Management of Forest Biomass Terminals

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Abstract

Terminals and log-yards are becoming increasingly important in Nordic forest supply chains because of the need to support the rising production capacity of pulp mills and heat and power plants. Most modern terminals and log-yards handle multiple assortments, must accommodate multiple incoming and outgoing modes of transport, and have multiple storage areas. This complexity makes it challenging to find ways of increasing their efficiency. The design of more efficient terminals will therefore require a detailed understanding of the current state of forest terminals and the activities that occur within them. The overall objectives of this thesis are thus to provide a general overview of the current state of forest biomass terminals in Sweden, to determine the scope for upgrading biomass fuel at terminals, and to find reliable ways of analyzing log-yard and terminal performance. To achieve these aims, data were gathered by means of surveys, questionnaires, time studies, analyzing fuel-chip quality, and discrete-event modeling.

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 terminals of < 2 ha handled half the country's total terminal biomass output. Comminution activities were performed at 90% of all terminals, creating opportunities to add value to the processed material. By screening fine particles, it was possible to reduce the average ash content of the processed assortments to 0.66-2.17% (corresponding to a 20-31% reduction in total ash content). Screening could thus be used to divide chipped material into various quality classes suited for different applications with different price points. Models developed using production data for log-yards reliably predicted real-world outcomes over the studied time period and highlighted the importance of gathering relevant real-world data for meaningful analysis and improvement of log-yard operations. This thesis provides an overview of Sweden's forest terminals, energy assortment quality, and potential operational improvements. The discrete-event models presented here are helpful tools for understanding log-yard operations and supporting decision-making by forest businesses.

Keywords: logistics, discrete-event modelling, inventory, storage, forest fuels, supply chain, screening

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Hantering av skogens biomassa terminaler

Sammanfattning

På grund av ökande produktionskapacitet på massabruk och värmeverk blir virkesgårdar och terminaler allt viktigare i de nordiska skogsråvaruförsörjningskedjorna. De flesta moderna virkesgårdarna och terminalerna hanterar flertalet sortiment, de måste kunna hantera flera olika typer av in- och utgående transporter och de har flera olika lagringsytor. På grund av denna komplexitet så blir det utmanande att hitta sätt att effektivisera arbetet. För att designa effektivare terminaler krävs därför en detaljerad förståelse av nuvarande virkesterminaler och de aktiviteter som sker inom dem. Det övergripande syftet med denna avhandling är därför att ge en allmän överblick av svenska biomassaterminaler, att fastställa vilket utrymme det finns för att förädla biomassa på terminalerna och att hitta tillförlitliga sätt att analysera prestandan på virkesgårdar och terminaler. För att uppnå syftet samlades data in genom undersökningar, enkäter, tidsstudier, kvalitetsanalyser av bränsleflis, och diskret händelsestyrd modellerande.

Den tydligaste skillnaden observerades mellan terminaler som var större respektive mindre än 5 ha. Av Sveriges totala terminalyta så ingår 65% i terminaler som är < 5 ha, och de terminaler som är < 2 ha hanterade hälften av landets totala terminals biomassa produktion. Sönderdelning av materialet skedde på 90% av alla terminaler, vilket skapar möjlighet till att öka värdet på produkten. Genom siktning av fina partiklar så kunde den genomsnittliga askhalten reduceras till 0.66-2.17%, vilket motsvarar en reducering av den totala askhalten med 20-31%. Siktning skulle därför kunna användas för att dela in krossat material i olika kvalitéer för olika ändamål och till olika prisklasser. Modellerna som utvecklades med verklig produktionsdata gav tillförlitliga prediktioner av virkesgårdarnas prestanda och visade även på vikten av att samla in relevanta och verkliga data för en meningsfull analys av och förbättring av virkesgårdarnas verksamhet. Den här avhandlingen ger en överblick över Sveriges biomassaterminaler, energisortiments kvalité, och potentiella verksamhetsförbättringar. De diskreta-händelsestyrda modeller som presenteras i detta arbete är användbara verktyg för att förstå virkesgårdars verksamhet och stödja skogsbolagens beslutsfattande.

Nykelord: logistik, diskret-händelsestyrd modellering, lager, lagring, skogsbränsle, försörjningskedja, siktning

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”Sometimes life is going to hit you in the head with a brick. Don’t lose faith”

Steve Jobs

Contents

List of Publications

This thesis is based on the work contained in the following papers:

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. *International Journal of Forest Engineering* vol 26(2), 114-123.

III Kons, K., La Hera P., Bergström. Modelling Dynamics of a Log-Yard Through Discrete-Event Mathematics (manuscript)

IV Kons, K., Bergström, D. Comparison of Present and Alternative Pulpwood Inventory Strategies and Machine Systems at a Log-Yard Using Simulations (manuscript)

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

I Took part in formulating the study's objectives, performed part of the complementary survey, analyzed all of the data, and wrote the manuscript with input from co-authors.

II Helped to plan the study's design and the formulation of its objectives, prepared collected samples for further analysis, analysed the data and wrote the manuscript with input from co-authors.

III Planned the study's design and the formulation of its objectives together with co-authors. Prepared data analyses and build discrete-event model, interpreted and analysed final results and wrote the manuscript with input from co-authors.

IV Planned the study and formulated its objectives with the co-author, developed the discrete-event model and interpreted and analysed the final results. Wrote the manuscript with input from co-author.

Abbreviations

AC	Ash content, dry basis
ANOVA	Analysis of variance
CHP	Combined heat and power plant
cm	Centimetre
DEM	Discrete-event mathematics
dt	Intergeneration time
dt_s	Server service time
FILO	First in - last out
g	Gram
GIS	Geographical information system
GLM	General linear model
GW	Gigawatt
h	Hour
ha	Hectare
kg	Kilogram
kW	Kilowatt
l	Loose
LIFO	Last in - first out
m	Meter
m^3	Cubic meter
MC	Moisture content, wet basis
MW	Megawatt
OD	Oven dry
PDF	Probability density function
PMH_0	Productive machine hour, excluding delay time
PSD	Particle size distribution

R&D	Research and development
s.o.b.	Solid over bark
s.u.b.	Solid under bark
t	Metric tonne

1 Introduction

In 2017, the total global output of forest products - wood fuels, pulpwood, sawlogs and veneer logs, industrial roundwood, wood chips and wood residues - was estimated to be approximately 4.3 B m^3 (FAOSTAT, 2019). Fuels accounted for 1.89 B m^3 of this total, a 4% increase over the mean for the preceding 10 year period (FAOSTAT, 2019). Even more pronounced increases in wood fuel production have occurred in Europe as a whole (31%) and Northern Europe in particular (51%). In Sweden, biomass supply to the energy sector accounted for 25% (approximately 71 M m^3) of the total energy supply in 2017 (Swedish Energy Agency, 2019). During the same time period, global production of industrial roundwood increased by 8%, reaching 1.9 B m^3 (FAOSTAT, 2019). However, industrial roundwood production in Europe and Sweden remained relativity stable, accounting for 31.3% of the total worldwide industrial roundwood production (FAOSTAT, 2019). Despite this apparent stability, Sweden has experienced changes in the demand for some roundwood assortments, such as pulpwood. The number of operational pulp mills in Sweden fell by 12% (from 45 to 40) over the last 16 years, while the average production capacity per mill increased by 27%, reaching 326 000 t of pulp by 2017 (Swedish Forest Industries Federation, 2019). Sweden's wood-fueled heat and power generation sector is also well developed: approximately 90% of the country's apartment buildings are connected to a district heating network supplied by over 290 heating plants and 209 heat and power plants (SVEBIO, 2016a,b). The extensive development of Sweden's bioenergy and pulp sectors has imposed considerable demands on existing forest supply and logistics chains both within Sweden and throughout the Baltic Sea region (WWF Latvia, 2003; Ericsson and Nilsson, 2004).

Many forest companies have established a series of forest biomass terminals and subsidiary companies to secure their raw material supplies, both domestically and in the wider Baltic Sea region. The scale of current forest supply networks necessitates the use of effective real-time data collection systems to support planning and logistics by tracking stock inventory and quality so as to maximize the overall benefit of raw material deliveries (Lee and Billington, 1992; Dahlin and Fjeld, 2004; Gunnarsson Lidestam, 2007).

Another factor that has driven the development of forest terminals in recent years is the growing demand for pulpwood. Since 2016, the Swedish pulp and paper industries have experienced increases in both production capacity and investment, accounting for 23% of all industrial investment in Sweden (Berg et al., 2018). The rising production capacity of pulp mills creates significant challenges in supply chain management because of the need to ensure uninterrupted production at the mills by expanding the area from which material is sourced while maintaining a competitive price for the delivered pulpwood (Swedish Forest Industries Federation, 2019). Introducing intermediate terminals between forests and mills is one way to cope with this increase in the supply area and the uncertainty associated with inventory keeping at the log-yards of mills (Enström et al., 2013; Kons et al., 2014; Virkkunen et al., 2015). Although the introduction of terminals adds new costs to a supply chain, terminal networks have grown in parallel to the increase in pulp mills' production capacity. Notably, there has been a pronounced increase in the number of bigger round wood satellite and feed-in terminals, which now account for around 20% of all terminals in Northern Sweden (Athanassiadis and Store, 2017).

1.1 Supply chains and logistics

In the global context, a supply chain is a network of organizations (companies) that moves products or services from suppliers to customers by exploiting its human, information, and material resources (Mentzer et al., 2001; Christopher, 2016). Accordingly, the task of supply chain management is to integrate all of the organizations involved in the supply chain and to coordinate and manage supply chain activities so as to maximize customer value and gain a competitive advantage in the marketplace (Stadtler, 2005; Christopher, 2016). Information on stock inventory levels at different points and quality along the supply chain is essential for effective supply chain management (Lee and Billington, 1992).

Logistics and logistics management are aspects of supply chain management that relate to planning, control, and control of goods and manufacturing processes within the boundaries of a single organization (Hugos, 2018; Badiru and Bommer, 2017; Surbhi, 2018). The main goal of logistics is to achieve full end-customer satisfaction by delivering a product of the desired quality in the desired quantity at the right time and place, at the right price (Swamidass, 2000; Christopher, 2016; Surbhi, 2018).

Operations management involves analyzing, improving, and controlling business processes (particularly internal processes) to improve efficiency and quality. One way of doing this is to create quantitative models to identify and solve problems relating to site location, transport routes, scheduling and inventory keeping (Heinimann, 2007). As Heinimann (2007) points out, the main challenges in the forest sector are to connect business management to supply chain management, and to develop efficient decision support tools that could deliver further improvements in key performance indicators.

1.2 The role of forest terminals in the supply chain

Forest biomass terminals have traditionally served as storage and transition points for roundwood deliveries within forest industry supply chains. However, the demands placed upon terminals have changed over time. In the 1970s and 1980s, there was considerable interest in evaluating the ability 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 1.1).

(a)

(b)

Figure 1.1: (a) Roundwood terminal in central Sweden after storm Gudrun in 2005 (Photo: Kalvis Kons), (b) Stockarydsterminalen AB, an energy industry biomass terminal (Photo: Tomas Nordfjell).

Performing extra material handling steps at terminals increases the overall cost of the delivered wood (Karttunen et al., 2010; Virkkunen et al., 2015; Eriksson and Björheden, 1989; Väätäinen et al., 2017). Additionally, unpredictable factors such as the weather affect the demand for energy, the progress of harvesting operations, and the supply of raw materials (Quayle and Diaz, 1980; Williamson et al., 2009; Malinen et al., 2014). Because of this variation in supply and demand, terminals are becoming increasingly important as storage and buffer points for the delivery of biomass, both to heating and CHP facilities and also to more traditional forest industries (Ranta et al., 2012). In addition, Kärhä (2011) 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 further 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 from facilities such as biorefineries may prompt the forest industry to produce a wider range of assortments to meet these varied requirements.

1.3 Terminals past and present

The ability of forest biomass terminals to deliver a wide range of products will be increasingly important in the future because it will reduce the number of suppliers 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 wider ranges 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, forest industry plants in densely populated areas may require feed-in terminals on 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; Olsson et al., 2016). The ability to increase profits by exploiting economies of scale has driven increases in the sizes of pulp mills, biorefineries, and CHP plants. These larger facilities must in turn source their raw materials from larger areas than would be required for smaller plants (Virkkunen et al., 2016; Tahvanainen and Anttila, 2011). 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 that forest raw material handling costs at rail/road transition and receiving terminals in Sweden can differ by as much as 60%, clearly demonstrating that (in)efficient terminal designs can strongly affect supply costs.

1.3.1 Terminal operations in the past

Terminal operations involve a sequence of major steps (Grammel, 1978) (Figure 1.2). In addition, there are invariably various material handling and relocation processes that must take place between these main operations.

Traditional centralized terminals were often based on 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).

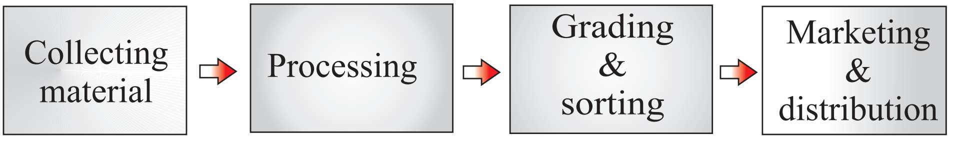
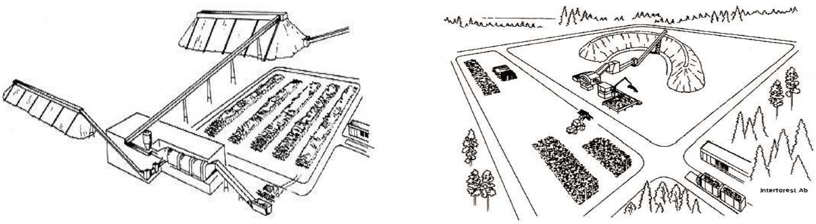


Figure 1.2: Operations at forest biomass terminals according to Grammel (1978).

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 by-products from the pulp and paper industry for energy production. This led to the introduction of new techniques for pulpwood and energy wood handling (Figure 1.3). With state support, many forest biomass terminals were established to secure raw material deliveries for the paper and energy industries, causing the annual production of forest fuels at terminals to rise dramatically to a peak in 1987 (Hillring, 1996).

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).

Aside from the chipping of raw material, one of the most common processing operations conducted at terminals was the delimbing of tree sections. The two main delimbing



(a) (b)

Figure 1.3: (a) Stand-alone tree section terminal for processing unlimbed pulpwood and fuel wood (b) Stand-alone biomass terminal for producing fresh fuel chips (Lönner, 1985).

technologies were: (1) modified debarking drums, which were often integrated into systems used in the pulp industry, and (2) specially constructed stand-alone delimbing drums, which were used at more remote terminals (Figure 1.4) (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 1.4). The main advantage of chain flail debarkers was that they could be relocated relatively cheaply.

(a) (b)

Figure 1.4: (a) A delimbing drum at a forest biomass terminal (Photo: Jonas Palm) (b) Chain flail delimbing during terminal operations (Photo: Kalvis Kons).

The main purpose of terminals was usually to provide a secure supply of raw materials 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; Eriksson et al., 2013). It should be noted that all screening methods inevitably cause at least some level of biomass loss (Hakkila, 1979).

In contrast, North American forest terminals were mainly used for merchandising or bucking and storing saw logs to increase product value. They were generally 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 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 in the present

One of the main problems in the logistics of primary forest fuels is that most assortments have low bulk densities. This makes it difficult to fully utilize the nominal 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 (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. While it is typically performed at landings, it has also become one of the main operations performed at terminals in recent years (Angus-Hankin et al., 1995; Ranta and Rinne, 2006; Routa et al., 2013). Comminution may be achieved by chipping or grinding (Figure 1.5); the former involves cutting the wood with sharp knives while the latter involves crushing it with blunt tools (Eriksson et al., 2013).

(a) (b)

Figure 1.5: (a) Energy wood being loaded into a Petersson chipper by a truck-mounted crane (b) Stumps being loaded into CBI Magnum Force crusher by a grapple and front-end loader (Photos: Kalvis Kons).

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 homogeneous material and consumes less energy (Spinelli et al., 2011). The properties of the biomass that affect its comminution most strongly are its density, moisture content, storage time, 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). The comminution process is also sensitive to the settings and properties of the machines used for comminution and biomass handling (Hartler, 1986; Uhmeier, 1995; Hellström et al., 2008, 2009; Abdallah et al., 2011; Eriksson et al., 2013; Nati et al., 2014). 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 more efficient forest fuel supply chains to ensure that the cost of fuel wood remains competitive with that of alternative fuels (Björheden, 2011).

(a) (b)

Figure 1.6: (a) Pulpwood being loaded onto a train at a satellite terminal in Northern Sweden (b) Pulpwood being unloaded at a feed-in terminal in Northern Sweden (Photos: Kalvis Kons).

Two primary goals for large satellite and feed-in terminals are to quickly and efficiently reload trains and to minimize the time over which round wood is stored (Figure 1.6). The increasing capacity of pulp mills and Sweden's relatively well-established railroad network have made big terminals particularly appealing. Many large terminals have purpose-built machine parks that are tailored to the material type to be handled, the modes of transport that must be accommodated, the characteristics of the terminal, and the primary business goals of its operator. Configurations of this sort increase the efficiency of unloading, reloading, and moving logs within the terminal area (Kons, 2018).

1.3.3 Terminal types

Forest terminals can be divided into five categories depending on their position within the supply chain and the purpose they serve. In addition, terminals can be classified as being either industry-oriented multi-purpose facilities or small-scale terminals (Virkkunen et al., 2015; Kons et al., 2014; BioRes, 2019).

The most common type of terminal in the Nordic forest industry is the transshipment terminal, which can be regarded as a kind of reference or benchmark when discussing other terminal types (Virkkunen et al., 2015). While these terminals usually have relatively low capacities, there are many of them and so they collectively handle a large proportion of the total biomass passing through terminals (Kons et al., 2014). Transshipment terminals usually act as buffers to even out variation in biomass supply due to seasonal changes, weather, and other (usually foreseeable) factors (Ranta et al., 2012). These small terminals are often filled during seasons when biomass demand is low, providing a reserve to cover periods of high demand. Therefore, transshipment terminals are typically located in close proximity to good road networks that can be used all year round to secure supply (Figure 1.3 (b)). To minimize investment costs, transshipment terminals are commonly established on old gravel pits or other low value plots of land. It has been argued that terminals of this type should not be included in biomass supply chains if possible because they increase overall supply costs (Virkkunen et al., 2015).

Another very important and more common type of terminal is feed-in terminals. These terminals are located close to the industrial sites they serve, and their size depends on the demands of those specific industries. They are commonly used when an industrial facility has insufficient on-site storage space or when on-site storage is limited by environmental restrictions (Wolfsmayr and Rauch, 2014). These terminals also serve as buffers to help cope with transient imbalances between supply and demand (Ranta et al., 2012). Feed-in terminals that handle high volumes of biomass are typically located close to good road networks and/or railroad systems (Figure 1.6 (b)). Like satellite terminals (see below), feed-in terminals are considered to represent a new terminal concept associated with the bio-economy (Virkkunen et al., 2015).

The final type of industry-specific terminal is the industry terminal (also commonly referred to as a log-yard, wood yard, or industry site). These terminals are directly adjacent to a mill or plant and are operated by the end customer (i.e. the owner of the mill or plant). The size of an industry terminal will depend on several factors including the size of the plant or mill, its storage capacity, environmental restrictions, transport infrastructure, and the availability of satellite, feed-in, and transshipment terminals in the supply chain (Virkkunen et al., 2015; Wolfsmayr and Rauch, 2014; Olsson et al., 2016).

One of the biggest and newest types of terminal is the satellite terminal (Virkkunen et al., 2016). These terminals are relatively large (ca. 10 ha) and are located close to abundant pools of raw forest material, far from industrial sites (Figure 1.6 (a)). As noted by Virkkunen et al. (2016), little is currently known about terminals of this type. Their main purpose is to increase the efficiency of long-distance raw material supply. Satellite terminals often have railroad connections and are situated close to well-maintained road networks to take advantage of transportation systems capable of handling large payloads, such as trains and high-capacity-trucks.

Another new type of terminal is the biomass logistics and trade center (BLTC), or biohub (BioRes, 2019). The purpose of these terminals is to deliver standardized biomass fuel products on local and regional scales. The biomass is sourced from local suppliers, upgraded/improved at the terminal (by converting it into products such as fuel pellets) and then delivered to the customers, which may include private households and heat and power facilities. Since these terminals mainly deliver small quantities of product to each customer, they also handle several products of higher value than those handled by industrial biomass terminals. Examples include split and dried firewood, as well as wood pellets for animal bedding and heat. BLTCs are becoming more common in Central and South Eastern Europe, as well as in Finland (BioRes, 2019).

Increasing or maintaining product value is an important objective at any terminal, whether it is oriented towards industry or the private sector. Any terminal in one of the classes discussed above could become a fuel or biomass upgrading terminal. Upgrading terminals are similar to satellite and feed-in terminals in terms of their potential to add value to the delivered raw material. Fuel upgrading terminals could be regarded as another "new" terminal type because the upgrading of raw material at terminals is currently rare (Virkkunen et al., 2015). However, we do not classify them as a separate type of terminal; instead, we regard upgrading as an additional activity that can be integrated into the operations of any type of terminal. As noted by Virkkunen et al. (2015), the natural drying of biomass during storage at a terminal could in principle be regarded as a fuel upgrading process because it increases the wood's net calorific value. Activities such as comminution, sieving, or reducing the drying time of pulpwood can also be regarded as upgrading activities because they can all maintain or increase the profitability of the biomass.

1.4 Biomass quality requirements of different end users

1.4.1 Biomass for pulp production

Time strongly affects many pulpwood quality parameters (Persson, 2001) including freshness, moisture content, debarkability, brightness and bleachability (Bjurulf, 1993; Öman and Söderstam, 2000; Liukkoxs and Elowsson, 1999). Therefore, it is important to minimize the lead time between the harvesting of pulpwood and its pulping. At terminals and log-yards, this is best achieved by processing biomass efficiently so as to minimize the time logs spend in storage and being transported on-site. While pulpwood is the main assortment processed at pulp mills, pulp chips from nearby sawmills are also an important feedstock. Reducing the moisture content of the wood used to produce pulp chips at sawmills typically increases its content of pins and fines, which adversely affect pulping processes (Berg et al., 1995). It is therefore also important to minimize the cycle times of wood and chips in sawmills. Screening can also significantly improve the quality of sawmill pulp chips by increasing the homogeneity of chip the size distribution (Färlin, 2008). It is important to note that while upgrading processes do offer notable ways of improving the quality of raw materials delivered to pulp mills, their potential is even greater in the context of energy production.

1.4.2 Biomass for energy production

Bioenergy generated from woody biomass is a key source of energy in the Nordic countries, accounting for 25% of the total primary energy supply (143 TWh) in Sweden in 2017 and 26% in Finland (LUKE Stats, 2017; Swedish Energy Agency, 2019). 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 - notably, secondary forest fuels such as bark, sawdust, and residues from pulp production - is traded as fuel wood (Hillring, 2006). In contrast, primary forest fuels are assortments sourced directly from the forest for use in 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 (Fernandez Lacruz, 2019).

Residual woody biomass from the forest industry, such as black liquor, accounts for 47 TWh of bioenergy deliveries and these sources of material are currently fully utilized (Swedish Energy Agency, 2018). Therefore, any increase in energy production from forest fuels will have to be supported by increased procurement of alternative un-processed forest fuels, which accounted for 52 TWh of bioenergy deliveries in 2017 (Swedish Energy Agency, 2018).

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 below 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).

1.4.3 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 power production. The distinction between traditional forestry products and energy assortments such as logging residues (which are often regarded as forestry by-products) is important. However, there are also 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. Tree 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.

Saw milling and the pulp and paper industries are the largest forest industries in the Nordic countries, producing vast quantities of bark as a by-product. Bark is a potentially important source of green chemicals. At present, it is mainly burned for energy generation

(Gandini et al., 2006; Miranda et al., 2012, 2013). The bark content of assortments such as birch logs is about 11.4% by mass, and that of branches and crowns is even higher (Hakkila, 1984; Pinto et al., 2009; Holmbom, 2011; 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. The levels of extractives in the FLR typically start decreasing immediately after harvesting (Alén, 2000; Ekman, 2000; Lappi et al., 2014), which introduces new handling and logistical constraints into the forest bio-chemical supply chain because extractive-rich material for biorefineries must be delivered much sooner after harvesting than is the case for energy assortments.

1.5 Analyzing terminal and log-yard system performance

1.5.1 General analysis

It is difficult to identify effective ways of increasing the efficiency of existing biomass terminals and log-yards. This is mainly because changing terminal operations can involve large investment costs, and there is inevitably at least some uncertainty about whether those investments will result in optimal solutions. Such investments may include expanding storage areas or purchasing new machines, among other things. Attempting to increase efficiency by trial and error risks introducing inefficiencies if it is done without a good understanding of how the working machines will interact with the storage areas to minimize cycle times, which is vital for increasing the pulpwood throughput of log-yards (Robinson, 2004). One way of making decisions when attempting to improve efficiency is to use optimization. Optimization can be implemented on the basis of human experience, but this approach has the drawback that it often requires an expensive process of trial and error that may generate sub-optimal results. Alternatively, optimization can be done using modern mathematical tools. This approach, which exploits the capabilities of modern computers, has been used successfully to improve efficiency in a variety of industries. The central element of computer-based optimization is systems analysis, which is a process whereby engineers try to understand the parameters that are important for optimizing a process by creating mathematical models representing the working principles of the system under investigation. Software representations of such mathematical models are known as simulators; they can be used to quickly predict a system's behavior under different conditions. In this way, one can determine how the system's outputs respond to variation of specific parameters. In forestry, simulations have been used to investigate, design, and optimize operational processes ranging from timber harvesting to wood supply and processing. For example, Asikainen (2001); Karttunen et al. (2013) and Väätäinen (2018) used simulations to investigate logging and wood chip transportation via barges and intermodal container supply chains for forest products. Arriagada et al. (2008) Fernandez Lacruz (2019) used simulations to estimate the costs of forest thinnings, while Eriksson et al. (2014), Berg et al. (2014) simulated stump harvesting and supply chains. Pinho et al. (2016) developed a simulation model for roadside chipping and wood chip deliveries to customers. Chiorescu and Gronlund (2001) and Salichon (2005) focused more on simulating the bucking accuracy of harvesters and its relationship to the features of the saw-logs as well as the performance of sawmills. Other researchers focused on optimizing log in-feed to sawmills and log sorting bins, and providing an overall description of workflows at sawmill log yards (Mendoza et al., 1991; Beaudoin et al., 2012; Rahman et al., 2014). Finally, Puodziunas and Fjeld (2008) and LeBel and Carruth (1997) used simulations to find ways of improving wood delivery scheduling for a sawmill and paper mill in order to reduce the amount of material handling necessary at the log-yard. In summary, the literature shows that considerable effort has been devoted to understanding wood supply chains based on specific case studies. However, there is little information on fundamental concepts relating to mathematical modeling itself. Building and describing simulation model is time-consuming because of all the mathematical principles required to properly describe a system. However, mathematical modeling is essential for successful simulation, and understanding the results one can obtain from simulations.

1.5.2 Discrete-event mathematics

Several mathematical methods can be used to analyze log-yards (Taha, 1992; Lättilä, 2012). One of the most popular methods for modeling forestry processes is discrete-event mathematics (DEM). DEM is a useful method for modeling industrial processes that involve a sequence of events, such as those performed at log-yards (Robinson, 2004). In terms of systems analysis, the objective of the work presented in this thesis was to derive a mathematical model of a log-yard in which logs enter the system via multiple modes of transport. An additional goal was to simulate how the machines work to handle these loads at the receiving log-yard of the pulp mill. Such a model could help reveal the parameters that most strongly influence the working performance of a log-yard. Once identified, optimization efforts could be focused on these parameters, hopefully resulting in significant gains in efficiency. The principles of DEM can be explained by considering a simple sequence of operations at a log-yard. The inputs to the system representing this yard are trucks carrying logs. If we suppose there is only one log-stacker to unload the trucks, then the trucks must be unloaded individually in turns. During the time it takes to unload one truck, the remaining trucks wait in a queue. After a truck has been unloaded, it exits the system, leaving a pile of logs in the storage area. The pile of logs represents the output of the process. Each truck in the queue progresses through the same sequence of events, causing logs to accumulate in the storage area. In DEM, the input of a model is known as an entity and often represents a physical object, e.g. a truck. An entity can possess attributes that are used in decision-making, such as the volume of the logs on the truck. Each entity becomes part of a waiting queue, where it remains until a server (in our example, the log-stacker) performs a service on it; in our example, the service is the act of emptying the truck. Upon exiting the system, the entity leaves another physical object in the process that is related to some attribute of an entity - for example, a pile of logs of a given volume. The core components of a DEM are thus entities, attributes, events, resources, queues, and time. Figure 1.7 shows a graphical representation of a general case. More complex processes and systems can be described by combining multiple models of this kind, in series or in parallel (Robinson, 2004).

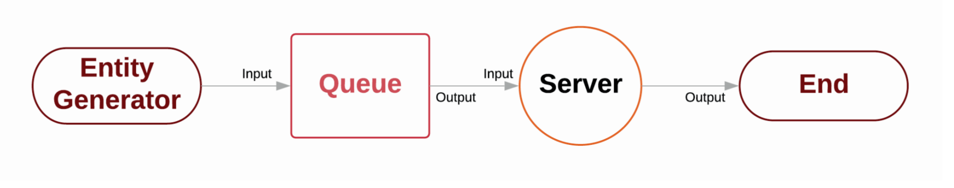


Figure 1.7: Flowchart depicting the flow and main components of a model described by discrete event mathematics

A major difficulty of using DEM stems from the number of functions and parameters required to properly describe a process. Since entities, attributes, and time are variables that may take a range of values clustered around some mean, it is often necessary to describe them using probability theory. This is typically done by using probability density functions (PDF) (Gnedenko, 2018; Zeigler et al., 2000; Silverman, 2018), which are functions that define the likelihood that a random variable will take a value in a certain range. For instance, when a machine unloads a truck, it will take a certain amount of time to do so. The time will differ somewhat from truck to truck, resulting in a set of values with a mean and some level of variation. PDFs make it possible to account for this variation in simulations.

Many different kinds of PDF are known. However, it can be challenging to identify the PDF and parameters that best describe the dynamics of a given process (i.e. that agree most closely with real-world data). This is mainly because real systems are rarely perfectly described by any known PDF. Nevertheless, selecting an appropriate PDF and parameters to describe an event is essential for reliable simulation. Therefore, when using DEM (or any other modeling approach), one must consider real process data to determine what sort of PDF best fits the behavior of the process under investigation, and to identify the parameters that must be included to make a model useful for analysis.

In summary, DEM can be used to capture and predict dynamic changes over time in a log-yard. A DEM model can describe a log-yard's behavior from the moment that logs arrive to the moment they enter the pulp mill. However, real process data are needed to enable realistic simulations.

2 Objectives

The objective of the research in this thesis was to improve the understanding of the ways terminals are used in modern Swedish forestry and to clarify the roles of forest biomass terminals and log-yards. An additional objective was to use this improved understanding to identify ways of improving terminals' operational efficiency and the quality of the raw material they process to better meet future challenges. At present, little is known about the characteristics of existing forest biomass terminals in terms of their sizes, the distribution of assortments they deal with, the volumes of material they handle, their infrastructure, and so on. More detailed information about terminals' characteristics is required to reliably model terminal operations and logistics in order to enable more efficient terminal design, identify optimal terminal locations, and accurately calculate supply costs. Because the work presented here was conducted in collaboration with industrial partners, a final goal was to help these partners make more informed decisions by considering the different issues and possibilities identified in the course of the work.

The thesis is based on studies that were presented in four articles (Figure 2.1). Briefly, the contents of these articles were as follows:

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

Paper II examined one of the most common operations at a terminal (chipping) and compared the properties 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.

Paper III described the development of software for simulating operations in an existing log-yard using discrete event modeling. To this end, the company being studied provided extensive data on its yearly operations. Additional data not recorded by the company were gathered by performing time studies and conducting interviews. This article presents 1) the mathematical concepts needed to analyze the gathered data, and 2) a brief introduction to discrete event modeling and a description of the way it was used to model the terminal's operations, including the decision making that machine operators perform during their working routines.

Paper IV describes the use of the model described in Paper III to find ways of fixing some of the shortcomings observed in the system. The main identified shortcoming was that logs tended to accumulate at the terminal, and that their quality deteriorated over time, resulting in a loss of value. There is thus a need for strategies to avoid this deterioration by minimizing the amount of time that logs are stored at the terminal. To this end, this article analyzed the expected effects of (i) replacing an existing machine with a new one, and (ii) emptying some of the more important storage areas once or twice per year. These measures were predicted to ensure that all logs eventually leave the system without being stored for extended periods.

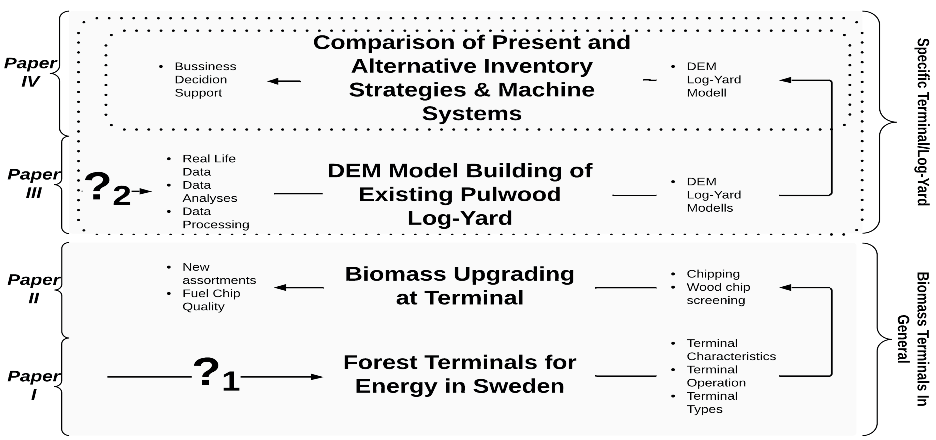


Figure 2.1: Conceptual framework of the thesis, showing the progression from general terminal-related questions in the initial articles to aspects of operations at a specific terminal in the later articles. Dashed lines link articles that complement one-another. $?_1$ indicates questions relating to forest terminals for energy materials in Sweden, and $?_2$ indicates questions about modeling systems and operations at existing terminals.

3 Materials and Methods

3.1 Paper I

3.1.1 Terminal characteristics

3.1.1.1 Data gathering

Data were gathered using a quantitative questionnaire sent out in 2012 by Biometria (formerly the Swedish Forest Industry's IT Company, or SDC) to all major forest companies and owner associations that deal with forest biomass fuels. 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. In total, 16 out of 18 forest companies and owners' associations provided information about their forest terminals for 2010 and 2011. Only terminals that had been in use for at least two years before the survey were contacted. These terminals were all expected to remain active throughout the year of the survey.

The gathered data included information about how long (in years) the terminals had been functioning, the size (in ha) of the area in permanent use, the nature of the ground surface (e.g. gravel or paved) at the terminal, the types of machines operated at the terminal, the measuring equipment used to estimate truck-load weights, the volumes of stored assortments, the frequency of stock inventories, and the number of customers served. The information on the nature of the ground surface at the terminal was collected to estimate the risk of soil contamination in stored assortments.

3.1.1.2 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 (Skogforsk, 2012) to facilitate comparative analysis. Forest biomass terminals handle a wide range of biomass assortments, ranging from energy wood to peat. To compare these assortments, it was necessary to know the types of assortment under consideration and their moisture contents.

3.1.1.3 Grouping of terminals

The total number of terminals surveyed was 270. However, area measurements were only provided for 246 terminals. Only these terminals were considered in subsequent analyses. In addition, certain analyses were only performed using data for terminals that provided information about specific variables, such as the volume of stored material, number of customers, or the equipment present at the site. Therefore, the number of terminals considered when performing specific calculations ranged from 112-246.

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. The 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 terminal age.

3.1.1.4 Terminal geographical data

Geographical information that could be related to the surface areas of the terminals was only available for 112 terminals. 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 railroad data were obtained from the Swedish Land Survey Authority. The shortest distances from the terminals to nearby CHP plants (with outputs of ≥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. straight lines from point to point. 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).

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 over 100 GWh in 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.

3.1.1.5 Statistical analysis of terminal characteristics

Paper I was mainly based on descriptive statistics. Additionally, the significance of differences between terminals of different sizes was evaluated using analysis of variance (ANOVA), as well as the Chi-Squared test and Fisher's exact test. A significance threshold of $P < 0.05$ was applied in all these statistical tests.

3.2 Paper II

3.2.1 Forest biomass chipping at a terminal

The chipping study was carried out at a terminal in northern Sweden. Five different biomass assortments were chipped: energy wood, bundled tree parts, fresh and stored logging residues and fresh tree parts from marginal lands (Figure 3.1). 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.

The bundles were produced around three months before the trials commenced, 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 into 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).

(a) (b) (c) (d) (e)

Figure 3.1: Assortments used in the study (a) Energy wood (b) Bundles (c) Fresh logging residues (d) Stored logging residues (e) Tree parts.

3.2.2 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. 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).

All five assortments were chipped using both sieve sizes, giving a total of 10 treatments (Figure 3.1). 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 chipper’s fuel consumption was read from the machine gauge after each run and measured by top filling when replacing the large sieve with the normal one.

3.2.3 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 were determined at the terminal’s measuring station, which was operated by the accredited third part measuring agency Biometria (formerly VMF Nord).

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 3.2).

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

(a) (b)

Figure 3.2: Milled and sealed samples for analysis of ash content (a) Energy wood (b) Stored logging residues.

3.2.4 Statistical analyses of fuel chip quality and chipper productivity

Paper II presents statistical comparisons of the treatments with respect to key fuel quality measurements (AC and PSD) based on a General Linear Model (GLM). Differences associated with p-values of $P < 0.05$ were considered statistically significant. Because only one experimental run was performed for each treatment, the only way to compare the chipper's 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.).

3.3 Paper III and IV

3.3.1 Discrete-event modeling of a log-yard

Modeling is a complex subject involving a variety of mathematical concepts. In principle, there are many methods that could be used to model any given system. Selecting an approach that is convenient and simple enough to model a given problem can be challenging, because every modeling approach has its own difficulties. Discrete-events mathematics (DEM) has been widely used for modeling in forestry research, mainly because many forestry processes are implemented as sequences of events, each of which can be characterized by means of time studies. Although there are other methods for modeling such systems, papers III and IV analyze operations at a log-yard using DEM as the main mathematical tool (Figure 3.3).

As explained in the introduction, the company studied in papers III and IV runs a log yard serving a pulp mill. Logs are delivered to this yard by trucks, trains, and ships. Unloading these logs can present significant decision-making challenges because of the limited availability of space and machines. The company was therefore keen to identify ways of making improvements throughout its production process. A convenient way of doing this is to create a model that can be used to analyze the process.

In general, the processing of logs at the log yard can be divided into two stages (Figure 3.3). The first stage corresponds to the delivery of logs to the yard's gate via some mode of transportation (truck, train, or ship). All these modes of transport are independent, and deliveries by different modes may occur simultaneously at any point during the working hours of the day. Upon arrival, the delivered logs enter a waiting queue where they remain until they are unloaded by one of four log-stackers. The unloaded logs accumulate in a designated storage area. The second stage of the process involves feeding the logs from these storage areas into the pulp mill. To this end, the log-stackers used in stage 1 transfer the logs to a debarking drum.

The novelty of this work stems from the fact that the company being studied had gathered a large amount of data on its operations. This greatly facilitated model development and made it possible to validate the developed models by testing their ability to reproduce empirical observations. Many of the parameters and variables used in the models could be extracted directly from the data supplied by the company. However, some of the parameters needed for model development were not represented in the supplied data and therefore had to be estimated. Parameter estimation is an aspect of data analysis, and can be performed in a variety of ways (see below).

Paper III introduces the mathematical concepts used to model the two stages of the log-yard's operations, presents the models that were developed, and outlines the procedures used to analyze the data and calibrate the model. The models describe the decision-making processes that machine operators perform when operating machines for transporting logs during stages 1 and 2. Two distinct ways of analyzing the data supplied by the company were identified; accordingly, paper III presents two different ways of modeling the system at the log yard:

- In the first case, data on trucks, trains, and ships are considered separately and the logs delivered by these modes of transport are placed in different storage areas. This approach is depicted in figure 3.3a. Modeling based on this approach necessitates the use of a variety of conditional statements to implement the logic of the log yard's operating principles. To accommodate these conditional statements, it was necessary to use several concepts from probability theory and decision theory that are rarely applied in the context of DEM.

- In the second case, the data on trucks, trains, and ships were considered together and it was assumed that logs from all three sources were stored in common storage areas. This approach is depicted in figure 3.3b, and leads to a simpler model that draws only on concepts commonly applied in the context of DEM.

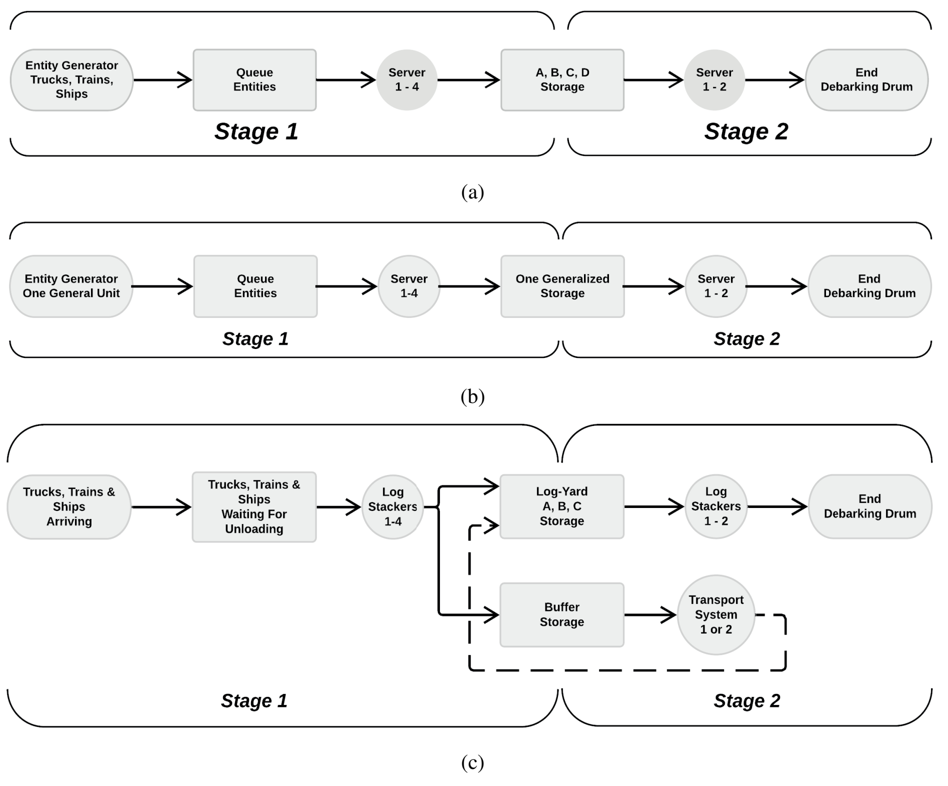


Figure 3.3: General structures of the DEM log yard models from papers III and IV: (a) detailed model (III), (b) simplified model (III), and (c) storage strategy and machine system analysis model (IV)

3.3.2 Data analysis

Probability density functions (PDFs) play a critical role in DEM. These functions are mathematical tools that define the probability that a variable will take a value within a given permitted range. In the context of DEM, they can be used to randomly select a value for a given quantity from within a defined interval having a characteristic mean. For instance, a PDF can be used to describe the times at which trucks arrive based on the knowledge that on average, one truck arrives every hour and that their times of arrival vary by $\pm$ 15 minutes. The arrival of trucks can thus be described using a PDF that specifies the probability of a truck arriving at a time (in minutes) in the interval $[45, 75]$.

The most common PDFs are the normal (or Gaussian), triangular, and binomial distributions, all of which are commonly used in DEM. However, as discussed below, real-world processes are rarely described well by these PDFs, so other alternatives must often be considered.

The data provided by the company include the exact times at which trucks, trains, and ships arrived at the log-yard over the course of one year, as well as the volume of material they were carrying. This information was used in the following ways:

- The timing data were used to define PDFs that enabled the model to randomize the arrival of trucks, trains, and ships. This gives rise to the quantity dt (the inter-generation time), which describes the rate at which entities are introduced into the modeled system.

- The volume data were used to define a PDF that enabled the model to compute the volume of material stored within the system. In the context of DEM, this PDF becomes an attribute associated with specific entities, allowing the total volume in storage to be computed based on the number of entities that have been generated.

Since the company provided data representing one year of its operations, it was important to decide how best to treat the data in order to obtain meaningful results. The data on the arrival of trucks, trains, and ships could be split into daily, weekly, or monthly blocks. Because the studied company's agreement with the pulp mill required it to deliver a given volume each week, it was considered best to divide the data into weekly sets. Splitting the data in this way generated 52 vectors, one for each week of the year. PDFs for delivery time and volume were then derived by using linear square regression to identify the parameter values offering the best fit to the data.

It was also necessary to decide whether the data on the arrival of trucks, trains, and ships should be treated together or separated by mode of transport. Since the volumes of logs supplied per delivery differ widely between these modes of transport, it was considered unfeasible to directly treat the data of these transport methods all together. One way of overcoming such problems is to normalize the data against some common unit. In the case of the log yard, we can normalize the data on deliveries by train and ship against that for trucks because trucks provide the smallest deliveries. Under this approach, each train and ship is represented by a certain number (x and y, respectively) of trucks, and all trucks representing a given train or ship are assumed to arrive at the log yard simultaneously. This makes it possible to work with data for trucks, trains, and ships all together, and also facilitates their separate treatment.

The methods described above were useful to analyze data and obtain relevant information to define PDFs to our model. As mentioned above, the data on trucks, trains, and ships can be treated separately or together, resulting in two distinct modeling approaches. Both approaches are described in detail in paper III, but are briefly summarized below for convenience.

- For the first model, the normalized data on the arrival of trucks, trains and ships were separated to facilitate PDF formulation. However, as noted in article III, only the data of trucks were described well by a known PDF. The data on train and ship arrivals did not match any standard distribution because the data indicate that train and ship deliveries were only made once per week. We therefore used a synchronization approach to determine when trains and ships would appear in the simulation; deliveries by these modes were assumed to occur randomly on any day of the week. The synchronization approach was based on probability theory, with the probability of appearance being highest for trucks, followed by that for trains and then that for ships. Additionally, each storage area of the log-yard was associated with a distinct queue. Conditional logic statements were used to tell the system how to store logs; area A was allocated to truck deliveries, area B to train deliveries, and area C for ship deliveries. An additional storage area (D) was available to store overflow from the other areas.

- For the second model, the normalized data on truck, train, and ship arrivals were treated together using a single PDF. Consequently, the system generated only one type of entity, eliminating the need for different storage areas. As a result, few conditional statements were needed in this model.

3.3.3 Storage management and machine alternatives

A major problem at the studied log yard is lock-in of logs, which happens when logs in the storage areas remain in the piles for long periods of time. This is particularly common for logs at the bottom of piles. The longer a log stays at the bottom of a pile, the more its quality is degraded, and thus the more value it loses.

Various strategies can be used to address this problem and reduce the amount of time logs spend in storage. Since the main problem occurs by logs staying at the bottom of the piles for too long, the main method would be to periodically empty areas where these logs are stored. At the studied yard, lock-in primarily occurs in storage area A, which is the yard's largest storage area. This yard could be emptied once or twice per year. Article IV considers three strategies for managing the lock-in problem:

- Strategy I is that currently used by the company, which causes the lock-in problem. This strategy serves as a point of reference for evaluating the other two.
- Strategy II involves emptying storage area A once a year.
- Strategy III involves emptying storage area A twice a year.

A second possibility analyzed in article IV is the introduction of a new machine whose purchase was being considered by the company. At present, logs are transported from storage area D to other storage areas by a dedicated machine because storage area D is far from the main yard and is only used as buffer storage. The company hires a contractor to do this work, who is only called on when needed. The contractor uses their own machines, namely a material handler and two shuttle trucks. We refer to this system as Machine System I.

Table 3.1: *Different machine system scenarios and strategies for emptying storage area A at the log-yard.*

Machine System	Empty Storage A		
	Strategy I[a]	Strategy II	Strategy III
Machine System I[a]	Business as usual	1 time per year	2 times per year
Machine System II	Business as usual	1 time per year	2 times per year

[a] reference system.

However, the company is considering purchasing its own machine to perform this work on its own schedule. The machine under consideration is a self-loading hauler with a trailer that would work for 84 h per week. We call this Machine System II.

The combination of two machine systems and three strategies for managing the lock-in problem gives rise to six cases, each of which was simulated. The cases are summarized in table 3.1.

To replicate the lock-in effect in the simulations, the queues in stage II of the model (Figure 3.3 (c)) were pre-loaded when the simulation was initiated. As a result, the simulated yard had ca. 70 000 – 75 000 m^3 of logs in storage when the simulations began. Storage areas A, B, C, and D were pre-loaded with approximate volumes of 35 000 m^3, 15 500 m^3, 4 660 m^3 and 15 500 m^3, respectively.

3.3.4 Model validation and statistical analysis

The results presented in paper III were obtained by averaging the results of 100 simulations with each of the two models under consideration. The models' performance was evaluated by performing simulations in which the inputs were based on empirical data supplied by the company rather than the PDFs. The output of these simulations was then compared to the corresponding information from the company-supplied dataset, revealing ways in which our mathematical approximations failed to reproduce real outcomes. To enable the use of empirical data as a model input, dt values were computed based on delivery timings and each delivery was assigned a unique identification number and log volume. Simulations using these data as inputs made it possible to see how real data are processed in each stage of each model, and to compare the results obtained at different stages to the corresponding empirical outcomes.

It should be noted that the PDFs used in the models were derived using only half of the available empirical data to avoid overfitting. Overfitting happens when a model learns the detail and noise in the training data to such an extent that its performance suffers when using new input data. However, when comparing the simulated results to empirical data, the full empirical dataset was used to test the models' ability to capture the properties of an unknown data set. The models were validated by observing the number of input entities generated in each case, and the output from the very last server in the process, and comparing them to the corresponding empirical data.

In paper IV each scenario involving machine systems I and II was simulated 30 times, giving a total of 180 runs. After each simulation run, the data for each storage area and total inventory levels over time were recorded. In addition, data from the server block representing two different machine systems were recorded, showing the machine work time and the volume of transported logs. Finally, the total log volume generated and delivered to the mill was recorded.

The statistical significance of differences between scenarios was tested using the Mann-Whitney two-tailed T-test ($P < 0.05$), one-way ANOVA, and the Kruskal-Wallis test with Dunn's correction ($P < 0.05$).

All data analyses, modeling, and simulations discussed in Papers III and IV were performed using MathWorks' MATLAB and the Simulink software package.

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. 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 $\geq$10 ha had no paved surfaces.

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. 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 $\geq$10 ha, which handled fewer assortments than terminals of the 5-10 ha class. 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.

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 collectively 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 $\geq$10 ha handled only 9% (168,085 OD t) of the total annual biomass turnover. 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.

4.1.2 Material flow and assortment structure at terminals

The yearly inventory turnover for the 207 forest biomass terminals was 1.8 million OD t. 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 <2 ha and only 8% of all terminals had areas of ≥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 included in this study (Figure 4.1).

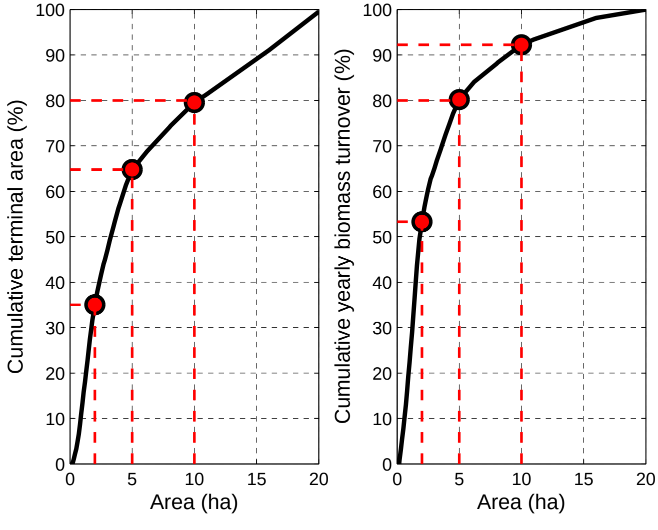


Figure 4.1: Cumulative terminal area (246 terminals) and yearly inventory turnover of biomass (207 terminals) in Sweden. (Reworked from Paper I).

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.

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. 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.

At terminals of <5 ha, inventories were generally conducted by terminal personnel (including truck drivers working for logistics companies). 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 Biometria (formerly VMF) while 56% of terminals in the 5-10 ha class and 100% of those in the ≥10 ha class used Biometria.

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. Volumetric 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.

Terminals of ≥5 ha 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%. Terminals of $\geq$5 ha were more likely to have measuring facilities such as measuring bridges, measuring houses, scales, and drying ovens. In addition, all terminals in the 5$\leq$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. However, all of the $\geq$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 ranged from 23.7-59.7 t/PMH_0 (for SLR, TP, FLR, EW, and B) and mainly depended on assortment type. 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.

4.2.2 Chip quality

In general, particles of 16 to 31.5 mm constituted the most abundant size fraction in all 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 (Figure 4.2). 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%.

As the particle size increased from 3.15 to 31.5 mm, the differences in PSD between the logging residues and other assortments diminished. 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%

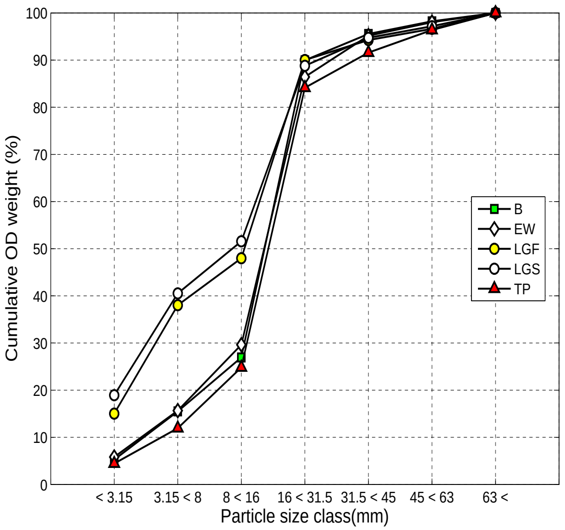


Figure 4.2: Cumulative particle size distributions for different assortments, where B - bundles, EW - energy wood, LGF - fresh logging residues, LGS - stored logging residues and TP - tree parts.

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 4.3).

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 ash contents than the others, particularly in their fine fractions (<3.15 mm). The SLR had the highest AC (2.98%) followed by FLR (2.88%) and TP (1.69%), as shown in figure 4.3. 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 $\leq$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 4.3). 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.

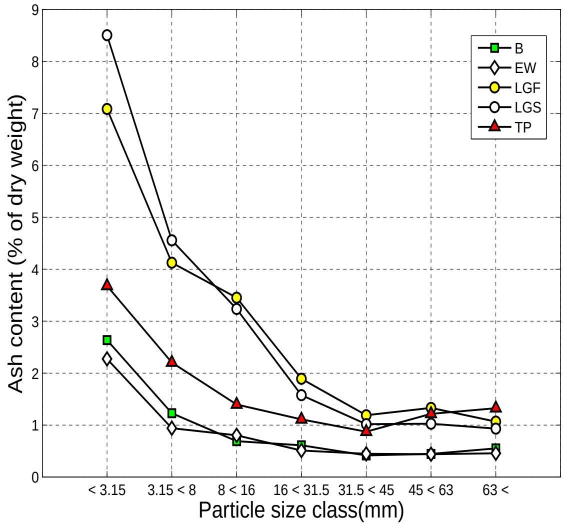


Figure 4.3: Ash contents of particles from different size classes in chips produced from different assortments (B - bundles, EW - energy wood, LGF - fresh logging residues, LGS - stored logging residues and TP - tree parts).

4.3 Paper III

4.3.1 Discrete-event modeling: reality vs mathematical approximation

Based on the means of 100 simulation runs each, models I and II predicted that over the course of one year, the yard would receive deliveries supplying 22223 and 21697 entities in total, respectively. For comparative purposes, the company's records indicated that the yard actually received 21685 entities over the year for which data were available. Figures 4.4 (a) and (c) show that based on the averages of 100 simulation runs, Model I's predictions deviated from the empirical data by 2.5%, while those for Model II deviated by only 0.1%.

Figures 4.4 (b) and (d) show the mean outputs (numbers of delivered entities) for models I and II. The output of model I differs from the empirical value by 2.4%, while that of Model II differs by 2.7%.In absolute terms, these differences are on the order of 18 to 31 entities.

The processed volume predicted by model I (877 076 m^3) was 4% higher than that indicated by the empirical data (844 363 m^3), while that predicted by model II (843 545

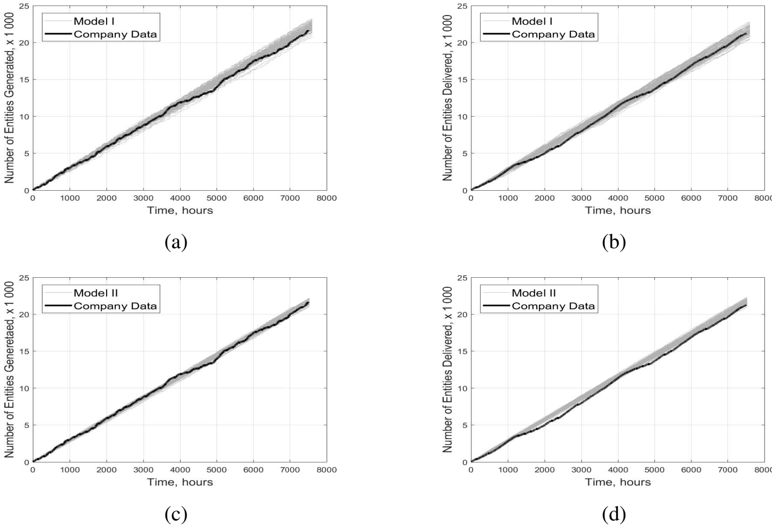


Figure 4.4: Total numbers of generated and delivered entities based on the averages of 100 simulation runs each representing a one-year period using Model I (a and b) and Model II (c and d).

m^3) was 0.1% lower than the value indicated by the empirical data. The models can also be compared based on the volume processed before the output is generated; these values correspond to the final volumes delivered to the mill. Models I and II predicted the volume delivered to the mill to be 3% and 2% higher, respectively, than the value reported by the company (824 569 m^3).

As noted in section 3.3.2, model I treats deliveries by different modes of transport separately, with concepts of probability for deliveries by each mode, whereas model II treats them all together and uses a single unified probability density function to determine when deliveries occur. Therefore, it is possible to compare the empirical data on deliveries by different modes to results generated using model I, but not to those generated using model II. Model I predicts that over the course of an average year, the yard will receive 34 deliveries by ship and 30 deliveries by train, whereas the empirical data show that the yard received 34 deliveries by ship and 24 deliveries by train. The model's predictions thus deviated from the empirical data by 6% for ships and 22% for trains.

The entities from the entity generator enter a waiting queue, where they remain until they are unloaded. The length of this queue depends strongly on the mode of transport by which the entities were delivered to the yard. In Model I, the arrival of one ship is

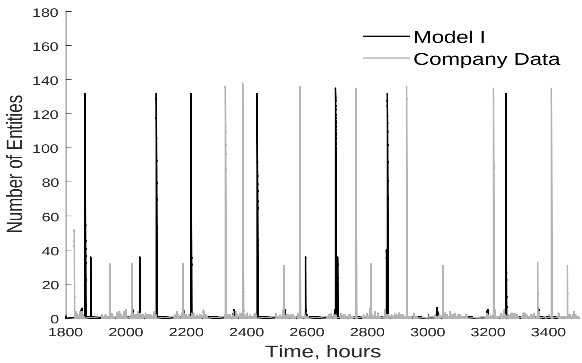


Figure 4.5: Number of entities waiting to be unloaded in Stage 1. The dark solid line shows data generated using model I, while the grey line shows empirical data supplied by the company.

represented by the simultaneous arrival of 132 trucks while the arrival of one train is represented by the simultaneous arrival of 36 trucks. Figure 4.5 shows how the length of the waiting queue varies over the course of a simulation (black line); the peaks correspond to the arrival of a ship or a train at the simulated yard. The corresponding empirical data are also plotted (in grey), showing that the simulation accurately reproduced behavior observed in the real world.

Model I predicts that the number of active servers depends on the queue size, increasing as the queue gets larger. Specifically, model I predicts that only one server will be active 71% of the time. However, when a train or a ship arrives, the waiting queue becomes very long, requiring all four servers to be active simultaneously. This occurred 26% of the time. It was less common for only two or three servers to be working simultaneously; this occurred 3% and 0.5% of the time, respectively. The empirical data indicated that at the real yard, one server was active alone 71% of the time, while two, three, and four servers were active simultaneously for 1.5%, 0.5%, and 27% of the time, respectively.

Finally, the predicted number of entities in storage was considered. Since each simulation exhibited somewhat different behavior, their results were analyzed at the level of individual runs. As shown in figure 4.6, the empirical data indicated that the maximum volume of material in storage was somewhat higher than was predicted by the model. Additionally, the empirical data revealed a number of transient spikes in the stored volume that were not captured in the simulation. Nevertheless, the model's prediction of

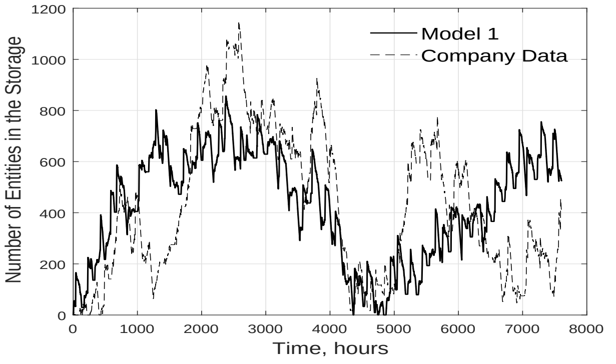


Figure 4.6: Total number of entities in storage over the course of one year based on a representative run using model I and the empirical data.

the volume in storage at the end of the year agreed quite well with the empirical result, presumably because the model's internal logic and mathematical approximations were derived from the empirical data.

4.4 Paper IV

4.4.1 Log yard inventory levels

The average volume of pulpwood arriving at the log yard did not differ significantly (0.51%) between any of the six simulated scenarios. The average volumes delivered to the pulp mill exhibited somewhat more pronounced (albeit still non-significant) differences (0.75%). The average total inventory levels at the log yard differed by no more than 5 248 m^3 (Table 4.1) between scenarios. Additionally, the incoming and delivered volumes in the modeled scenarios were very similar; the mean difference between the total incoming and delivered volume was only 1 967 m^3.

There were however significant differences ($P < 0.05$) between strategies 1, 2, and 3 with respect to the distribution of the total volume between storage areas A, B, C and D (Table 4.1). The year-average volumes stored at areas A and B under strategy 2 were 13% and 9% lower, respectively, than under strategy 1, while those for strategy 3 were 15% and 13% lower, respectively, than those for strategy 2. Conversely, the year-average volumes at areas C and D under strategy 2 were 28% and 13% higher, respectively, than under strategy 1, while those for strategy 3 were 21% and 8% higher, respectively, than

Table 4.1: *Pulpwood inventory levels at the four storage areas and the total inventory level for the log yard over the 52-week period under six scenarios, each of which was simulated 30 times. Each scenario is assigned a label of the form SxMy, where x takes values of 1 or 2 and denotes the inventory strategy used in the scenario and y takes values of 1, 2, or 3 and denotes the machine system used to transport logs between storage areas D and C in the log yard. The max and min values for each storage area in each scenario are the absolute maximum and minimum inventory levels observed at the indicated area in 30 simulations. The average max and min values (shown in parentheses) are the maximum and minimum inventory levels at the indicated storage area based on the averaged results of the 30 simulations. See also figures 4.7, 4.8 and 4.9.*

		Inventory Level, m^3									
		Storage A		Storage B		Storage C		Storage D		Total	
	Max (Avg Max)	36 176	(36 064)	18 155	(17 067)	5 203	(4 690)	71 111	(46 474)	127 606	(100 610)
S1 M1	Avg	35 624		16 237		1 317		42 220		95 422	
	Min (Avg Min)	31 181	(34 467)	11 898	(15 329)	0	(305)	9 405	(35 592)	61 257	(88 553)
	Max (Avg Max)	36 213	(36 062)	18 162	(17 006)	5 200	(4 690)	74 417	(43 429)	130 262	(98 794)
S1 M2	Avg	35 631		16 233		1 825		38 104		91 828	
	Min (Avg Min)	29 489	(34 527)	11 898	(15 515)	0	(578)	1 410	(33 575)	52 836	(85 749)
	Max (Avg Max)	36 198	(36 064)	18 168	(17 097)	5 203	(5 013)	88 131	(71 628)	125 973	(97 875)
S2 M1	Avg	31 007		14 597		1 776		46 166		93 569	
	Min (Avg Min)	3 480	(6 275)	0	(6 567)	0	(278)	6 275	(35 592)	58 163	(85 553)
	Max (Avg Max)	36 217	(36 068)	18 206	(17 060)	5 194	(4 912)	89 196	(70 178)	124 874	(98 351)
S2 M2	Avg	31 093		14 893		2 252		44 368		92 639	
	Min (Avg Min)	3 218	(6 379)	890	(8 424)	0	(756)	2 689	(35 421)	53 818	(87 161)
	Max (Avg Max)	36 177	(36 062)	18 170	(17 314)	5 191	(4 928)	98 950	(69 254)	127 686	(95 781)
S3 M1	Avg	25 982		12 367		2 209		49 594		90 174	
	Min (Avg Min)	2 598	(6 008)	0	(6 250)	0	(255)	1 260	(33 932)	40 832	(83 995)
	Max (Avg Max)	36 269	(36 062)	18 148	(17 362)	5 187	(5 032)	98 511	(67 599)	126 683	(98 816)
S3 M2	Avg	26 552		13 320		2 646		47 793		90 341	
	Min (Avg Min)	3 438	(6 156)	0	(8 078)	0	(731)	0	(34 678)	43 630	(84 851)

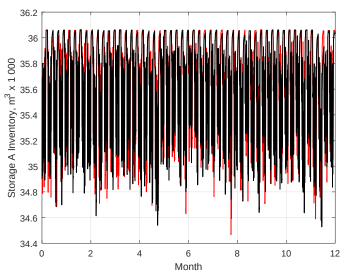
those for strategy 2.

4.4.2 Machine work at the log yard

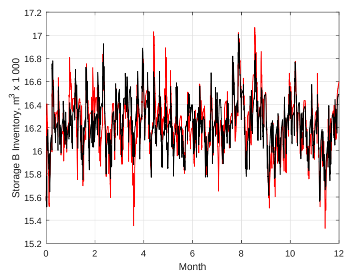
The machine system used to move logs from the buffer storage area D back to storage area C did not appreciably affect the inventory levels. However, there were differences in the machines' work patterns. On average, the total working time for machine system 2 was 189% higher than that of machine system 1. Additionally, the total average machine working time (for both machine systems) under inventory strategy 2 was 14% lower than that for strategy 1, while that for strategy 3 was 16% lower than that for strategy 2. Despite the large differences in total work time between machine systems 1 and 2, the volumes transported differed less sharply. On average, machine system 2 transported 16% more volume per year than machine system 1. In keeping with the observed trends in work time, the delivered volume under strategy 2 was 17% lower than under strategy 1, while that under strategy 3 was 20% lower than that under strategy 2.

4.4.3 Cycle times of logs in storage

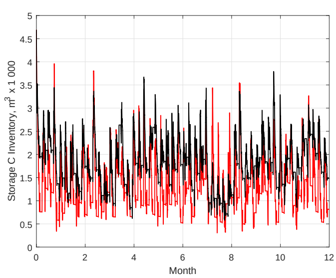
Figure 4.7 shows the changes in inventory levels over one year under strategy 1 using machine systems 1 and 2. The variation in the inventory levels at storage areas A and B is relatively small (ca. 6000 m^3 for area A and 6300 m^3 for area B), and both areas remain close to their maximum capacities at all times. There is much more variation in the inventory levels at storage areas C and D. Paper IV shows that storage area C can go from empty to full (its capacity is ca. 5000 m^3) in a matter of days under strategy 1. This mainly occurred when the yard received a high-volume delivery from a ship. Storage area D provided additional buffering capacity to accommodate changing volume flows; its inventory level varied by as much as 67 000 m^3 over 30 simulations.



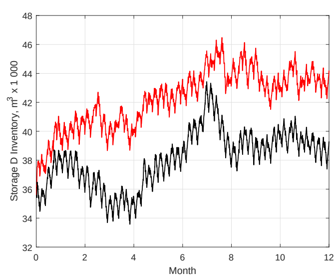
(a) Inventory level of storage A



(b) Inventory level of storage B



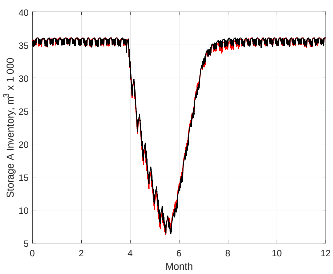
(c) Inventory level of storage C



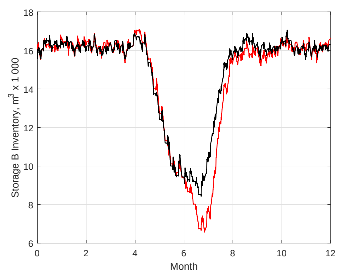
(d) Inventory level of storage D

Figure 4.7: Average inventory levels for Strategy 1 with machine systems 1 (red line) and 2 (black line).

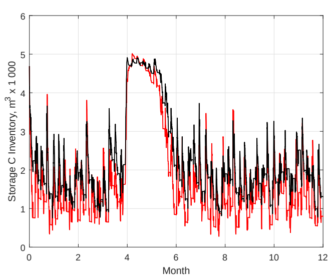
Under strategy 2, storage area A is emptied once per year, reducing the average inventory level in storage areas A and B while increasing that in areas C and D (Figure 4.8). Under Strategy 2, the timing of the moment at which the inventory level at area A reaches its minimum can vary considerably (by up to 63 days for machine system 1 and 47 days for machine system 2) depending on the inflow of material. As storage area A is emptied, machine work due to the transport of logs between areas D and C is halted for two weeks under scenario S2M1, and for four weeks under scenario S2M2. Paper IV discusses this behavior in more detail. However, once the inventory level in area A reaches its minimum value, the machine work and storage levels increase until they are close to their initial values.



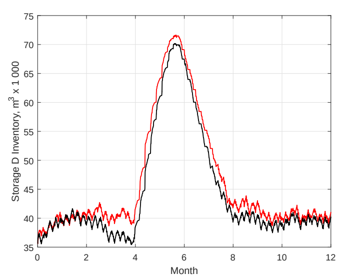
(a) Inventory level of storage A



(b) Inventory level of storage B

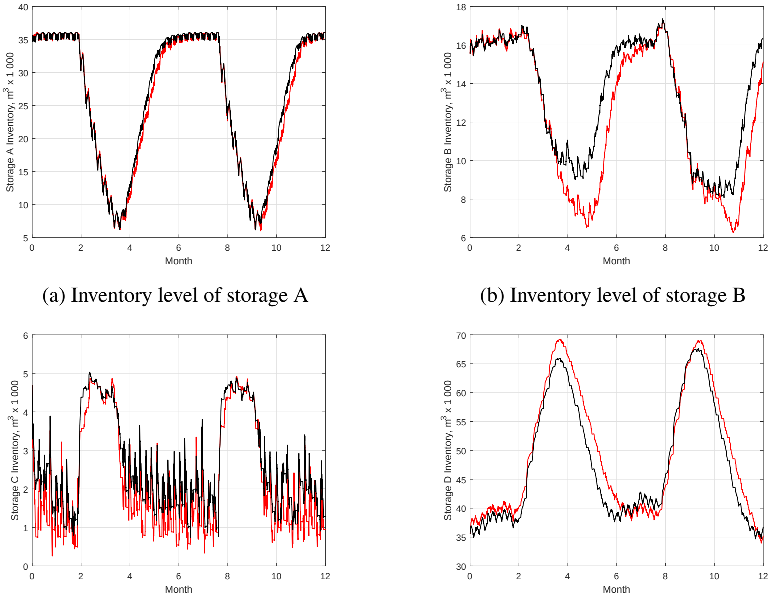


(c) Inventory level of storage C



(d) Inventory level of storage D

Figure 4.8: Average inventory levels for Strategy 2 with machine systems 1 (red line) and 2 (black line).



(a) Inventory level of storage A

(b) Inventory level of storage B

(c) Inventory level of storage C

(d) Inventory level of storage D

Figure 4.9: Average inventory levels for Strategy 3 with machine systems 1 (red line) and 2 (black line).

In Strategy 3, storage area A is emptied twice per year, reducing the log turnover time to ca. six months (Figure 4.9 (a)). In this case, the timing of the moment at which the inventory level at area A reaches its minimum varied by as much as 55 days on the first emptying and 31 days on the second emptying when using machine system 1; the corresponding values for machine system 2 were 31 and 21 days, respectively. Because storage area A is emptied twice a year, the average inventory levels at storage areas A, B are lower than under strategy 2, while that at areas C and D is higher. In addition, under Strategy 3, machine work due to the transport of logs between areas D and C is halted for 10 full weeks while storage A is being emptied when using machine system 1 and 3 full weeks when using machine system 2.

5 Discussion

5.1 Main results

The work presented in this thesis was motivated by the personal interest of the author and the objectives of Sweden's national forest IT and timber measurement company, "Biometria" relating to the state of biomass terminals in Sweden and the other Nordic countries. The objective of papers I and II was to provide an overview of Sweden's biomass terminal types, their properties and infrastructure, and future terminal development opportunities such as those offered by biomass screening. The problems observed at some log yards and terminals in Sweden motivated the work presented in paper III, which demonstrated the value of analyzing company data and using DEM to analyze the performance of existing log yards. The results presented in paper III were then used in paper IV to analyze specific areas of interest within a pulp mill's log yard in order to improve pulpwood turnaround times and optimize machine work capacity. The results obtained in these studies have been used to increase awareness of forest terminals and their operations within the forest industry, academia, and society in general.

5.2 Used research methods

Three different research methods were used during the work presented in this thesis. Paper I was relied on an interview method (Bradburn et al., 1979): questionnaires were sent to 18 forest companies regarding their use of forest biomass terminals in Sweden. The initial survey was industry oriented and conducted by "Biometria", but was subsequently expanded by the author and his colleagues. While the results obtained provided important insights into Sweden's biomass terminals, they had certain industry-related limitations. These limitations were in large part due to data confidentiality and the objective of preventing data being traced back to its company of origin. Because of this, it was impossible to link data on the terminals to geographical data in order to perform more detailed analyses. There was also considerable variation in the terminal data, which may have been partly due to human error or variation in approaches to completing the survey forms. Combining the surveys with qualitative research methods as described by Patton (2005) and Charmaz (2006) would have given a much deeper understanding of terminal usage in supply and logistics chains and trends in their development. However, this would also have been significantly more labor-intensive due to the need to transcribe and analyze additional interview material. This drawback could be alleviated by focusing only on a small number of particularly relevant companies, which could be identified after preliminary data analysis by considering criteria such as the numbers of terminals owned by the companies, the amount of biomass they handle, or the nature of their ownership.

Paper II evaluated chipping operations and fuel chip properties at a terminal. A time study was conducted to evaluate a chipper's performance, and fuel chip quality was evaluated in terms of MC, AC and PSD by laboratory testing based on Swedish standards. The results obtained provided important information on chipping performance and the potential benefits of implementing wood chip screening at terminals. According to Purfürst and Lindroos (2011), it is important to account for variation in operator skill when evaluating machine performance. In our case, all machine operations were performed by the same operator and it was only possible to repeat each treatment a limited number of times. Both of these factors limited the scope for statistical analysis and may have reduced the generalizability of the results. However, chipping operations are much simpler (and thus less sensitive to operator skill) than operations such as harvesting. The average chipping time for the five assortments included in the study amounted to 93% of the total work time, indicating that the operator had a good level of skill and worked efficiently. The chipping time was also directly sensitive to the way in which the biomass piles were formed, which was outside the authors' control. To ensure a valid comparison of fuel chip properties, the chipper's knives were maintained in a sharp state and care was taken to ensure that their length remained constant independently of the sieve size. While these conditions gave satisfactory results given the study's objectives and setting, it would be desirable to test the effect of varying the knife length because neither the assortment being processed nor the sieve size were found to significantly affect chipper productivity. However, Nati et al. (2010) and Eliasson and Johannesson (2014) found that knife length can strongly affect chipper productivity and the PSD of fuel chips.

Several mathematical methods can be used to analyze different aspects of log-yard performance. DEM was used for this purpose in Papers III and IV because it is a useful method for modeling industrial processes that operate as a sequence of events (Cohen et al., 1985) such as those performed at log-yards. From the perspective of system analysis, it would be desirable to develop a mathematical model capable of accounting for deliveries by multiple modes of transport and methods of wood handling at the receiving log yard of the pulp mill. Such a model could help reveal the parameters that affect the log yard's operational performance, and thereby facilitate performance optimization. However, many if-else logical conditional statements were needed to model the processes used at the terminal and log yard studied in Papers III and IV. This imposes a significant computational burden, increasing simulation run times and complicating the modeling process, making further optimization problematic. For example, one simulation run using Model 1 from Paper III took ca. 10:46 min whereas runs using Model 2 (which lacks if-else statements) could be executed in ca. 17 sec. Several ways of accelerating and simplifying model development (and reducing the amount of coding it requires) have been explored (Schroer and Tseng, 1988). One way to reduce the impact of logical conditional statements on model performance is to use the Stateflow tool in Mathworks Simulink (Sutarto et al., 2006; Chen et al., 2016), which is suitable for logical and plant modeling. An another way of reducing reliance on if-else statements in a model is to assign more complex "smart" attributes to entities in the entity generator. Decision making in the DEM model is done by observing the signal values for blocks of interest and processing them to allow further decisions to be made as the simulation progresses. The use of attributes significantly reduces the amount of signal processing and the computing power needed during a simulation run, enabling the use of larger time steps in the simulation without sacrificing the resolution of the results. This is illustrated by the example of model II from Paper III, which has the minimum possible number of logical conditional statements because it uses a single weighted intergeneration time PDF (Saghir et al., 2017) to predict deliveries by all modes of transport. Unfortunately, one of the biggest factors limiting the scope for model development is the lack of long-term real-world data that could be used to construct suitable PDFs and logical conditional statements suitable for use in models. Today it is very difficult to acquire such data from actors within the forest industry. This is largely due to the involvement of multiple stakeholders (including factory managers, log-yard managers, and contractors) in the running of sites. This situation is unlikely to change until log yard managers recognize the benefits that could be gained by gathering this data. However, even if such data were routinely gathered, it may not be readily available to academics because the objectives of academia (to spread knowledge) are not always aligned with those of industry (to gain a competitive advantage in the marketplace).

Section 5.5 discusses the data used in Papers III and IV in more detail, as well as potential ways of gathering and using additional relevant data to support further development of DEM-based log yard and terminal models.

5.3 Terminal characteristics

As noted by Lönner et al. (1983) and Hillring (1995), there was considerable interest in the forest biomass terminals for energy production during the 70's and 80's because of the oil crisis of 1973. This interest subsequently diminished until demand for forest fuels began rising in the early 2000s, which led to the passage of a new Timber Measurement Act in 2015. This act introduced new regulations governing the characterization of forest fuels (Swedish Forest Agency, 2014; Björklund, 2014), and made it necessary for the operators of forest biomass terminals to find ways of complying with the new laws. In addition to the legislative changes, several facilities that consume forest biomass were extensively upgraded and a number of new biorefinery, pulp mill, and CHP projects came online. These new facilities greatly increased the demand for new and traditional forest biomass assortments, creating a need to increase the capacity of existing supply chains and establish integrated terminal networks with wood and log yards (SCA, 2019; Södra, 2019; Stockholm Exergi, 2019).

Because of the need to better understand the nation's terminal network given the changing business environment in Swedish forestry, Paper I focused on characterizing the different types of forest biomass terminal operating in the country today. Most of the terminals examined in this paper aligned well with one of the three terminal categories (satellite, feed-in, and transshipment terminals) proposed by Virkkunen et al. (2015). The properties of terminals smaller than 5 ha (transshipment terminals) differed markedly from those of larger terminals (feed-in and satellite terminals). Bigger terminals are generally older, with better stationary measuring facilities. These terminals worked exclusively with a third-party organization, Biometria (formerly VMF), for all measurements. With regards to inventory keeping, 89% of the larger terminals had established standardized stock measurement practices whereas only 41% of smaller terminals performed standardized measurements. However, when considering Sweden's biomass terminal network as a whole, it is important to note that smaller (<5 ha) terminals play an important role in supplying raw materials to the bioenergy sector because more than half of the country's total biomass output flows through them (Figure 4.1). As also noted by Fridh (2017), this is indicative of poor supply chain management in relation to the terminal network because standardized stock measurements and inventories are rare at smaller terminals. This is in stark contrast with the situation in Finland, where the terminal network is similarly dominated by smaller facilities but the largest 30% of these terminals process 70% of the country's annual biomass output (Virkkunen and Raitila, 2016; Raitila and Virkkunen, 2016; Sikanen et al., 2016). According to Lee and Billington (1992), keeping track of stock inventory and its quality parameters is essential in an efficient supply chain. Unfortunately, the results presented in Paper I indicate that smaller terminals in Sweden struggle to do this. However, since some of these smaller and more intensively used transshipment terminals are located in close proximity to industrial sites, they could be integrated more extensively with log yards and industrial terminals, which generally have excellent supporting infrastructure. This could be particularly beneficial for bigger pulp mills and biorefining facilities because they usually have a surrounding network of transshipment and feed-in terminals to ensure continuity of raw material supply and adequate buffer storage.

Feed-in and satellite terminals with areas of 5-10 ha are also of particular interest in terms of their influence over long distance and high quality deliveries to industry. In Sweden, larger terminals handle several biomass assortments and have 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, which could partially offset their extra operating costs by reducing overall administrative costs and supply risks (Väätäinen et al., 2017; Palander and Voutilainen, 2013; Virkkunen et al., 2016). Moreover, in contrast to terminals in Finland, larger terminals are usually located in close proximity to railroads, offering the potential for easy long-range biomass transportation (Sikanen et al., 2016). The routine use of rail transport considerably expands the procurement areas of large pulp mills, biorefineries, and CHPs in densely populated areas and reduces the traffic intensity in their vicinity (Karttunen et al., 2013; Wolfsmayr and Rauch, 2014). This is particularly important for facilities such as Värtaverket CHP (whose demand for wood fuel amounts to ca. 3M m^3/year) in Stockholm and the SCA Östrand pulp mill and biorefinery (expected pulpwood demand ca. 4M m^3/year), which are located close to the cities and have considerably increased traffic flows in their surroundings since opening (SCA, 2019; Stockholm Exergi, 2019).

A terminal's strategic, tactical and operation goals depend on its ownership. In Finland, most large terminals are owned by a large CHP (Sikanen et al., 2016). However, in Sweden the situation is mixed. Here, terminals are commonly owned by forest or energy companies, or by local municipalities in cooperation with the private sector. Company-owned terminals are often considered to be "closed" terminals, meaning that the terminal has only one owner and is used purely to serve the company's interest in ensuring a secure raw material supply and a competitive advantage. Most industry terminals and log yards can also be regarded as "closed" facilities even though they may be interconnected with other types of terminals. On the other hand, "open" terminals (typically established using EU funds and the support of municipal authorities) are required by EU regulations to allow any company that so wishes to sign a contract granting access to the terminal's facilities. From the perspective of a private sector entity, operating an open terminal helps expand one's customer base as well as the range and volume of assortments to handle, which reduces terminal operating costs (Matisons, 2018; Virkkunen et al., 2016; Raitila and Korpinen, 2016; Impola and Tiihonen, 2011). It is therefore becoming increasingly common for round wood terminals to enter the wood chip and recycled wood markets and vice-versa, becoming more like bio-hubs and biomass trading centers (BioRes, 2019; Bio-Hub, 2019). Many of the terminal operators surveyed in Paper I also handled pulpwood. However, pulpwood was not considered further in the study due to its focus on energy assortments. Ultimately, terminals of all classes have one fundamental goal: to maintain or increase the value of the products they handle so as to maximize their profitability.

5.4 Biomass quality at terminals

5.4.1 Upgrading terminals

According to Virkkunen et al. (2015) upgrading terminals are special sub-types of satellite and feed-in terminals because of their potential to add value to the delivered biomass by drying, screening, mixing, and densifying it. Fuel upgrading terminals could also be considered a "new" terminal type, because fuel upgrading is rarely performed at terminals for the time being (Virkkunen et al., 2015). However, we would not classify them as a separate type of terminal; instead, we see them as terminals that have integrated upgrading processes into their established workflows. This is because even the natural drying that occurs during biomass storage at a terminal could be classified as a fuel upgrading process in that it increases the net calorific value of the biomass (Figure 5.1)

The upgrading terminal concept can also be applied to pulpwood handling to some extent; the main difference between an upgrading energy biomass terminal and an upgrading pulpwood terminal is that they seek to improve different aspects of material quality. A key quality parameter for pulpwood is log freshness (Persson, 2001). Well organized satellite and feed-in terminals can keep pulpwood cycle times as short as possible, minimizing

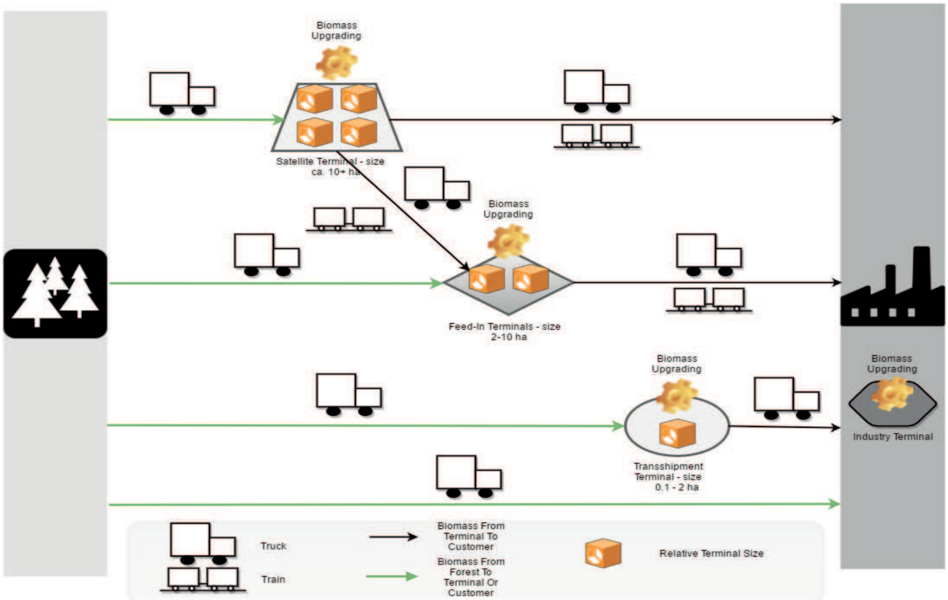


Figure 5.1: Supply of forest raw materials through the terminal network.

quality degradation. Such terminals can also keep good records of material quality and if necessary, use a climate-adapted sprinkler system to delay the drying of stored logs (Jansson, 1999).

5.4.2 Pulpwood storage

Pulp mills usually handle only one round wood assortment - pulpwood. The main drivers of pulpwood log handling are log freshness and the physical location of the logs in the yard (Liukkoxs and Elowsson, 1999). To keep logs as fresh as possible, the log cycle time in the terminal and log-yard should be short. Log freshness was one of the main factors of interest for the pulp mill considered in Paper IV, because logs stored at the large end-user's log-yard were sometimes locked-in at the storage site for a year or more; in some cases, this degraded their quality to the extent that they could only be used as energy wood. Paper IV showed that running the log-yard in the traditional way meant that only one small storage area maintained a short cycle time and avoided lock-in. Today, the strategy for managing the degradation of stored logs at the studied log yard is to blend small amounts of older logs with fresh ones when the opportunity arises. Paper IV showed that the log yard could avoid the lock-in problem by emptying the main log yard storage area once or twice per year. To do this, the yard would have to allocate additional buffer storage space, increasing buffer storage capacity by 22% (for once-yearly emptying) or 36% (for twice-yearly emptying). A deeper understanding of risk management preferences and key performance parameters (KPI) for log-yard managers(March and Shapira, 1987; Chan, 2003) could enable further optimization of log relocation by either reducing total inventory levels at log yards or better integration with feed-in terminal networks.

To conduct such large-scale log relocations, a yard requires adequate machine capacity. As shown in figures 4.7, 4.8, 4.9, both existing and alternative machine systems can support the necessary volume flow between the main log yard and the buffer storage area. However, machine system II, consisting of a material handler with a trailer, transports 16% more volume from the buffer area to the log yard than the currently used system (which is operated by a contractor). Additionally, the capacity utilization of machine system II is 19% higher, on average, than that of machine system I, indicating much higher machine availability in the studied working environment over the course of a year. In paper IV, it was assumed that both machine systems would only be used to transport logs from the buffer storage area to the main log yard. In reality, due to its multi-purpose nature, the material handler could also be used in other areas of the log yard, further increasing its utilization rate.

As mentioned before, machine system I consists of three working machines (a material handler and two trucks with trailers) whereas machine system II consists of a single material handler with a trailer. Therefore, if all three machines of system I are used simultaneously, its hourly operating costs will be three times those of machine system II. Additionally, machine system II is owned by the log yard, and the profit margin due to its use could be 10% lower than that for machine system I. Under these assumptions, although machine system II has more working hours, it is still on average 13% more cost-effective for the log yard than machine system I.

5.4.3 Biomass quality during storage

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 do not just store material; they also offer an expanded range of options for ensuring a secure raw material supply to end-users (Kanzian et al., 2009). In addition, the presence of well-organized and integrated terminals in the supply chain makes it possible to offer customers a wide range of assortments, allowing the supply chain to adapt rapidly to changes in demand and ensure that appropriate assortments are always available (Enström et al., 2013). In total, 14 different biomass assortments (except pulpwood) were present (in various combinations) at the terminals studied in Paper I.

Today, forest biomass is stored in two main forms: (1) un–comminuted biomass such as energy wood (roundwood of low quality), loose logging residues, stumps, etc., and (2) comminuted biomass (including bark and sawdust). Each form has 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 5.1).

Table 5.1: 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

The decision to mainly store un–comminuted material is easy to explain: it minimizes biomass losses and the temperature build up during storage while simultaneously reducing the MC of the biomass and improving its fuel quality (Jirjis and Lehtikangas, 1993; Filbakk et al., 2011). By weight, the three main assortments stored at these terminals were energy wood, logging residue chips and loose logging residues (LR). The quantity of stored energy wood was much greater than that of all other assortments. Energy wood is particularly suitable for prolonged storage because its MC decreases during natural drying and it does not undergo significant biomass loss during storage. Similar favorable effects occur in stored LR, although Pettersson and Nordfjell (2007) observed that LR assortments can 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 polluting 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. Additionally, Virkkunen et al. (2015) and Impola and Tiihonen (2011) showed that energy wood has lesser space requirements than other assortments when stored at terminals. However, the energy industry demands comminuted material (as do many bio-refineries), so comminution must be performed at some point to supply the customer with the material they desire. As Fernandez Lacruz (2019) showed, while deliveries from terminals may be costlier than direct deliveries from the forest, risk management considerations may compel end-users to pay the terminals' premium.

Paper I showed that comminution of various raw materials was performed at around 90% of the terminals included in the study, including all 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 is already an important aspect of terminal operations. Kärhä (2011) and Venäläinen et al. (2016) 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.

However, long-term wood chip storage is impractical because wood chips are relatively difficult to handle. In the 1950s, when the first chip storage facilities were established, devastating biomass losses occurred. 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. This 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 and bioenergy industries because a certain level of buffer storage is required. Therefore 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. Paper I shows that because of the problems associated with wood chip storage, chipped material represents only 18-29% of the total biomass stored at terminals (Table 5.1).

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 be managed to limit biomass losses and potentially even increase the chips' fuel quality. One is to cover chip piles by a special fleece-like material to improve their drying and protect them from precipitation (Bergström and Matisons, 2014; Iwan et al., 2017; Hofmann et al., 2018). On other hand, 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 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; Virkkunen et al., 2015).

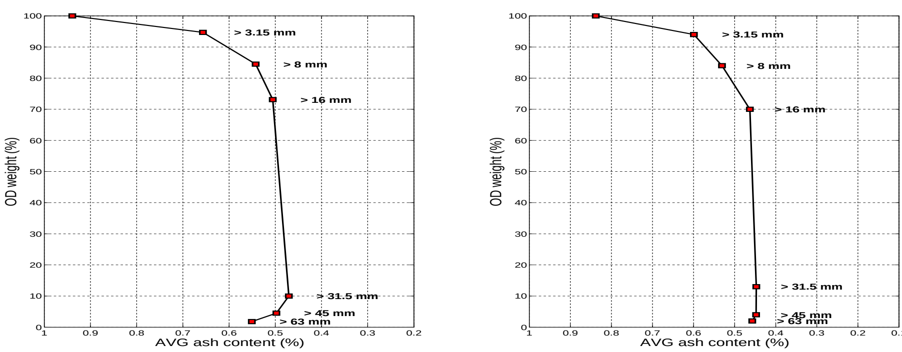
In the 70s and 80s, the scope for suppressing degradation of stored chips by chemical treatment was investigated, but the costs proved to be economically prohibitive (Springer, 1979). However, today chemical treatment with calcium (Ca) could potentially increase chips' durability during storage and also 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). Calcium 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.

5.4.4 Screening biomass to improve 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 and oversized 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 (Virkkunen et al., 2015).

Paper I shows that terminals of all sizes handle several assortments: the number of different assortments handled within different terminal size classes ranged from 10 to 14. The large number of unique assortments (e.g. shavings, bark, and sawmill chips) handled at certain terminals, and the small delivery volumes of these assortments, may indicate that these terminals were located in close proximity to forest industry sites that produce or consume such assortments. Other assortments stored and processed at terminals in general include comminuted and un–comminuted logging residues, tree parts and their chips, as well as energy wood. This indicates that some existing terminals are already 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 (Joelsson and Tuuttila, 2012; SCA, 2019).

The wood chip analyses presented in Paper II showed that the ash content (AC) of the chipped material generally decreased with increasing particle size, at least up to a certain point. The initial AC of the bundles and energy wood was typically below 1% while that of tree parts was 1.7%. The AC and particle size distributions observed in this work are consistent with those reported by Fernandez-Lacruz and Bergström (2017) and Pettersson and Nordfjell (2007). Further screening by removing particles of <8 mm from the stored and fresh logging residues reduced their average AC values from 2.98-2.88% to 1.56-1.79%. This demonstrated that simply separating out fine particles (i.e. particles of $<$ 3.15 mm) generated during the chipping process could potentially reduce the average AC of the final fuel product by up to 28% (Figure 5.2, 5.3, 5.4).

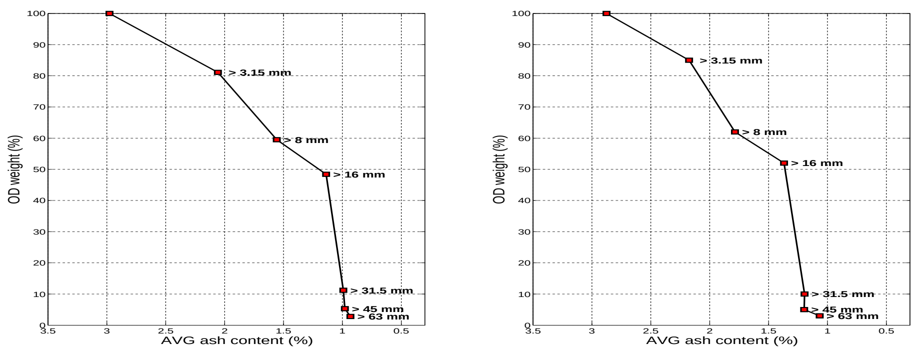


(a) Bundles

(b) Energy wood

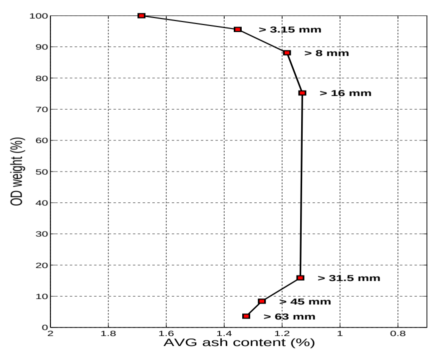
Figure 5.2: Effect of biomass screening for different assortments in terms of the remaining OD weight (%) and average ash content (%) of the material left after separating out fractions smaller than 3.15 mm, 8 mm, 16 mm, 31.5 mm, 45 mm and 63 mm.

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



(a) Stored logging residues (b) Fresh logging residues

Figure 5.3: 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

Figure 5.4: 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.

quality for some energy assortments. By removing particles of <16 mm, the average AC of the B and EW assortments could be reduced to 0.54% and 0.53%, respectively, yielding material suitable for producing 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 ash and derived from more nutrient- and extractive-rich fractions, they may be useful for soil improvement or 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 (Fridh, 2017). Compared to the pulp and paper industries, which have strict quality standards for chip size, shape, and bulk density (SCAN-test, 2001; SCAN-test Standard, 1992), CHPs have rather more relaxed requirements and primarily assess fuels on the basis of their MC and AC values (Fridh, 2017). However, there is one assortment (coniferous tree parts) that could, if handled correctly, have the potential to meet pulp mills' quality requirements relating to bark content, freshness, and particle size distribution while still delivering extractive-rich biomass for biorefineries. According to Bergström and Matisons (2014), the bark content of spruce tree parts freshly debarked with an old mobile chain flail debarker can be as high as 2.8%. Additional screening of chips formed from such logs could further reduce their bark content to 1.5%, making them acceptable to some pulp mills (Färlin, 2008). Debarking and bark separation of fresh birch energy logs could also add extra value to this assortment at a competitive cost because the bark can be a source of valuable extractives for the veneer, beauty, and medicine industries (Pāže et al., 2013). Meanwhile, fresh bark and twig residues can also be processed and delivered to biorefineries. Finally, it should be noted that separating fines could reduce the cost of fuel transportation if it were done at the delivering terminal (Greene et al., 2014).

(a) Sawmill bark screening for energy with a mobile star screen at a terminal in northern Sweden (Photo: Kalvis Kons)

(b) Bark screening with a mobile screen at a terminal in northern Sweden(©TM Henningssons Åkeri AB).

Figure 5.5: Bark screening at terminals in northern Sweden.

As mentioned in section 1.3.1, screening and new assortment marketing was a common practice at terminals in the past (Figure 1.2) but 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 5.5).

There are also some equipment manufacturers who still produce screening equipment (e.g. Doppstadt GmbH and Backers Maschinenbau GmbH), although these machines are most commonly used to screen soil, waste, and other materials rather than wood chips. It seems unlikely that 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. One assortment that can be profitably screened today is bark. Bark screening is mainly done to remove oversized particles, stones, and mineral contaminants before delivery to energy conversion plans (De La Fuente and Kons, 2017).

5.5 Further development of existing terminals and log-yards

5.5.1 The importance of data and system analyses

Forest terminals and log-yards are in many ways similar to warehouses and mining sites in that their working areas are well defined, allowing transportation equipment to move along clearly delineated routes and execute repetitive tasks. Within the forest supply chain, terminals and log-yards are perhaps the components that are most amenable to automation and optimization (Basile et al., 2012). However, their automation will require a detailed understanding of their operations that can be encapsulated in robust mathematical models (Colla and Nastasi, 2010). Such models should be built with a clearly articulated purpose, using methods that are suitable given the available data and existing knowledge about the system in question.

The studies presented in papers III and IV were conducted in co-operation with an existing pulp mill. Their purpose was to find ways of modeling the mill's log yard in order to better understand the system's parameters and logic, and to identify the data and analytical steps needed to enable meaningful modeling. Modeling an existing log yard is a challenging task because the model must realistically replicate real-life decision making and empirical performance data. The creation of realistic DEM models that can support optimization efforts requires vast amounts of data gathered over long periods of time. Such datasets are often unavailable because few forest companies implement the necessary data collection procedures. Forest industry IT systems as Biometria's VIOL and products using machine GPS tracking and log allocation can help overcome this lack of data (Biometria, 2019). Papers III and IV describe the construction of synchronized and weighted PDFs for the time between deliveries and the log volume delivered to the yard based on a year's worth of data supplied by the collaborating company. Figure 5.6 presents a histogram based on the weighted volume PDF, showing that the amount of data supplied by the company made it possible to capture the yearly variation in the volume delivered to the log yard and in deliveries by different modes of transport over the course of a year.

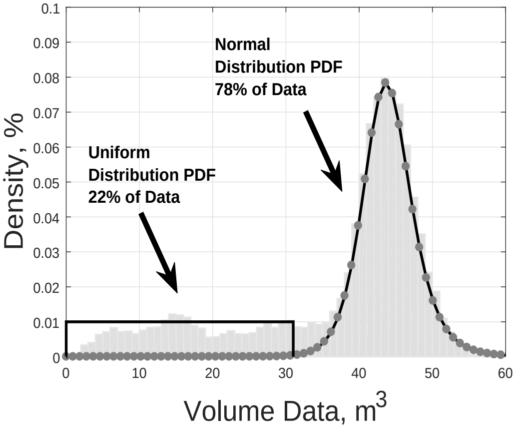


Figure 5.6: Histogram of volume delivered to the log yard per entity, with two regions fitted to uniform and normal PDFs.

Results obtained using model I from paper III and by considering the company's data revealed inefficiencies in the unloading of deliveries made by different modes of transport (Table 5.2). Logs delivered by truck could only be unloaded by a single log-stacker; consequently, only one stacker was used for 71% of loads. However, when the yard received a delivery by train or ship, it had to use all four of its log-stackers simultaneously. Thus, 26% (27%) of the delivered loads were unloaded using four stackers. It is unlikely that log yard could shift all incoming volume to trucks and therefore improve machine utilization rates. Alternative could be to separate train and ship unloading as an independent streamlined operation to avoid workload peaks and increase the overall streamlining of the yard's operations.

The drawback of relying on data for a single year is that it is impossible to say whether similar behavior would be observed over a longer period. For example, a data set covering six years would give much more insight into year-to-year variation in the process. Un-

Table 5.2: Comparison between the predictions of model I and company data on the number of log-stackers needed to unload truck loads arriving at the log yard over one year (Paper III)).

	Unloaded Truck Loads per Number of Working Log-Stacker			
	1 Log-Stacker	2 Log-Stackers	3 Log-Stackers	4 Log-Stackers
Model I	71%	3%	1%	26%
Company Data	71%	1%	0%	27%

fortunately, no such data were available. Our models accurately reproduced the outcomes observed over the year for which data were provided; it remains to be seen whether they can describe the long-term performance of the company's processes.

Like Robichaud et al. (2014) and Väätäinen (2018), we used short term time studies and interviews with log yard managers to model the decision making processes involved in the log yard's operations so they could be analyzed in conjunction with performance data and used for fitting purposes. The problem with relying on short term time studies and decision making data provided by log yard managers is that they may not accurately reflect the yard's operations in the long term; instead, the managers' responses are more likely to reflect the operational environment the managers wish to see, which often deviates from reality. Gaussian (normal), Weibull, and triangular PDFs rarely accurately reproduce real world processes and are therefore imperfect tools for simulating log yard activities. Additionally, the lack of long term data made it difficult to build a reference model and compare it to alternatives; consequently, the model development and validation processes necessarily involved a degree of guesswork relating to the actions of machine operators and logistics managers in cases where data-based systems analysis was not possible. Despite this, the model was successfully validated; thus, if there is no major variation in the company's operations that was not captured by the available data, our models can provide reliable estimates of the yard's behavior over the course of a year (Banks et al., 2005; Robinson, 2004). However, the number of conditional if-else statements used in the models and the limited amount of available data will make it difficult to optimize log yard operations using model I as described in papers III and IV.

The use of logical conditional statements in models creates multiple bifurcations in simulations, making mathematical optimization difficult or impossible. While there is not much one can do about this without implementing efficient procedures for long-term collection of data on machine work (and thus decision making), the need for some logical conditional statements can be eliminated by developing analytical mathematical expressions such as those used in the simpler model (model II) described in paper III. The strength of Model II is that its simplicity makes it possible to run simulations representing linear sequences of events with very few decision-making stages. Its simplicity also means that relatively little programming is required to adjust it based on new data. Because of these attributes, model II is particularly useful in cases where certain details are not needed - for example, when seeking to predict whether the log yard will be able to cope with a given increase in shipment volume without regard to the type of assortments to be delivered or the mode of transport by which they will arrive.

5.5.2 Inventory tracking

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 3.1.1.2, different assortments are measured in different units because the various energy assortments have very different physical and chemical characteristics. This makes it difficult 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 Biomateria's VIOL database system. This ID number contains information on the log's origin, time of harvesting, and so on. This information is widely available in the pulp, paper and saw mill industries. Unfortunately, however, few companies routinely use it to improve their operations. 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 also being adopted by pulp mills (Figure 5.7). The GPS Timber Pulp© system created by Sokigo AB and Datapolarna 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 on its performance at a Swedish saw mill seemingly confirmed that it added value to the log handling process (Lindgren, 2009).

(a) (b)

Figure 5.7: (a) A log yard as visualized on a logstacker operator's display unit (b) Use of GPS Timber at a saw mill. ©GPS Timber.

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 allow this biomass to be tracked at every stage in the terminal's operations. Unfortunately, the adoption of such IT systems at pulp mills is much lower than at saw mills, and no such systems are currently available for energy assortments.

The most important characteristics of energy assortments are their mass and MC, which determine their energy content (Jirjis, 1995; Björklund, 2014). Weight can be measured using either stationary scales or scales built into 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 companies have attempted to develop quicker ways of determining MC, and it is only a matter of time until their improved techniques become widely adopted at industrial facilities (Jensen et al., 2006; Fernandez-Lacruz and Bergström, 2014; Fridh et al., 2014; Fridh, 2017). 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 by allowing contractors to plan their work more effectively and logistics managers 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 measurement is 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 utilizing forestry data bases like VIOL would obviate these problems and also facilitate research and development (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 collect information from multiple terminals.

5.5.3 Considerations when establishing new terminal

Each terminal is unique and no one solution fits all cases when considering terminal development. However, there are several issues to consider if seeking to make future terminals as economical as possible. In particular, as Virkkunen et al. (2015) has shown, economies of scale are important when considering terminal profitability. The issues with the greatest impact on the economic performance of new log yards and satellite and feed-in terminals are summarized below.

- The life cycle of a terminal is quite long - it can be almost 50 years (BioHub, 2019). Therefore, it is important to recall that it is usually easier to build things correctly from the beginning than to fix them after problems emerge.
- The ground surface at a terminal strongly affects the efficiency of many terminal operations.
  - Asphalt surfaces are more expensive than hard-packed gravel, but can make terminal management easier in the long run and can also help prevent mineral contamination of biomass for energy and biorefining purposes (BioHub, 2019).
- Running a terminal involves many minor costs that can add up at the end of the year (BioHub, 2019). Notable expenses that are commonly overlooked include:
  - Snow ploughing and de-icing.

  - Anti-slip materials for trucks in winter time.
  - Cleaning bark and other biomass contaminants that have become mixed with snow and require special treatment.
  - Anti-dusting gravel surfaces by spraying water, lignin, or a salt solution, and planing the surface to keep it smooth.

- The type of assortment and volumes handled will determine the type of machines that are needed. Many terminals have both bulk and round wood assortments, necessitating the use of at least two types of machines (BioHub, 2019). It is important to match machine productivity as closely as possible with the biomass turnover at the terminal. It should be noted that some machines can also be used for terminal maintenance work, increasing their overall capacity utilization.

  - Streamlining terminal process will increase terminal efficiency. Matching machine productivity with amount of volume to be handled can be difficult if the terminal is served by multiple modes of transportation, such as trucks and trains or even ships. In such case terminal developers should consider deeper analyses to compare the relative merits of owning and contracting additional machine capacity depending on the number of trains and ships to be served. If the number of trains and/or ships is high, their deliveries could be handled using separate production lines with specifically allocated machines.

- The terminal's layout strongly affects assortment cycle times. It is worth analyzing various alternative layouts and packaging systems because even small improvements can have significant benefits (Hopper and Turton, 1999).

- Big terminals may have a high intensity of incoming traffic but it will not be evenly distributed over the course of the day or a season. When determining the capacity of a terminal's measuring and receiving facilities, this must be taken into account by using reliable methods to estimate the inter-arrival times of transport units and the time it will take to serve them (Väätäinen et al., 2005; Aalto et al., 2018).

- As noted by Sikanen et al. (2016), information exchange between terminals and other actors in the supply chain is important and can help increase the efficiency of operations both within terminals and throughout the supply chain by improving the coordination of work. This could also be a cheap solution to queuing problems at the measuring stations of the terminals because it could prevent over-investment in infrastructure.

6 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 over half of its total terminal biomass turnover. About 76% of the total biomass that passes through these smaller 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. Consequently, there is a need for further development and wider adoption of accurate mobile measurement systems.

- Improving the measurement facilities and stock inventory practices at terminals of >5 ha could be very beneficial for large CHP plants and pulp mills because it could increase the security of their raw material supplies and reduce the time spent on measuring biomass at facility gates, where traffic intensity can be very high.

- In total, 14 different assortments (excluding pulpwood) are handled at Swedish energy biomass terminals. This high number of different assortments increases the complexity of terminal management and operations. It also indicates that terminals are already handling many assortments that could be suitable feedstocks for refineries producing biochemicals and biofuels, and that some terminals could potentially be transformed into multi-assortment biomass hubs and trading centers selling products with more added value.

- Most (around 75%) of the biomass stored at 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. This creates opportunities for terminals to implement efficient comminuting and upgrading systems to increase product value and transport efficiency for further biomass deliveries.

- 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. This could enable the production of better-defined assortments for different end customers and has the potential to increase the total value of the biomass processed at the terminal. However, more commercial-scale studies on biomass screening are needed to evaluate the profitability of such an approach.

- Large-scale data collection, analysis, and processing are crucial for modeling existing terminals and log yards to help improve stakeholders' decision-making processes. Such large-scale data collection will make it possible to significantly expand our understanding of existing and future forest biomass and log handling terminal activities by means of modeling and simulation, and will also support future terminal automation.

- Improving the planning of log-yard logistics may enable the streamlining of terminal processes to increase terminals' operational efficiency and reduce the cycle times of logs in storage, thereby reducing pulpwood quality losses. Reducing logs' cycle times could increase pulping efficiency and simplify the planning work of terminal managers and operators when dealing with old logs in storage.

- Traditional special-purpose machines contracted by log-yards could be replaced with multi-purpose machines that may offer lower productivity in specific tasks but are more compatible with log-yards' operations, increasing the flexibility available to terminal managers when planning terminal operations.

Overall, the results presented here demonstrate that there is considerable variation in the properties of Sweden's biomass terminals and their management routines. Consequently, the existing terminal infrastructure should be reasonably well placed to serve the growing bio-economy and deliver diverse assortments to bio-refineries, pulp mills, and energy plants. The fuel quality of all chipped assortments, and logging residues in particular, could be significantly increased by screening out 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.

With respect to the forest supply chain as a whole, the results presented here suggest that mathematical modeling approaches could be used to analyze and improve key performance parameters of larger and more complex satellite, feed-in, and receiving terminals that handle multiple assortments and modes of transportation.

7 Future research

The introduction of integrated IT systems and comprehensive terminal and log-yard raw material tracking systems that utilize both GPS and new MC measurement system could improve the 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 representative samples 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 wood chip pile or loading equipment, which presents a safety hazard and makes it difficult to obtain samples from the middle of the pile. It would therefore be useful to develop new loading machines that can perform automatic sampling while loading.

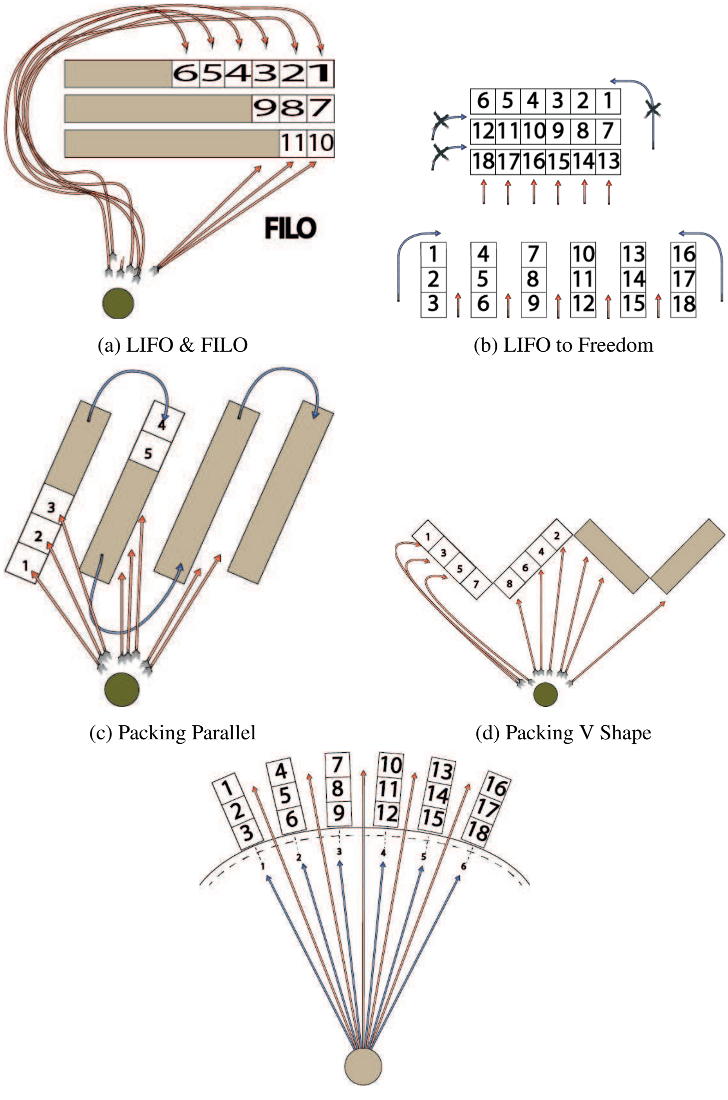
The treatment of wood chips with chemical additives in combination with the introduction of fire detection systems at terminals could significantly improve the storage of chipped biomass while reducing its risk of spontaneous ignition. Such practices could be particularly useful at smaller terminals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

It would also be useful to gather additional real-world data on log-yard operations and to update existing log-yard models using this data. In particular, detailed machine operational data and data on the daily demand of pulp mills and their wood chip storage dynamics would enable comprehensive model tuning to better predict real-world outcomes. A model tuned in this way could offer deeper insights into log yard systems and forest supply chain operations in general, potentially revealing unanticipated managerial strategies that could improve log yard performance. Additionally, modern log yards are rarely stand-alone entities in the supply chain; rather, they are typically managed in conjunction with various feed-in, satellite, and transshipment terminals. The DEM models presented in this thesis could be further developed to include these other terminals so as to enable system-level performance analyses that could provide solutions to common problems in supply chain management including operational problems and the challenge of identifying reliable metrics for evaluating performance and efficiency (Lee and Billington, 1992).

Consciously or unconsciously, managing a terminal or log-yard requires a lot of risk management to sustain uninterrupted plant operation (March and Shapira, 1987; Jüttner et al., 2003). One aspect of this risk management problem relates to the design of the log yard, which must minimize log cycle times while maintaining adequate inventory levels to meet the needs of the plant(s) that the log yard serves. Paper IV focused on the question of how quickly storage area A could and should be emptied while maintaining an acceptable minimum level of inventory as buffer storage. While the solutions considered in that paper have beneficial impacts, it is possible that better ways of avoiding lock-in effects at large log yards could be identified by integrating concepts from risk management theory into the models presented here.

Finally, it may be possible to develop more efficient log yard layouts by revising the models presented here to incorporate concepts developed in studies on risk management theory and the packing problem (Dowsland and Dowsland, 1992). All the log stacks at the studied yard were arranged such that machines could only approach from the front, as indicated by the straight arrows in the upper part of figure 7.1 (a). This gives rise to a so-called last-in, first-out (LIFO) system in which it is difficult to access the logs that were unloaded first. To relieve the constraints imposed by this layout, packing problem theories could be used to develop alternative layouts. Optimizing the layouts of the storage areas in this way could reduce log cycle times and thus improve overall log yard performance.

All the alternative layouts suggested above reduce the log yard's total inventory capacity to some extent, which must also be accounted for in the risk management analyses. However, since the log yards of interest handle large bulk volumes, even small improvements in log accessibility and storage time could have noticeable financial and operational benefits (Hopper and Turton, 1999).



(a) LIFO & FILO

(b) LIFO to Freedom

(c) Packing Parallel

(d) Packing V Shape

(e) Equidistant

Figure 7.1: Alternative log yard layouts with the potential to improve log cycle times. (a) The LIFO and FILO layouts commonly used today (b) LIFO layout in top to free access below. (c) Free access to logs packed in parallel. (d) Free access to logs packed in a V-shaped layout. (e) Equidistant packing to equalize the transport distances for all log stacks. Arrows indicate a possible transportation distance from the factory to the log stacks.

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Popular Science Summary

Forest industry supply chains are very sensitive to seasonal changes as well as both predictable and unpredictable changes in weather. Bad weather conditions can limit access to planned harvest sites in forests and to harvested logs and other assortments placed at roadsides for delivery to sawmills, pulp mills, and heat and power plants. The industry must therefore implement safeguard measures to cope with these supply disruptions. One such measure involves storing large quantities of raw material at industry sites or at terminals between the forest and the end-user. Forest terminals reduce risks relating to wood supply and can also increase the area from which manufacturing sites can source raw materials. In 2015, the Swedish government introduced a new timber measurement act that requires forest companies to adopt better practices when measuring forest fuel assortments such as low quality logs, branches, and tree tops, as well as chips and other products derived from these assortments. This means that in addition to storing material and supporting its transfer between different modes of transportation, forest terminals must be able to measure and characterize the material they handle. These new regulations coincided with a period of rapid evolution in the more traditional forest sector during which some pulp mills closed down while others expanded and took on the role of biorefineries. This increased the demand for wood at specific sites and created a demand for a greater variety of delivered wood assortments. To cope with these new demands, the Swedish forest sector requires more efficient and integrated storage at manufacturing sites and terminals.

This work had three main goals: a) to provide an overview of Sweden's biomass terminals by characterizing them in terms of their size, the equipment they possess, their condition, the forest-based materials that they store, and so on; b) to determine which new forest assortments could be created at terminals by chipping different biomass assortments and then screening or sieving them to create wood chips with specific desirable properties; and c) to develop mathematical models that could be used to analyze and improve operations at existing terminals and end-user storage sites.

The biggest differences among Swedish terminals were those between terminals smaller and larger than 5 ha. Bigger terminals are better equipped with measurement equipment and rely heavily on accredited measuring companies to perform measurements. However, it is important to note that smaller terminals play significant roles in supplying raw materials in Sweden: they handle more than half of the raw forest material that passes through the country's terminals. Unfortunately, because standardized measurements and inventories are rare at smaller terminals, around 76% of the biomass that they handle is poorly accounted for. Most of the biomass stored at the terminals is bulky and must be chipped or ground before further transportation. Chipping of bulky biomass was done at 90% of all terminals, creating opportunities to add value.

The quality of biomass for energy generation depends on several different properties. The ash and moisture content of the wood chips determine how much energy can be obtained from them, while the particle distribution of wood chips can significantly affect feeding and combustion processes at heat and power plants, as well as pulping processes at pulp mills. After chipping biomass at a terminal and then screening wood chip samples in the laboratory, it was possible to reduce the average ash content of the biomass to 0.66-2.17%, corresponding to a total ash content reduction of 20-31%. Dividing chipped material into different quality classes by screening could enable the generation of products tailored to different applications with different price points. It could also improve the storage properties of the chipped material because separated larger chips have better storage properties than mixed wood chip piles.

Many of Sweden's terminals and storage sites at mills have evolved along side one-another, and improving their performance while they are in operation can be challenging. One method commonly used to analyze such systems involves generating mathematical models and using them in simulations. Several models were developed in the course of this work, revealing the importance of using production data from active terminals to analyze and improve their daily operation. Terminals are also perhaps the components of the forest supply chain that are most amenable to automation. In principle, they could be designed and operated in a manner similar to that of enclosed warehouses with well-defined paths for all machines operating within their boundaries. However, before a terminal can be automated, it must be analyzed and mathematical models of its operations must be developed. The mathematical models presented in this thesis could help terminal managers make decisions about terminal operations and log storage strategies.

Populärvetenskaplig sammanfattning

Skogliga råvarukedjor är känsliga för variation i väder och säsong. Dåliga väderförhållanden kan begränsa tillträdet till både avverkat virke vid skogsbilvägar och planerade avverkningstrakter. De industrier som är beroende av råvaran måste därför ha ett skyddsnät som hjälper dem att hantera dessa problem. Ett sånt skyddsnät är att lagra stora mängder råmaterial vid industri eller på terminaler som är placerade mellan skogen och slutanvändaren. Skogliga terminaler minskar risken rörande råvarutillgång och kan öka arean från vilken tillverkningsindustrin kan hämta råvaror. 2015 så tillkom en ny lag om virkesmätning i Sverige. Denna kräver att skogsbolag på ett bättre sätt mäter skogliga biobränslen såsom låg kvalitets stockar, grenar och trädtoppar eller flis och andra produkter som kommer från dessa biobränslen. Det här innebär att skogliga terminaler måste kunna mäta och karaktärisera materialet de hanterar och inte bara förvara det och underlätta för byte av transportsätt. Introduktionen av den nya lagen sammanföll med en period av snabb utveckling inom den traditionella skogliga sektorn som innebar att några massabruk fick stänga ner medan andra expanderade och tog på sig rollen som bioraffinaderi. Det här gjorde att behovet av trärråvara koncentrerades runt specifika områden och råvaran behövde levereras i fler olika sortiment. För att hantera dessa nya krav så behöver skogssektorn en effektivare och mer integrerad lagringslösning på industri och terminaler.

Den här avhandlingen har tre huvudsakliga mål: a) att erbjuda en överblick av Sveriges biomassaterminaler genom att karaktärisera dem utifrån deras storlek, maskinpark, deras tillstånd, det skogliga material som de hanterar, osv; b) att fastställa vilka nya skogliga sortiment som kan skapas på terminalerna genom att flisa olika biomassasortiment och sedan sikta och sortera dem utifrån olika kvaliteter c) att utveckla matematiska modeller som kan användas för att analysera och förbättra verksamheten på befintliga terminaler och förvaringsplatser hos slutanvändaren.

Den största skillnaden mellan Sveriges olika terminaler finns mellan terminaler som är större, respektive mindre än 5 ha. Större terminaler är bättre rustade med mätinstrument och är beroende av ackrediterade mätbolag för att utföra mätningarna. Dock är det viktigt att notera att de små terminalerna har en signifikant roll i råvaruförsörjningen i Sverige då de hanterar mer än hälften av den skogliga råvaran som passerar genom landets terminaler. Olyckligtvis så är ca 76% av biomassan de hanterar bristfälligt redovisad då mätutrustning och inventeringar är sällsynta på små terminaler. Majoriteten av biomassa som förvaras på terminalerna är skrymmande och måste flisas eller malas innan transport. Sönderdelning av skrymmande biomassa genomfördes på 90% av alla terminaler, vilket skapar möjlighet till att öka värdet på produkten. Kvaliten på biomassa som ska användas för att skapa energi beror på flera olika saker. Askhalten och fukthalten i fliset beror avgör hur mycket energi som kan utvinnas från dem medan partikelfördelningen i fliset påverkar matningshastighet och förbränningsprocesserna på värme- och kraftverken liksom massaframställningen på massabruken. Genom att flisa biomassa på terminaler och sedan sikta och sortera dem i laboratoriemiljö så kunde det genomsnittliga askinnehållet i biomassan reduceras till 0.66-2.17%, vilket motsvarar en reducering av det totala askinnehållet med 20-31%. Att sortera flisat material i olika kvalitetsklasser genom siktning erbjuder en möjlighet att ta fram biomassaprodukter i olika prisklasser och som är skräddarsydda för specifika ändamål. Det skulle också kunna förbättra lagringskvalitéerna i det sönderdelade materialet eftersom större separerade flis har bättre lagringskvaliteter än blandade flishögar.

Många av Sveriges terminaler och brukens förvaringsplatser har utvecklas sida vid sida och att förbättra deras prestanda medan verksamheten fortgår kan vara utmanande. En metod som vanligen används för att analysera sådana system involverar att generera matematiska modeller och sedan använda modellerna i simuleringar. Ett flertal modeller utvecklades inom ramen för detta arbete, vilket uppdagade behovet av att använda riktiga produktionsdata för att analysera och förbättra deras dagliga verksamhet. Terminaler är kanske också den komponent i den skogliga råvarukedjan som är enklast att automatisera. I princip så skulle de kunna utformas och drivas på liknande sätt som slutna lager med väldefinierade vägar för alla maskiner som arbetar inom sina gränser. Men innan en terminal kan automatiseras så måste terminalen analyseras och det måste utvecklas matematiska modeller över dess verksamhet. De matematiska modeller som presenteras i den här avhandlingen kunde hjälpa beslutfattare att ta beslut om terminalverksamheten och strategier för virkeslagring.

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Now it is time for new challenges and explorations!

Kalvis Kons, Umeå, Sweden, July 2019