065	16 494	1 445	264
Dry Sawmill Chips	5 000	-	-	-
Shavings	1 970	-	10 000	1 700
Cut Off	1 852	-	-	1 700
Recycle Wood	1 395	2 470	-	-
Peat	80	-	-	-
All assortments pooled	977 605	407 710	265 410	168 085

[a] Energy wood - low quality roundwood used for energy generation.

The most numerous terminals were those with areas of <2 ha. These small terminals also had the highest average utilization rate (0.78 OD t/m^2) and handled 977,605 OD t of OD biomass during the studied year, which was more than half the total quantity of biomass handled by the complete set of terminals examined in this work. In contrast, terminals of ≥10 ha handled only 9% (168,085 OD t) of the total annual biomass turnover (Table

3, 4). However, on average, each terminal of ≥10 ha handled three times as much biomass as the average <2 ha terminal. Terminals in the 5≤10 ha size class handled 2.5 times more biomass than those of 2≤5 ha. On a per-terminal basis, the 5≤10 ha terminals handled more biomass than those of any other size class (Table 3).

4.1.2 Material flow and assortment structure at terminals

The yearly inventory turnover for 207 forest biomass terminals was 1.8 million OD t (Table 4). The largest terminal had an area of 20 ha and the smallest only 0.1 ha. Overall, 74% of all terminals considered in the study had areas of less than 2 ha and only 8% of all terminals had areas of more than 5 ha.

Terminals of <2 ha, <5 ha, and <10 ha accounted for 35%, 64%, and 78%, respectively, of Sweden's total terminal area. Similar trends were observed for the total volume of biomass handled: terminals of <2 ha, <5 ha, and <10 ha handled 54%, 76%, and 91% of the total biomass output for terminals covered in this study (Figure 10).

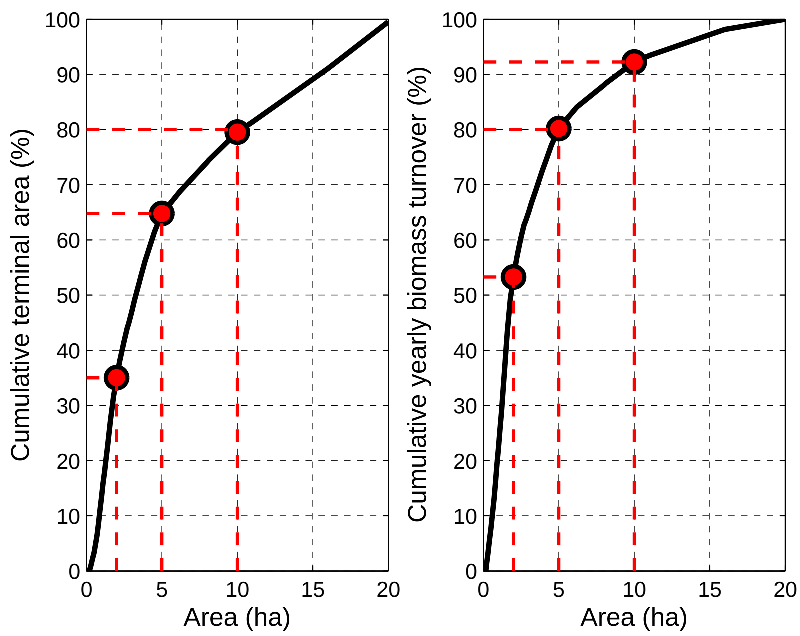


Figure 10: Cumulative terminal area (246 terminals) and yearly inventory turnover of biomass (207 terminals) in Sweden. (Reworked from a Paper I).

There was also a high level of variation between terminals with respect to the extent of paving, the number of assortments handled, and the number of customers served. Comminution was performed on site at 90% of the studied terminals. There were no statistically significant differences between any of the terminal size classes with respect to any of the studied variables other than annual biomass turnover.

4.1.3 Terminal geographical locations

In total, 27% of the terminals were located within 30 km of the coast. Most of these terminals (23 of 30) were less than 2 ha in size. There were no ≥10 ha terminals within 30 km of the coast. The closest forest industry sites to the terminals were sawmills: on average, each terminal was 18 km away from the nearest sawmill by road (Table 5).

Table 5: *Average distances (km, (sd)) from terminals to nearby forest industry sites (road distance) and railroad, closest terminal (Euclidian distance)*

Distance to facility	Terminal size class, ha				
	<2 ha	2≤5 ha	5≤10 ha	≥10 ha	All Terminals
CHP[a]	43 (31)	43 (30)	56 (42)	42 (32)	44 (32)
Pulp mill	63 (39)	63 (60)	85 (64)	144 (76)	66 (48)
Sawmill	20 (18)	16 (13)	12 (10)	5 (5)	18 (17)
Railroad	5 (8)	4 (7)	0 (0)	1 (1)	5 (8)
Closest terminal	21 (14)	22 (20)	38 (14)	7 (7)	22 (16)

[a] Combined heat and power plants with an annual energy output more than 100 GWh.

The average distance between a terminal and the nearest railroad was 5 km (Euclidean distance), with larger (≥5 ha) terminals being situated closer to railroads than smaller ones. The forest industry sites that were most distant from the terminals were pulp mills; the distance to the nearest pulp mill increased with terminal size.

4.1.4 Terminal inventory practices and equipment

The most common method of taking inventories at the studied terminals was to measure stock levels once a month or 3-4 times per year (Table 6). Follow-up intervals between inventories varied widely at terminals of <2 ha: in some cases inventories were performed annually while in others they were done on an ad hoc basis. At terminals of ≥5 ha, inventories were most commonly performed on a biannual, quarterly, or monthly basis.

Table 6: *Inventory frequencies and practices, prevalence of different types of equipment, and terminal ages for terminals of different size classes. In all cases, values recorded in the table represent the percentage of terminals in the relevant size class that exhibit the indicated property*

Variable and category	Size class, ha			
	<2	2≤5	5≤10	≥10
Number of inventories per year:				
1	20	21	22	-
2	15	-	-	50
3-4	22	17	56	25
12	21	41	22	25
24	6	3	-	-
>24	3	7	-	-
When necessary	13	10	-	-
Inventory performed by:				
Terminal personal	97	81	44	33
VMF[a]	20	19	56	100
Metria[a]	6	-	-	-
Focus industrimätning AB[a]	3	15	-	-
Other	6	11	-	-
Inventory method:				
GPS measuring	5	15	-	-
Visual	77	78	22	-
Measuring	51	30	78	100
Other	5	15	-	-
Equipment at terminals:				
Measuring bridge[b]	22	14	56	67
Measuring house[c]	13	7	22	33
Forklift	14	5	44	50
Wheel loader	92	82	78	83
Scale	39	41	100	67
Drying oven	12	7	22	33
Other	8	23	22	-
Age of terminals (years):				
>2	21	34	-	-
3-5	39	21	-	-
6-10	17	21	50	67
11-15	12	7	-	-
16-20	7	7	-	-
>20	4	10	50	33

[a] VMF, Metria and Focus industrimätning AB are independent third party measuring companies.

[b] Measuring Bridge: Construction used for the bulk volume measurements.

[c] Measuring House: Building used to protect the measurement equipment and to provide comfortable working conditions for the workers at the measurement station.

At terminals of <5 ha, inventories were generally conducted by terminal personnel (including truck drivers working for logistics companies) (Table 6). Most of the inventories at these smaller terminals were consequently performed by visual inspection: this method was used at 60% of all <2 ha terminals and at 59% of those in the 2≤5 ha class. Inventories at terminals of <5 ha were conducted by a wider range of individuals, including employees of several third party firms. Terminals of ≥5 ha primarily relied on terminal personal and the Swedish Timber Measurement Association (VMF) while 56% of terminals in the 5≤10 ha class and 100% of those in the ≥10 ha class used VMF.

Smaller terminals generally used multiple measurement techniques to inventory their stock, including visual inspection and GPS measurements. Physical measurements (length, width and height) were also quite common (Table 6). Physical measurement was strongly preferred at terminals of ≥5 ha and was the method of choice at all terminals of ≥10 ha and 78% of terminals in the 5-10 ha class. Conversely, it was only used at 30% of 2-5 ha terminals and 51% of the <2 ha terminals.

The ≥5 ha terminals were generally better equipped than smaller ones. The most common pieces of equipment across all terminal size classes were wheel loaders: their incidence ranged from 78% to 92% (Table 6). Terminals of ≥5 ha had more extensive measuring facilities such as measuring bridges, measuring houses, scales, and drying ovens. In addition, all terminals in the 5≤10 ha class had on-site scales.

The ages of terminals in the <5 ha class ranged from less than 2 years to more than 20 years (Table 6). However, all of the ≥5 ha terminals were either between 6 and 10 years old or more than 20 years old.

4.2 Paper II

4.2.1 Terminal chipping operations

The productivity of chipping operations varied from 23.7-59.7 t/PMH_0 and was mainly affected by assortment type (Table 7). The same pattern was observed for fuel consumption. Switching from the large sieve to the normal one had no significant effect on either productivity or fuel consumption ($p = 0.742$ and 0.991, respectively). Chipping work accounted for between 88 and 98% of the chipping machine's total operational time, i.e. chip production was halted for 2-12% of the time. The assortments' MC values varied between 45 and 66%; the bundles and fresh logging residues had significantly lower MC values than the other assortments (Table 7).

Table 7: *Properties of the chipping operations and resulting fuel chips. B=bundles, EW=energy wood, FLR= fresh logging residues, SLR=stored logging residues, TP=tree parts, L=large sieve size, N=normal sieve size. Values in the moisture content row for chips produced from the same assortment using different sieve sizes differ significantly based on Tukey's post-hoc test if they are labeled with different superscripted letters ($p<0.05$). Standard deviations are given in brackets*

Production properties	Assortment										AVG all
	B		EW		FLR		SLR		TP		
	L	N	L	N	L	N	L	N	L	N	
Productivity (t/PMH$_0$)	58.1	59.7	39.3	41.4	25.9	31.1	23.7	29.7	27.4	27.4	*36.4*
Average grapple load (t/crane cycle)	0.51	0.51	0.38	0.41	0.29	0.33	0.22	0.27	0.28	0.29	*0.35*
Chip bulk density (t/m^3)	0.35	0.33	0.23	0.25	0.35	0.40	0.29	0.30	0.24	0.24	*0.30*
Moisture content wet basis (%)	45 (0.12)^b	46 (0.40)^b	63 (0.67)^a	60 (5.66)^a	50 (1.31)^b	50 (1.55)^b	62 (3.46)^a	61 (5.66)^a	59 (7.54)^a	66 (0.72)^a	*57*
Fuel consumption (l/t biomass)	1.47	1.54	2.21	2.16	1.65	1.57	1.79	1.9	2.97	2.94	*2.02*
Fuel consumption (l/h)	85	92	87	90	43	49	42	56	81	81	*71*
Chipping time/Work time (%)	97	93	98	95	95	92	93	90	86	88	*93*

4.2.2 Chip quality

In general, particles of 16 to 31.5 mm constituted the most abundant size fraction in all of the assortments, accounting for 37-63% of the total mass of chips. For each individual assortment, the share values calculated for the PSD and AC of chips produced using the standard sieve did not differ significantly from those for chips produced with the large sieve, so the data for the two sieve sizes were merged.

The PSDs of the logging residues (fresh and stored) differed significantly from those for the other assortments (Table 8, Figure 11). Specifically, the average fine particle (i.e. particles with diameters of < 3.15 mm) content of these two distributions was 17% while that of the other assortments was only 7%.

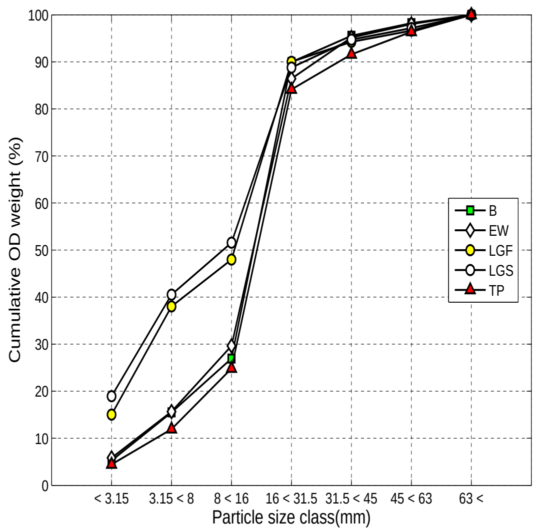


Figure 11: Cumulative particle size distributions for different assortments. For assortment abbreviations, see Table 7.

As the particle size increased from 3.15 to 31.5 mm, the differences in PSD between the logging residues and other assortments diminished (Table 8). The content of oversized particles (>63 mm) was generally below 4% for all distributions; such large particles were least abundant in the chipped bundles and most abundant in the chipped fresh logging residues. Most of the AC was located in particles of $\leq$3.15 mm, which accounted for between 31% and 41% of the total ash content. Particles with diameters of 3.15-8 mm had ash contents that were 1.7-2.4 times lower than those of the fines ($\leq$3.15 mm). In general the AC decreased as the particle size increased (Figure 12).

Table 8: *Particle size distributions for chips produced from different assortments. The relative abundance of each size fraction is expressed as a percentage of the total dry sample mass. Standard deviations are given in brackets. Different superscripted lowercase letters indicate significant differences between assortments (column-wise) based on Tukey's post-hoc test ($p<0.05$). Different subscripted capital letters indicate significant differences between particle size classes within the same assortment (row-wise) based on Tukey's post-hoc test ($p<0.05$)*

Assortment[a]	Particle size (mm)						
	< 3.15	3.15 < 8	8 < 16	16 < 31.5	31.5 < 45	45 < 63	63 <
B	5.3 (1.4)$^{a}_{C}$	10.2 (1.4)$^{ab}_{BC}$	11.4 (1.9)$^{a}_{B}$	63.0 (5.1)$^{a}_{A}$	5.6 (2.1)$^{ab}_{BC}$	2.7 (1.7)$^{a}_{D}$	1.8 (1.5)$^{a}_{D}$
EW	5.8 (5.9)$^{a}_{CD}$	9.8 (8.9)$^{a}_{B}$	14.0 (2.5)$^{a}_{B}$	56.8 (10.7)$^{ab}_{A}$	8.7 (3.0)$^{a}_{BC}$	2.9 (1.5)$^{a}_{DE}$	2.0 (1.8)$^{ab}_{E}$
FLR	15.0 (3.1)$^{b}_{BC}$	23.0 (3.8)$^{c}_{B}$	10.0 (3.0)$^{a}_{C}$	42.0 (7.6)$^{ab}_{A}$	4.2 (3.4)$^{b}_{D}$	2.4 (1.6)$^{a}_{D}$	3.4 (2.2)$^{b}_{D}$
SLR	18.9 (5.1)$^{b}_{BC}$	21.6 (4.4)$^{bc}_{B}$	11.0 (1.8)$^{a}_{C}$	37.2 (5.8)$^{b}_{A}$	5.9 (1.8)$^{ab}_{D}$	2.5 (1.4)$^{a}_{E}$	2.8 (1.5)$^{ab}_{E}$
TP	4.4 (1.8)$^{a}_{D}$	7.5 (1.7)$^{a}_{C}$	12.9 (2.0)$^{a}_{B}$	59.3 (4.5)$^{a}_{A}$	7.4 (2.2)$^{ab}_{C}$	4.8 (1.4)$^{a}_{CD}$	3.6 (1.7)$^{b}_{D}$

[a] For assortments abbreviations see Table 7.

Table 9: *Average ash content (% of dry weight) for different assortments and particle size classes. Standard deviations are shown in brackets. Different superscripted lowercase letters indicate significant differences between assortments (column-wise) based on Tukey's post-hoc test (p<0.05). Different subscripted capital letters indicate significant differences between particle size classes within the same assortment (row-wise) based on Tukey's post-hoc test (p<0.05)*

Assortment[a]	Particle size (mm)						
	< 3.15	$3.15 < 8$	$8 < 16$	$16 < 31.5$	$31.5 < 45$	$45 < 63$	$63 <$
B	2.6 (0.3)$^{bc}{}_{A}$	1.2 (0.1)$^{c}{}_{B}$	0.7 (0.0)$^{c}{}_{C}$	0.6 (0.0)$^{c}{}_{CD}$	0.4 (0.1)$^{c}{}_{E}$	0.4 (0.1)$^{b}{}_{E}$	0.6 (0.3)$^{b}{}_{DE}$
EW	2.3 (0.5)$^{c}{}_{A}$	0.9 (0.2)$^{d}{}_{B}$	0.8 (0.2)$^{c}{}_{B}$	0.5 (0.1)$^{c}{}_{C}$	0.4 (0.1)$^{c}{}_{C}$	0.4 (0.1)$^{b}{}_{C}$	0.5 (0.2)$^{b}{}_{C}$
FLR	7.1 (3.9)$^{a}{}_{A}$	4.1 (0.9)$^{a}{}_{B}$	3.5 (1.9)$^{a}{}_{B}$	1.9 (0.6)$^{a}{}_{C}$	1.2 (0.2)$^{a}{}_{CD}$	1.3 (0.4)$^{a}{}_{CD}$	1.1(0.4)$^{a}{}_{D}$
SLR	8.5 (1.4)$^{a}{}_{A}$	4.6 (0.9)$^{a}{}_{B}$	3.2 (1.2)$^{a}{}_{B}$	1.6 (0.3)$^{a}{}_{C}$	1.0 (0.1)$^{ab}{}_{D}$	1.0 (0.4)$^{a}{}_{D}$	0.9 (0.5)$^{a}{}_{D}$
TP	3.7 (0.4)$^{b}{}_{A}$	2.2 (0.2)$^{b}{}_{B}$	1.4 (0.2)$^{b}{}_{C}$	1.1 (0.1)$^{b}{}_{CD}$	0.9 (0.1)$^{b}{}_{D}$	1.2 (0.4)$^{a}{}_{C}$	1.3 (0.4)$^{a}{}_{C}$

[a] For assortments abbreviations see Table 7.

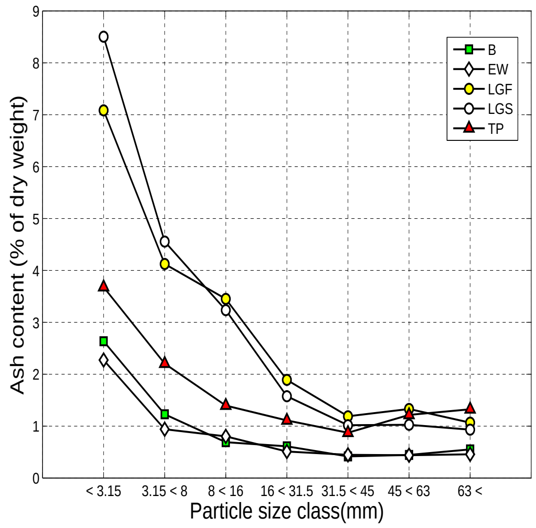


Figure 12: Ash contents of particles from different size classes in chips produced from different assortments. For assortment abbreviations, see Table 7.

The most notable difference between the assortments with respect to their AC values was that the fresh and stored logging residues (FLR and SLR, respectively) had much higher AC than the others, particularly in their fine fractions (<3.15 mm) (Table 9). The SLR had the highest AC (2.98%) followed by FLR (2.88%) and TP (1.69%), as shown in Table 9 and Figure 12. B and EW had the lowest AC values (0.94% and 0.84%, respectively). For the logging residues, the AC decreased rapidly with increasing particle size, going from 7.79% for particles of ≤3.15 mm to 1.73% for particles of 16 - 31.5 mm. The decrease in AC for all assortments other than FLR and SLR became insignificant once the chip size exceeded 16 mm (Figure 12, Table 9). For B and EW, the AC did not exceed 3% in any particle size class. Particles of >63 mm from the TP, EW and B assortments had higher AC values than similarly large particles from the other assortments.

5 Discussion

Terminals of <5 ha accounted for a large proportion of Sweden's total terminal area and handled a substantial fraction of its total biomass production by volume. These smaller terminals are generally newer than their larger (>5 ha) counterparts (Table 6). There was also a clear difference in terminal management approaches between terminals of <5 ha and those of >5 ha: smaller terminals were more likely to use mobile measuring equipment such as wheel loaders while larger terminals had better (static) measuring facilities. Terminals of different size classes appeared to take inventories in different ways: <5 ha terminals relied more on terminal personnel to conduct inventories and less on third party organizations. Standardized stock measurements were only performed routinely at 51% of these smaller terminals. Standardized measurements were even less common at terminals with areas of 2-5 ha. Terminals of $\geq$5 ha took the opposite approach to inventories, using the third party organization VMF exclusively for all measurements. However, in many cases multiple inventorying methods were used at a single terminal. When considering these results, it is important to note that smaller (<2 ha) terminals play an important role in supplying raw materials to the bioenergy sector since more than half of the country's total biomass output flows through them. However, because standardized stock measurements and inventories are rare at terminals of this size, around 76% of the biomass they handle is poorly accounted for. It is possible that some of this biomass is measured by end users.

5.1 Assortment availability for energy production and bio-refining

When considering terminals, one should recall that all forest industry facilities and CHPs must maintain up to date inventories of raw materials stored on site (Springer, 1979). Forest biomass terminals don't just store material;

they also offer an expanded range of options for ensuring security of supply to these end-users of biomass and wood (Kanzian et al., 2009). In addition, the presence of well-organized and integrated terminals in the supply chain should make it possible to offer a wide range of assortments to customers, allowing the supply chain to adapt rapidly to changes in demand and ensure that appropriate assortments are always available (Enström et al., 2013). By weight, the three main assortments stored at the terminals examined in this work were energy wood, logging residue chips and loose logging residues (Table 4). Terminals of all sizes handled several assortments: the number of different assortments handled within each terminal size class ranged from 10 to 14. The large number of unique assortments handled by certain terminals, such as shavings, bark, sawmill chips etc., and their small delivery volumes may indicate that such terminals were located in close proximity to forest industry sites that produce or consume such assortments. The widest range of assortments was handled by terminals in the < 2 ha class, which collectively dealt with 14 different assortments; these facilities also had the highest rates of terminal space utilization. The maximum number of different assortments per single terminal in this size class was six. The assortments stored and processed at these smallest terminals often include comminuted and un–comminuted logging residues, tree parts and their chips, as well as energy wood. This indicates that even today some terminals are primarily if not exclusively handling woody biomass assortments that may be of interest as raw materials for bio-refineries producing bio-chemicals and bio-fuels (Section 1.4.2). Some of these smaller and more intensively used terminals located close to industrial sites could thus find unique market niches as crucial suppliers for bio-refineries, as discussed by Joelsson and Tuuttila (2012). The terminals with areas of 5-10 ha are also of particular interest because they handle the greatest number of assortments. Indeed, the terminal with the greatest number of assortments handled at a single site (8) was in this size class. These larger terminals also have the second highest rate of space utilization, and the greatest annual biomass turnover per terminal. In addition to handling a wide range of assortments, they are capable of consolidating rather large shipments for delivery to their customers (Table 3). Moreover, they are usually located in close proximity to railroads, offering the potential for easy long-range biomass transportation (Table 5). The routine use of rail transport could considerably expand the procurement areas of large CHPs in densely populated areas and reduce the traffic intensity in their neighborhoods (Karttunen et al., 2013; Wolfsmayr and Rauch, 2014).

5.1.1 Chipping and chip quality

Comminution of various raw materials was performed at around 90% of the studied terminals, including all of those with areas of ≥5 ha. This comminution is usually done without taking any additional steps to increase the density of the processed material or to compact it. The high rate of comminution at terminals suggests that chipping/grinding and the handling of comminuted material will be important parts of terminal operations in future. Kärhä (2011) predicted that it would become increasingly common for chipping to occur at terminals in order to increase the supply of certain energy assortments, and the results presented in Paper I appear to validate this prediction to at least some extent. Chipping is usually preferred to grinding because it produces fuel with better properties. However, it can only be performed with material that contains few contaminants.

With the large number of different assortments handled at the terminals, it became of interest to see how some of these assortments affected chipping and chip quality at the terminal. Previous studies have suggested that both sieve size and knife length affect chip size and machine productivity (Nati et al., 2010; Ghaffariyan et al., 2013; Eliasson and Johannesson, 2014). However, no such effects were observed in this work; the main factors that influenced the chipper's productivity were the assortment type, the initial density and moisture content of the biomass, and the assortment's behavior during feeding into the chipper (Table 7). Productivity was much higher when loading bundled assortments than with loose logging residues because the former are easier to grab and feed, especially when dealing with large pieces of material (Ghaffariyan et al., 2013). The absence of a productivity decrease when replacing the large sieve with the standard one may have been because the holes in both sieves were too large compared to the knives' lengths. This may indicate that chip size is more sensitive to knife length than to sieve size when the sieve is relatively large. In keeping with this hypothesis, Eliasson and Johannesson (2014) found that sieve size had only a modest effect on the PSD when using sieves of a similar size to those examined herein, and concluded that the sieve's main role in a large drum chipper is to prevent the passage of oversized particles. Consequently, chip size is primarily determined by the properties of the knives. The overall particle size distributions observed in this work are comparable to those reported previously for similar materials (Nati et al., 2010; Nuutinen et al., 2014).

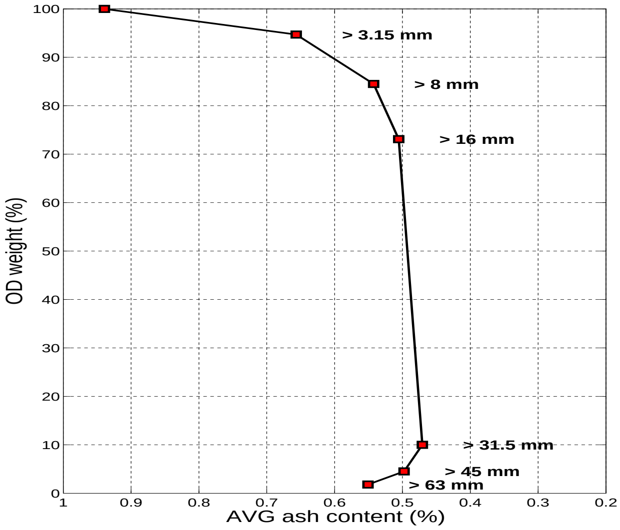
Many studies on chipping have focused primarily on the effects of different chipper types and configurations on the PSD of the resulting chips; relatively little attention has been paid to the effect of varying the assortment used (Asikainen and Pulkkinen, 1998; Spinelli et al., 2005) or to the AC of the different particle size classes in chips produced from different assortments (Gruduls et al., 2013; Greene et al., 2014; Nuutinen et al., 2014). Paper II described a study in which a single chipper and two different sieves were used to process five distinct assortments. The results obtained demonstrated that varying the assortment can have a much greater effect on the PSD and AC of the chipped material than the sieve size does. It was also found that the AC of chips produced from logging residues was much greater than that of chips from other assortments; this observation is consistent with the results of Greene et al. (2014).

One of the main drawbacks of the study presented in Paper II was the low number of experimental runs per treatment, which meant that the number of replicate runs was insufficient to determine whether the chipper's productivity and fuel consumption differed significantly between the studied assortments. It would therefore be desirable to conduct a follow-up study with multiple replicate runs to better understand the energy requirements associated with the processing of different assortments over the supply chain as a whole (including transportation to industrial sites). However, since many previous studies have examined chipper productivity it was decided that this work should focus primarily on chip characteristics.

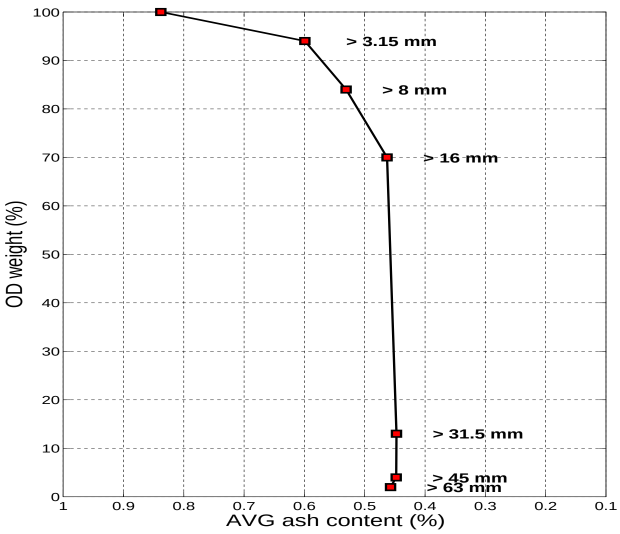
5.1.2 Screening of biomass for improved quality

One way of increasing the range of assortments offered at terminals and increasing the fuel quality of chipped material would be to screen off fine particles from chipped assortments such as logging residues. The resulting materials could be sold as different assortments with different fuel qualities. Such separations could in principle be performed at terminals.

In general, the AC of the chipped material decreased with increasing particle size up to a certain point. In the case of the B, EW, and TP assortments, this trend continued up to a particle size of 16 mm whereas for the two LR assortments it continued up to a particle size of 31.5 mm. Screening off particles of <8 mm from the chipped assortments reduced their average AC values from 2.98-2.88 % to 1.56-1.79%. This demonstrates that separating out the fine (< 3.15 mm) particles generated during the chipping process could potentially reduce the average AC of the final fuel product by up to 28% (Figure 13, 14, 15).

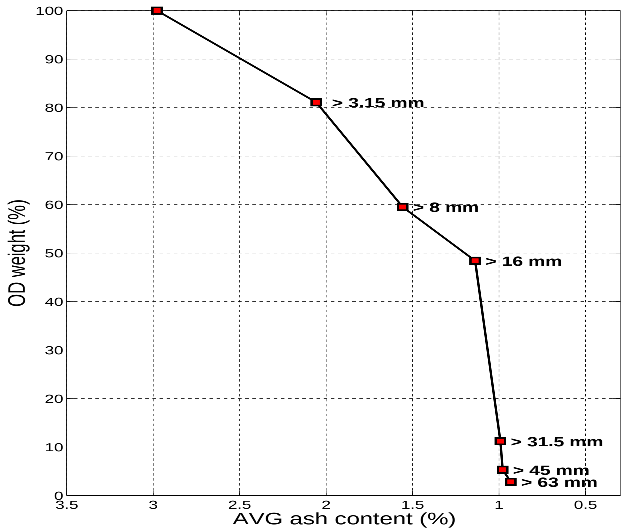


(a) Bundles

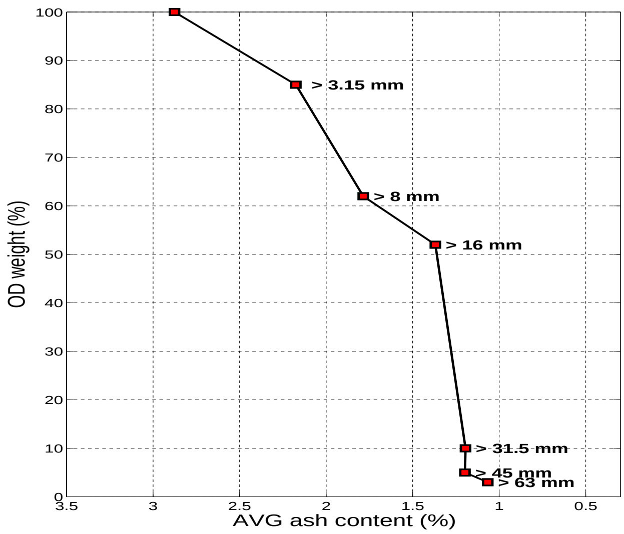


(b) Energy wood

Figure 13: Effect of biomass screening for different assortments in terms of the remaining OD weight (%) and average ash content (%) of the material left after separating out fractions smaller than 3.15 mm, 8 mm, 16 mm, 31.5 mm, 45 mm and 63 mm.

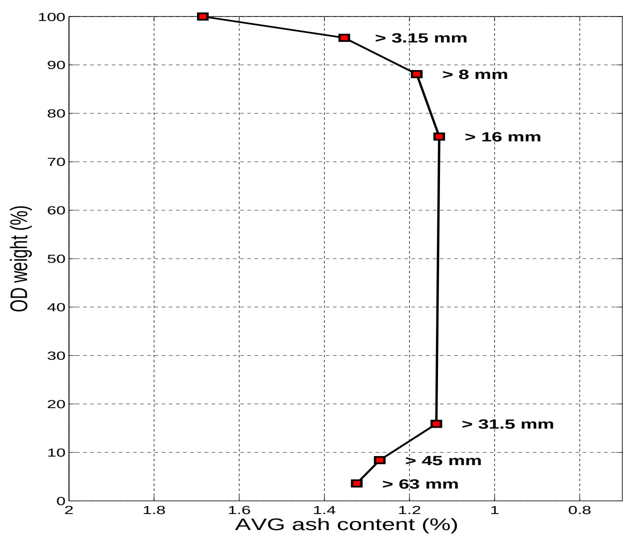


(a) Stored logging residues



(b) Fresh logging residues

Figure 14: Effect of biomass screening for different assortments in terms of the remaining OD weight (%) and average ash content (%) of the material left after separating out fractions smaller than 3.15 mm, 8 mm, 16 mm, 31.5 mm, 45 mm and 63 mm.



(a) Tree parts

Figure 15: Effect of biomass screening for different assortments in terms of the remaining OD weight (%) and average ash content (%) of the material left after separating out fractions smaller than 3.15 mm, 8 mm, 16 mm, 31.5 mm, 45 mm and 63 mm.

However, this would necessitate sacrificing 17% of the LR chips' total dry mass. The separated fine particles could potentially be offered as a new "low value" assortment, with the remaining material being sold as a "high value" assortment for use during the peak heating season. Removing the fines from the non-LR assortments would reduce their average AC by 26%, at the cost of 4.4-5.8% of their total dry mass. This clearly demonstrates that screening after comminution could be a very cost-effective way of increasing fuel quality for some energy assortments. By removing particles of <16 mm, the average AC for the B and EW assortments could be reduced to 0.54 and 0.53%, yielding material suitable for the production of premium quality pellets (EN 14961-2:2012, 2012). The separated fines could potentially lend themselves to uses other than combustion. For example, since they are comparatively rich in ashes and are derived from more nutrient- and extractive-rich fractions, they may be useful in the production of valuable chemicals (Nurmi, 1993). Alternatively, since the combustion process at a heating plant can be optimized for a particular fuel if its properties and quality are well defined, the ash-rich fines could be burned efficiently during seasons when the heating demand is low and it is not necessary to burn higher quality fuels. Compared to the pulp and paper industries, which have strict quality standards for chip size, shape and bulk density (SCAN-test Standard, 2001, 1992), CHPs have rather more relaxed requirements and primarily assess fuels on the basis of their MC and AC values. Finally, it should be noted that the separation of fines could reduce the cost of fuel transportation if it were done at the delivering terminal (Greene et al., 2014).

Figure 16: Bark screening with a mobile machine at a terminal in northern Sweden ©TM Henningssons Åkeri AB.

Even though screening was a common practice at terminals in the past it is almost completely absent from modern terminal operations. However, some terminals in northern Sweden still have mobile screening equipment, which is primarily used for separating out fine particles and contaminants from bark (Figure 16).

There are also some equipment manufacturers who still produce screening equipment (e.g. Doppstadt GmbH and Ultra Plant International Ltd), although such machines are most commonly used to screen soil, waste and other materials rather than wood chips. It seems unlikely that woody biomass screening will once again become a regular part of terminal operations until the wood chip market has matured to the point that there is a demand from biorefineries for specific assortments.

5.2 Constrains of biomass storage and inventory tracking at terminals

5.2.1 Biomass storage

Today forest biomass is stored in two main forms: (1) un–comminuted biomass such as energy wood (roundwood of low quality), logging residues, stumps etc. and (2) comminuted biomass (including bark and sawdust). Each form of biomass has its advantages and disadvantages. At the studied terminals, around 75% of the stored biomass was un–comminuted. This value rose to 82% for terminals with areas of 5-10 ha (Table 10). The decision to mainly store un–comminuted material is easy to explain: it minimizes biomass losses and the temperature buildup during storage while simultaneously reducing the MC of the biomass and improving its fuel quality (Jirjis and Lehtikangas, 1993; Filbakk et al., 2011). These favorable effects may be especially pronounced during the storage of assortments such as LR; Pettersson and Nordfjell (2007) observed that LR assortments experience major biomass losses during handling at various points within the supply chain. The advantage of terminal storage is that some of this lost material can be recovered and incorporated into other assortments or simply trapped to avoid the pollution of water streams with nutrients and debris generated during comminution and handling (Sinclair and Wellburn, 1984). Because un—comminuted biomass responds favorably to storage, it can be stored at terminals for relatively long periods of time. However, the energy industry and bio-refineries demand comminuted material so comminution must be performed at some point in order to supply the customer with the materials they desire.

Table 10: *Forms of biomass stored at terminals of different size classes in Sweden*

Terminal size class,	Chips		Others		Total Mass,
ha	OD t	% of total mass	OD t	% of total mass	OD t
<2	277 460	28	700 145	72	977 605
2≤5	89 601	22	318 109	78	407 710
5≤10	47 599	18	217 810	82	265 410
≥10	48 771	29	119 314	71	168 085
All Terminals	463 431	25	1 355 378	75	1 818 809

In the 1950s when the first chip storage facilities were established, devastating biomass losses were incurred as a consequence of several new and unanticipated problems. In particular, significant losses occurred as a result of biomass decomposition and the self-ignition of wood chip piles (Fuller, 1985). Biomass losses and temperature increases in wood chip piles are mainly caused by microbial activity, which increases the temperature in the pile and leads to fungal growth, which may in turn induce chemical reactions that cause further increases in temperature and acidity (Jirjis, 1996; Fuller, 1985). However, it is not possible to completely avoid the storage of wood chips in the pulp, paper, or bioenergy industries because a certain level of buffer storage is required. Biomass is often comminuted shortly before delivery to the plant in order to avoid storing chips for extended periods of time and risking significant biomass loss. Similar behavior is observed at Sweden's biomass terminals, where chipped material represents only 18-29% of the total stored biomass (Table 10).

Unfortunately, it is not always possible to maintain such comparatively low levels of chip storage, and sometimes chips must be kept on-site for extended periods. There are several ways that such prolonged storage periods could potentially be managed to limit biomass losses and maybe even increase their fuel quality. In particular, fractionating and screening the wood chips at the terminal would lead to the creation of separate chip piles that could be treated according to their properties. In general, the rate of temperature increase is lowest in chunked wood and large wood chips (Kofman, 1994; Jirjis, 2005). Moreover, the rate of degradation processes in a chip pile is sensitive to the chips' compaction and nutrient content, and can be minimized by adjusting the pile's height, width and rotation period (Kubler, 1982; Springer, 1979; Fuller, 1985).

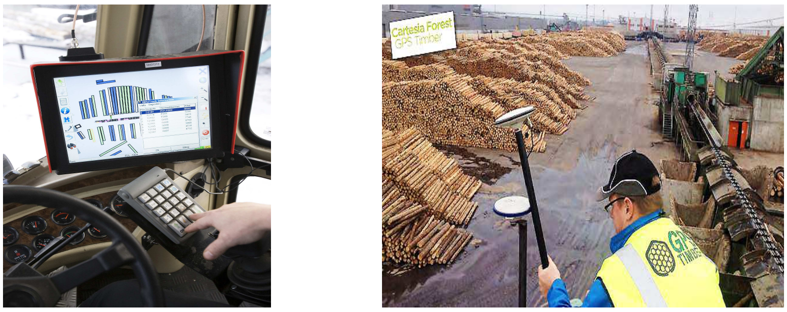
In the 70s and 80s, the scope for suppressing degradation of stored chips by chemical treatment was investigated, but the costs proved to be economically prohibitive (Springer, 1979). However, today chemical treatment with calcium (Ca) could potentially increase the chips' durability during storage and also improve their combustion properties in CHP plants while reducing the corrosion of CHP and gasification boilers (Öhman et al., 2004; Olwa et al., 2013). Adding Ca to stored chips would increase the pile's pH, which could in turn suppress microbiological activity (Zumdahl and Zumdahl, 2007). Ca could be added using adapted chippers that would spray the chips as they were fed out from the machine. Depending on the intended storage period, the Ca could be applied as a solution or in powder form. A solution would lead to more extensive adsorption and binding to the chips, but would also increase their initial MC. For terminals with limited storage space, such a treatment may enable the construction of taller piles, improving the rate of space utilization. The production of bio-energy assortments is highly sensitive to marginal gains, so every detail of the supply chain matters. The potential for improving fuel quality with only a marginal investments in production could make customers willing to pay a premium for the resulting product, although further maturation of the market would be required before such material could be offered.

5.2.2 Inventory tracking at terminals

In recent years, Sweden has introduced laws on wood measurement which state that prior to sale, all assortments (including energy wood) must be measured according to best practices, with internal control provided by accredited measurement companies (Björklund, 2014). These regulations have consequences beyond the simple requirement for accurate measurements given the currently poor tracking of energy assortments. As mentioned in Section 3.1.2, different assortments are measured in different units because the different energy assortments have very different physical and chemical characteristics, which makes it challenging for customers to compare and assess their relative value and quality. The new measurement requirements could potentially be fulfilled by simply measuring biomass at a terminal and sampling it to determine its MC and AC. Alternatively, later on, the biomass could be continuously tracked as it is processed at the terminal and then delivered onwards to the customer.

Today in Sweden, when trees are harvested and logs are forwarded to the roadside landing, they are assigned an identification (ID) number by the SDC's database system VIOL. This ID number contains information on the log's origin, time of harvesting, and so on. This information is widely used in the pulp, paper and saw mill industries. For example, knowing the freshness of each log that is supplied means that the pulping processes can be optimized or that the initial quality of each saw log can be preserved. GPS-based log tracking systems are used at several European saw mills and are becoming increasingly common in pulp mills as well (Figure 17). The GPS Timber Pulp© system created by Cartesia GIS AB is claimed to provide a number of benefits for saw mills including decreased fuel consumption, increased efficiency of warehouse utilization, greater productivity of personnel and machines, and reduced sorting time (GPS Timber, 2015). Although the system has been around for some time, its benefits have not been studied extensively. However, one study that did investigate its performance at a Swedish saw mill seemingly confirmed that it added value to the log handling process (Lindgren, 2009).

The other benefit of the GPS tracking system is its ability to be synchronized with the VIOL database. Synchronization means that as soon as a truck arrives at a terminal, the terminal personnel know what sort of material it is carrying, how fresh it is, and where the truck should be unloaded within the terminal. Built-in GPS trackers inside the terminal's machinery



(a) *(b)*

Figure 17: (a) A log yard as visualized on a logstacker operator's display unit (b) Installation of GPS Timber at a saw mill. ©GPS Timber.

allow this biomass to be tracked at every stage in the terminal's operations. Unfortunately, no such products are currently available for energy assortments.

The most crucial measurements of energy assortments are weight and MC, which determine their energy content (Jirjis, 1995; Björklund, 2014). Weight can be measured either with stationary scales or with scales built in to the terminal's machinery. The latter approach would in principle be compatible with the real-time tracking of the weight distributions of delivered assortments. At present, MC determinations take around 24h and are sometimes only obtained after the biomass has been combusted. The long time required for MC determination also delays payments to suppliers and makes load rejection difficult in cases where the material does not fulfill MC requirements. Several groups have attempted to develop quicker ways of determining MC, and it is only a matter of time until their improved techniques become widely adopted within industrial facilities (Fernandez-Lacruz and Bergström, 2014; Fridh et al., 2014; Jensen et al., 2006). Many of these improved methods use software that would enable the cloud synchronization of newly acquired MC data with systems such as GPS Timber.

Adopting a complete terminal material tracking system utilizing both GPS and a new MC measurement system would enable improved operational and logistical management of terminals because contractors would be better able to plan their work and logistics managers would be able to assess their inventories from their offices. However, for this vision to be realized, it will be necessary to develop improved sampling techniques because MC measurements are only meaningful if performed on samples that are representative of the material being processed (Björklund, 2014).

At present most of the work done at terminals is performed by contractors, and logistics managers sometimes have very little idea about what is going on. This can make the conduct of inventories difficult and time consuming. The introduction of GPS-based tracking systems would obviate these problems and also facilitate R&D by providing large quantities of data on material handling, storage times and MC levels. In addition, contractors using such products would be able to collate information from multiple terminals, potentially leading to increased biomass turnover and reduced investment costs.

6 Future work

The introduction of comprehensive terminal material tracking systems that utilize both GPS and some new MC measurement system could improve the logistical and operational management of forest terminals by enabling contractors to plan their work more effectively and allowing logistics managers to perform detailed and reliable inventories from their offices. However, this will require the development of new sampling technologies to ensure that the samples used for MC determination accurately represent the delivered material (Björklund, 2014). At present, most sampling is done at the receiving gate or by truck drivers prior to loading. The first method makes it difficult to obtain a representative sample because wood chip loads are heterogeneous and may be compacted during transportation, with fines shifting towards the bottom of the load. The second method may require the truck driver to be in close proximity to the loading equipment, which presents a safety hazard and also makes it difficult to obtain a sample from the middle of the pile. It would therefore be useful to develop new loading machines that can perform automatic sampling while loading.

The chemical treatment of wood chips in combination with the introduction of fire detection systems at terminals could significantly improve the storage of chipped biomass while reducing its risk of spontaneous ignition. Such practices could be particularly useful at smaller terminals that handle large volumes of wood chips. Further studies on the efficiency of chemical treatment and the minimization of biomass losses would be particularly interesting.

7 Conclusions

The main conclusions of the studies presented in this thesis are as follows:

- Terminals with areas of <2 ha contribute significantly to Sweden's overall biomass supply because they account for most of the country's total terminal area and handle more than half of its total biomass turnover.

- About 76% of the total biomass that passes through Swedish terminals may be poorly accounted for and monitored due to the lack of standardized stock measurements. This creates uncertainty during logistical planning and material handling.

- Improving the measurement facilities and stock inventory practices at terminals of >5 ha could be of considerable interest to large CHP plants because it could potentially increase the security of their fuel supplies.

- In total, 14 different assortments are handled at Swedish terminals. This indicates that terminals are already handling many assortments that might be suitable as feedstocks for refineries producing biochemicals and biofuels.

- Most (around 75%) of the biomass stored at the terminals is in uncomminuted form. The storage of comminuted biomass is deliberately minimized where possible to reduce biomass losses and the risk of spontaneous ignition.

- Terminal operations such as screening can reduce the ash content of wood chips and improve their fuel quality, at the cost of a reduced biomass volume. Screening fines (particles of <3.15 mm) from chipped logging residues reduces their ash content by ca. 28% at the cost of around 17% of their total biomass.

Overall, the results presented herein demonstrate that there is considerable variation in the properties of Sweden's biomass terminals and their management routines. Consequently, the existing infrastructure should be reasonably well set up to serve the growing bio-economy and deliver diverse assortments to bio-refineries and energy plants. The fuel quality of all chipped assortments, and logging residues in particular, could be significantly increased by screening off fine particles. However, the economic value of such screening depends heavily on the costs of the refining process and the value/utility of the separated fine particles, which should therefore be investigated.

Further studies on the use of chemical additives to improve the storage properties and combustion of wood chips would also be useful, and could potentially result in more thoroughly optimized processes for biomass conversion industries together with a re-imagining of modern wood chip production. Finally, the development of GPS systems for tracking energy wood assortments similar to those already established for saw logs could greatly improve the handling of material at terminals, especially in conjunction with a reliable method for rapid moisture content determination.

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