Weight Scaling

Methods to Determine the Quantity of Pulpwood

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Weight Scaling – Methods to Determine the Quantity of Pulpwood

Abstract

Scaling pulpwood according to its weight for payment purposes is done in many places around the world. In North America, pulpwood is commonly scaled according to its green weight, while in Central Europe the wood is commonly scaled according to its dry weight. In Sweden pulpwood is measured according to its volume.

This doctoral thesis aims to study the prerequisites for Sweden to weight scale its pulpwood. Historical observations of the green density plus meteorological data were used to create a model that predicted the green density of Norway spruce pulpwood that arrived at Braviken pulp and paper mill. By obtaining the weight of the wood and the prediction of green density, the volume could be obtained. To study the prerequisites for scaling wood according to its dry weight, the variation in moisture content was described within and between logs of Norway spruce. Further, dual energy X-ray absorptiometry was recognized and studied with respect to its potential to quickly and accurately determine the moisture content in wood samples. Different techniques for sampling roundwood to determine the moisture content were also studied.

The results of this thesis showed that the green density could be determined with similar precision as the volume measurement performed today. Moreover, it was shown that there was a large variation in the moisture content both within single discs and between logs of Norway spruce. It was shown that with dual energy X-ray absorptiometry, it was possible to determine the moisture content in chips of Scots pine and Norway spruce in good concurrence with the gravimetric method. The different techniques to sample roundwood showed similar results for a regular chainsaw and a modified chain sampler, but none of them worked totally satisfactorily and they both contained systemic errors.

The main benefits of weight scaling are that it is faster compared to volume measurement, it has potential to be less laborious while the new technique using X-ray absorptiometry to determine the moisture content in the wood provides the opportunity to sort arriving wood dependent on its moisture content.

Keywords: pulpwood, Norway spruce, Scots pine, moisture content, dry matter content, weight scaling, wood measurement, dual energy X-ray absorptiometry.

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It’s a long way to the top….

A, Young., M, Young., B, Scott.

Contents

List of Publications

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

I Mikael Hultnäs, Mats Nylinder, Anders Ågren. Predicting the green density as a means to achieve the volume of Norway spruce (*Picea abies*) (submitted).

II Mikael Hultnäs, Maria Jonsson. Variation in moisture content of Norway spruce and its consequences for sampling to determine the dry matter content (submitted).

III Mikael Hultnäs. (2011). Methods to determine the dry matter content of roundwood deliveries. *TAPPI Journal* (June), 33-37.

IV Mikael Hultnäs, Ragnar Kullenberg, Erik Persson, Mats Nylinder. (2009). Determination of moisture content in spruce woodchips by dual energy X-ray absorptiometry. Proceedings of the International Mechanical Pulping Conference, Sundsvall, May 31 to June 4, 2009. 213-219.

V Mikael Hultnäs, Victor Fernandez-Cano. Determination of the moisture content in wood chips of Scots pine and Norway spruce using Mantex Desktop Device, based on dual energy X-ray absorptiometry (accepted for publication in Journal of Wood Science).

Papers III and V are reproduced with the permission of the publishers.

The contribution of Mikael Hultnäs to the papers included in this thesis was as follows:

I Hultnäs collected and prepared the material by sorting it, identification and removal of outliers and performance of the descriptive statistics. Some statistical processing and analysis of the developed model. The text except the statistical modelling part in material and method was written by Hultnäs.

II Hultnäs collected and processed the material, statistical analysis, and was primarily responsible for writing of the text.

III Hultnäs was the sole author.

IV Hultnäs collected and measured the samples and wrote the article.

V Hultnäs collected the material, conducted statistical processing, analyzed the results, wrote the article and was the supervisor for the bachelor thesis that was the basis for the first part of the article.

Abbreviations

MC	Wet based moisture content
MDS	Mantex Desktop Scanner
ME	Error while determining the moisture content
m^3ub	Cubic meter solid under bark
NIR	Near infra red
RF	Radio frequency
SE	Standard error
ST_{cs}	Variation for the sampling technique, chain sampler
ST_{saw}	Variation for the sampling technique, chainsaw
VBD	Variation between discs in the same log
VBH	Variation between harvest areas
VBL	Variation between logs in the same pile
VBP	Variation between piles on the same truck
VBT	Variation between trucks from the same harvest area
VID	Variation inside a disc

1 Introduction

Sweden produces approximately 12 million tons of pulp a year, and is one of the leading producers and exporters of pulp in the world (Loman, 2011). The pulp and paper industry in Sweden consumes about 44 million m^3 of wood annually (Anon, 2010). Roundwood contributes approximately 35 million m^3, and the remaining 9 million m^3 consists of wood chips from sawmills (Anon, 2011). Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) are the dominant species in Sweden and contribute approximately 80 % of the wood supply to pulp mills. The remaining 20 % is hardwood, mainly birch (*Betula pendula, pubescens*) and aspen (*Populus tremula*) (Anon, 2011).

All pulpwood that is used by the pulp and paper industry is measured to determine its quantity; this measurement is the basis for payment. The measurement is normally performed at the pulp mill by one of the three independent wood measurement associations in Sweden (VMF Syd, VMF Qbera and VMF Nord) (Pettersson, 2011). The measurement of roundwood is, with some exceptions, performed as volume measurement. While for wood chips the measurement is performed as weight measurement with determination of its dry weight. The trading unit used for pulpwood in Sweden is m^3ub. This unit is defined as the solid volume of the log without branches and bark; the space between the piled logs is deducted. In general the volume measurement is considered to be accurate and cost effective, but contains subjective parts such as the determination of the solid volume percentage for the piles. The accuracy and precision of the volume measurement also varies between individual scalers and their performance over time.

In Sweden wood volume has traditionally been used to trade pulpwood. This has been the case since the growth of the pulp industry in the late 19th century (Pettersson, 2011). Volume is a well established way to quantify pulpwood, and over time it has also been the only practical solution to quantify the wood, e.g. during the time of manual harvesting and rafting of wood when no scales were available. For sawmills, volume is an adequate measure, however, for pulp mills, the weight of the wood might be a more adequate measure, as the dry weight of the wood is closely correlated to the yield of pulp (Nylinder, 1972, Nylinder, 1982, Björklund, 1988, Orvér, 2002).

Green weight is commonly used in North America to scale pulpwood, while in Europe (primarily Germany and Austria) the dry weight of the wood is used (Lothner et al., 1974, Björklund, 1988, Dicke and McCreight, 1999). The introduction of weight scaling of pulpwood in Sweden has been discussed for several decades (Nylinder, 1967, 1972, Björklund, 1988, 1989, Thygesen, 1994, Thygesen and Nylinder, 1996). The discussions have focused on weight scaling with determination of the moisture content (MC)[1]. The Swedish Wood Measurement Council (Virkesmätningsrådet) made a policy statement in 1984, that the dry weight is the most adequate unit of assessment for all fiber and energy assortments from the forest (Björklund, 1989). Despite the discussions concerning dry weight, studies concerning the use of green density as a tool to obtain the volume of the wood have been conducted, mainly in the northern part of Sweden and Norway (Orvér, 2001, Enger, 2005).

1.1 The volume measurement performed in Sweden today

To measure the volume of pulpwood, the height, length and width of each pile of wood on trucks is measured with a graded stick to assess the outer shape of an imagined frame that surrounds the load and to assess the gross volume of the wood. The solid volume percentage of each pile is then determined by assessing the parameters listed below (Anon 2006):

- Bark thickness
- Average diameter
- Piling
- Crookedness
- Delimbing

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1. Throughout the thesis MC means the wet based MC and is calculated as the quotient of the weight of the water and the green weight of the sample.

- Tapering

The solid volume percentage is then multiplied by the frame volume giving the gross volume of each pile on the truck. To assess the net volume of the load of wood, a deduction is made for e.g. the occurrence of decay, undersized diameters, etc. (Anon 2006).

Random sampling of logs is used to calibrate and achieve greater accuracy of the volume measurement. The purpose of random sampling is to retain a high level of accuracy for the measurement at a reduced cost (Orvér, 2002). A certain number of random samples are taken from each delivery[2] of wood, where each sample equals a pile of wood from a truck. The sampling procedure is as follows: when the pile assessments are done, the scaler is notified that a pile was chosen to become a random sample (done automatically by a computer). The pile is then unloaded in a designated area and measured log-by-log under bark with respect to its length and diameter. Deductions are also made according to the same premises as for the pile measurement (decay, undersized dimensions, etc). The result of the measurement is then compared with the results from the pile measurement and a quotient between these results can be calculated ($m^3_{\text{log-by-log measurement}} / m^3_{\text{pile measurement}}$). The quotient is then used to level the pile measurement for the entire delivery of wood. With this procedure the measurement is assumed to be unbiased (Orvér, 2002).

1.2 Factors influencing the green density of wood

Two factors influence the green density of wood: basic density and MC. Basic density in pulpwood is affected by e.g. genetic properties such as tree species, and variation within species. It is also influenced by physiological properties such as cambial age, location in stem, productivity of the growth site and competition between trees. The basic density varies between stands, between logs from final felling, and thinnings and between butt logs and top logs e.g. (Hakkila, 1966, Nylinder, 1972, Spångberg, 1998, Wilhelmsson et al., 2002, Repola, 2006, Jyske et al., 2008). In general, basic density decreases with increased latitude and increased elevation for a given width of the annual rings (Wilhelmsson et al., 2002, Nylinder and Fryk, 2011). Broader annual ring widths caused by increased cambial growth per time unit during the growth periods decreases the basic density of logs (Wilhelmsson et al., 2002). Thus, in

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2. A delivery of wood can e.g. be all wood delivered from forest company A to pulp mill B during a year, or all wood delivered from the forest owners in a certain area.

general, increased site fertility and wide spacing leads to wider growth rings and decreased basic density (Hakkila, 1966). Some general basic densities have been reported to be 419 – 436 kg/m^3 for Scots pine pulpwood, 398 - 412 kg/m^3 for Norway spruce pulpwood and 507 – 512 for Birch pulpwood (Andersson, 1983, Vadla, 2006).

The second parameter influencing green density is the MC (Nylinder et al., 1995). The MC in logs is dependent on several factors such as (Nylinder, 1972):

- Tree species
- Location in the stem
- Heartwood content
- Stand properties
- Time of harvest
- Length of time in storage

It has been pointed out by several authors that there is a strong correlation between the diameter of the logs and the MC (Nylinder, 1972, Kokkola, 1993, Enger, 2005, Vadla, 2006). This correlation is due to the relationship between diameter and heartwood. An increase in the diameter of the log increases the heartwood content and results in a decrease of the MC and green density.

When pulpwood arrives at the pulp mill, the MC shows a distinct seasonal variation (Nylinder, 1972, Björklund, 1988, Kokkola, 1993). The seasonal variation is highly dependent on the length of time in storage and how the wood is stored after harvest, e.g. if the pile of wood is placed in the sun or shadow, size of pile etc. (Kokkola, 1993, Liukko, 1997, Persson, 2001). The MC can decrease four times faster if the logs are kept at the harvest site and not placed in a pile at roadside (Filipsson, 1999). Berg et al. (1995) and Liukko (1997) list the driving forces behind the dehydration of pulpwood that leads to the variation in the MC:

- Temperature
- Relative humidity
- Precipitation
- Insolation
- Wind
- Amount of intact bark left on the logs
- Log dimensions

Each parameter has a direct and/or correlate effect on the dehydration of the wood.

1.3 Green density to obtain the volume of wood

To use the green weight and conversion factors to obtain the volume of the wood is a commonly used method in North America. The main reason to scale wood according to its green weight and then obtain the volume is that it is fast. Conversion factors between weight and the volume of logs have been extensively studied over the past decades, mainly in North America but also in the Nordic countries (Schumacher, 1946, Lothner et al., 1974, Clark III et al., 1985, Dicke and McCreight, 1999, Bond, 1999, Orvér, 2001, Enger, 2005).

A few attempts were made in the Scandinavian countries to obtain the volume by using green density (Orvér, 2001, Enger, 2005). Orvér (2001) performed a study over several years where he, with the help of weight, aimed to determine the volume of wood arriving at different pulp mills in northern and central Sweden. The average diameter, abnormal dehydration, amount of Norway spruce, snow and ice content were considered to have an influence on the conversion factor between weight and volume that were used in the study. For softwood pulpwood from central parts of Sweden, assessment was not as good when the green density was used as compared to traditional volume measurement. However, for the northern part of the country the results were comparable to those obtained when using traditional volume measurement. The reason for the poor accuracy in central Sweden was claimed to be the increased variation in the basic density in the central part compared to the northern parts of the country. For birch pulpwood, no correlation between accuracy and latitude could be seen when the volume was obtained by using the green density (Orvér, 2001).

A similar study was performed in Norway, where in addition to the weight, information about tree species, log diameter, time of delivery and altitude of harvest was recorded. The conclusion of the study was that the results were similar to what was achieved with the traditional volume measurement (Okstad, 1998, Enger, 2005).

During the last twenty years the time between harvest and transportation of the pulpwood to the mills has decreased considerably (Wilhelmsson and Moberg, 2004). The demand from the mechanical pulping industry to obtain fresh wood has resulted in relatively strict freshness criteria for Norway spruce pulpwood (Anon, 2006). These circumstances have resulted in increased possibilities to use the green density to obtain the volume of the wood.

1.4 Dry weight as a basis to trade roundwood

The main reason to use dry weight to quantify pulpwood is that the dry weight is directly correlated with the yield of pulp (Nylinder, 1972, Nylinder, 1982, Björklund, 1988, Orvér, 2002). The dry weight is commonly used in Germany and Austria for pulpwood and it is used for sawmill chips in Sweden (Björklund, 1988).

To be able to use dry weight to trade pulpwood, the MC of the pulpwood needs to be determined. There is no method available that directly determines the MC of an entire load of logs; therefore, sampling of the wood is necessary.

1.4.1 Sampling to determine the dry matter content in wood

The MC is well known to vary within and between logs of Norway spruce and Scots pine. Tamminen (1964) and Nagoda (1968) have shown that the MC varies over the year, between heartwood and sapwood and between inner and outer sapwood. Furthermore, it has been shown that the MC decreases from the stump up to approximately 10 % of the tree height and thereafter increases towards the top of the tree (Tamminen, 1964). Nylinder et al. (1995) and Kravka et al. (1999) showed that in Norway spruce and Scots pine, substantial variation in the MC can occur in all directions inside a living tree. Further it is shown that the MC of pulpwood varies seasonally, within and between logs (Björklund, 1988, Wilhelmsson and Moberg, 2004). The variation in MC within and between logs and between different trucks with wood determines the number of samples needed to reach a certain level of precision when the MC is to be determined. The variation of MC that occurs in the logs emphasizes the importance of a method that can take representative samples of the wood.

As mentioned previously, pulp mills in Germany have, for a long time, been using the dry weight to quantify their pulpwood. Samples to determine the dry weight are taken with a chain sampler (Figure 1, left).

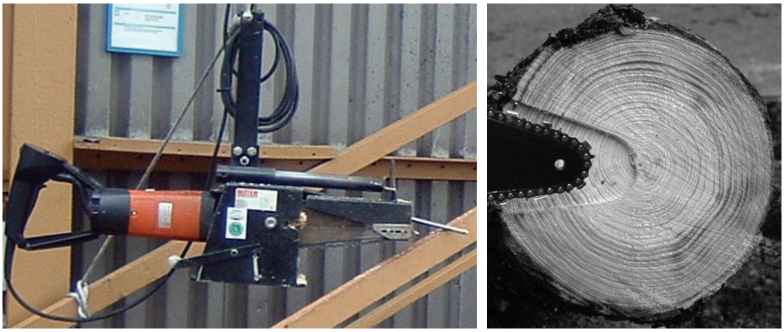

Figure 1. The chain sampler in its suspension (left). A sample taken with the chain sampler (right). Photo (left): Lars Björklund. Illustration (right): Hans Fryk

The idea behind the chain sampler is that the tip of the v-shaped sword should be pressed radially from bark to the pith of the log to produce a sample containing a representative amount of heartwood and sapwood (Figure 1, right). The sample is collected as shavings in a bag placed on the lower side of the chain sampler (Björklund, 1988). Normally one sample per log from ten different logs is taken diagonally from one side of the pile of wood on the truck. The intention is to cover the variation in MC along and between the logs in the pile.

Several studies have been conducted using the chain sampler (Braathe and Okstad, 1964, Okstad, 1971, Leinonen, 1974, Björklund, 1988, 1989). The Swedish and Norwegian studies showed that the chain sampler tended to underestimate the MC probably due to the shavings drying while they were taken from the logs (Braathe and Okstad, 1964, Okstad 1971, Björklund, 1988). While the Finnish study found that the MC was overestimated with the chain sampler (Leinonen, 1974). The Swedish and Norwegian studies also pointed out that during winter, snow and ice is likely to be underrepresented in samples taken with the chain sampler, resulting in the MC being further underestimated (Braathe and Okstad, 1964, Okstad, 1971, Björklund, 1988).

To obtain an optimal sample with the chain sampler it is important that the tip of the sword is placed in the pith of the log as in Figure 1. If the sword is pressed too deep into the log, the heartwood would be overrepresented and the MC would be underestimated. If the sword is placed too shallow, above or below the centre of the log, the sapwood would be overrepresented and the MC would be overestimated (Figure 2) (Björklund, 1988).

Figure 2. The effect of the representativeness of the sample if the chain sampler is placed in different ways (Björklund, 1988). Illustration: Hans Fryk.

The chain sampler has been criticized due to its weight, approximately 20 kg. To be able to use the chain sampler some sort of suspension is required, as shown in Figure 1 left. Also the force it takes to press the tip of the sword into the log is substantial and requires quite "fit" personnel.

A regular chainsaw (Figure 3, left) with an attached bag to collect shavings is regularly used in some places, for example Austria, and has been studied in Sweden (Björklund, 1989, Larsson, 2011). The sample is taken by sawing vertically through the logs in a pile of wood on the truck. The aim is to saw through half of each log giving a representative sample containing sapwood and heartwood (Figure 3, right) and to include as many logs as possible in each sample. The chainsaw was reported to underestimate the MC (Björklund, 1989, Larsson 2011). However, the underestimation of the MC was reported to be lower for the chainsaw compared to the chain sampler (Björklund, 1989).

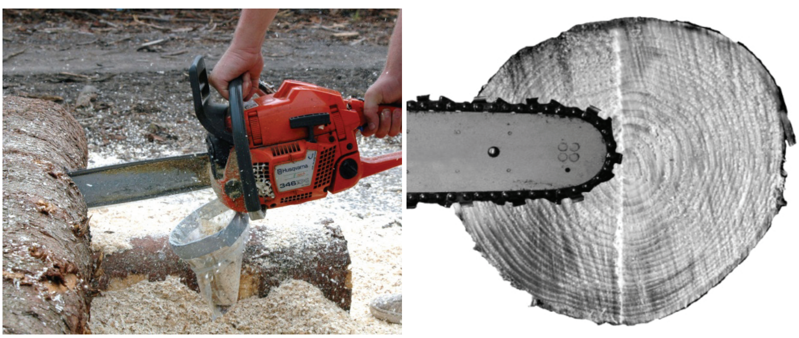

Figure 3. A chainsaw with a bag mounted below (left) to collect the shavings when the log is sawn through to half (right). Photo and illustration: Hans Fryk

A third option that was studied was a drill mounted on a truck that bored a hole into the logs while they still were loaded on the truck (Figure 4). Each hole made by the drill was approximately 60 mm wide and 1000 mm deep. The shavings that came from each hole were collected at the bottom of the drill (Nylinder, 1984, Nylinder and Fryk, 1985). For each sample that was taken with the drill, several logs were included; through this a representative sample containing the sapwood and heartwood content was obtained (Björklund, 1988). The results showed that the drill consistently underestimated the MC and a correction factor was needed. The error was reported to be greater for the drill than for the chain sampler and the chainsaw. The studies also showed that the drill overestimated the amount of snow in the piles of wood during winter time (Nylinder, 1984, Nylinder and Fryk, 1985, Björklund, 1988).

Figure 4. The drill mounted on truck while taking a sample from a truck of pulpwood. Photo: Mats Nylinder

1.4.2 Determination of MC in samples

When a sample of wood is taken, the MC needs to be determined. Today the gravimetric method is used at all Swedish pulp mills. The gravimetric method comprises the following - the raw samples are weighed and then dried in an oven at 105 ± 2°C for at least 24 hours until they reach a stable weight, where after the MC of the samples can be determined and the dry weight of the truck load with wood can be calculated (Anon, 2009). The drawback with this method is the time it takes for the samples to reach a stable weight.

The MC of the wood can not only be used to serve as basis for payment (the dry weight), but is also recognized as one of the most important process parameters in pulp production (Sundholm, 1999). By using the gravimetric method to determine the MC, it is impossible to use the result to e.g. sort the pulpwood with respect to its MC when the wood arrives at the pulp mill.

Over the past decades, several techniques were tested and evaluated for their potential to serve as alternative options to the gravimetric method. Near infrared (NIR) (Berg et al., 2005, Dahlquist et al., 2005), gamma rays (Persson, 1994), radar (Blomqvist and Nylinder, 1986), microwaves and radio frequency (RF) (Lundgren, 2005, Duarte da Paz, 2008) are some of the techniques tested, but so far, none of them have become truly successful and the gravimetric method is still the method used (Nyström and Dahlquist, 2004)

1.5 Rules and regulations

Wood measurement in Sweden is regulated by the Wood Measurement Act (Anon, 1966). The Wood Measurement Act states that all measurement of pulpwood for the purposes of trade should be performed according to the regulation set by the Swedish Forest Agency (Anon, 1966). The Swedish Forest Agency has, in their regulation, defined the greatest allowable deviation for a single delivery of pulpwood (Anon, 1999). If the pulpwood is measured according to volume, the deviation for a delivery of pulpwood that exceeds 400 m^3ub may not be greater than 9 % of the volume (Anon, 1999). If the wood is measured with respect to weight, the deviation between the measured weight and the true weight cannot be greater than what is shown in Table 1 (Anon, 1999).

Table 1. *The highest deviation allowed for pulpwood when the quantity is determined by the weight according to the regulation set by the Swedish Forest Agency (Anon, 1999).*

	Weight of wood (ton)	Highest allowed deviation (%)
Green weight	≤ 100	4.5
	> 100	3
Dry weight	≤ 50	9
	> 50	6

1.6 Objectives

The objective of this doctoral thesis is to evaluate the prerequisites necessary to use weight as a method to quantify pulpwood in Sweden. This is done by evaluating two different methods; the use of green density to obtain the volume, and by determining the dry weight of the wood.

This thesis investigates whether it is possible to use a statistical model to predict the green density of Norway spruce that arrives at a mechanical pulp and paper mill. The predicted green density could then be used to obtain the volume of the wood.

Secondly, the prerequisites to determine the dry weight of a delivery of pulpwood are studied by describing the variation of MC within and between logs of Norway spruce, both from newly harvested logs and from logs arriving at a pulp and paper mill. Having reliable knowledge of how the variation of MC occurs in logs is a prerequisite to retain a high level of accuracy and precision when sampling to determine the dry weight of the wood.

Further, different techniques to determine the MC in wood are studied. Dual energy X-ray absorptiometry is recognized as a method with potential to replace the gravimetric method used today. Dual energy X-ray absorptiometry is then evaluated with respect to its potential to quickly and accurately determine the MC in wood compared to the gravimetric method.

Two different techniques to obtain samples from roundwood are addressed in an additional study to the articles included in this thesis.

The two methods to quantify pulpwood presented are compared to each other and the rules and regulations set by the Wood Measurement Act and the Swedish Forest Agency.

The studies in this thesis only consider how to quantify the pulpwood and no concern is taken to quality aspects such as presence of decay, crookedness of logs, etc. Further, the measurement is considered to take place at the pulp mill. When the volume is obtained by predicting the green density, the volume is expressed as cubic meters under bark. When the dry weight is determined, the weight includes bark.

2 Material and methods

A more detailed compilation of the material and methods is found in each of the included papers. At the end of this chapter, a complete section on the material and methods for the additional study concerning different sampling techniques for roundwood are presented. The additional study is not included in any of the articles in this thesis.

2.1 Paper I. Predicting the green density as a means to achieve the volume of Norway spruce (*Picea abies*)

To predict the green density of Norway spruce pulpwood, data were collected from Braviken pulp and paper mill in Norrköping, Sweden. The data consisted of weight and volume of wood arriving during the years 2003 – 2007. After removal of outliers and volumes that lacked corresponding weights, the data consisted of 3.3 million m^3 ub (95 000 trucks) in total for all years. The volume of wood was obtained by pilewise measurement and each truck was equal to one replicate. Information concerning wind, precipitation, humidity and temperature were collected from five meteorological stations belonging to the Swedish Meteorological and Hydrological Institute, the meteorological stations were located in the wood supply area of the pulp and paper mill.

In order to predict the mean density, efforts were made to find a model with the meteorological data as explanatory variables. It was decided to use variables lagged two or three periods due to practical considerations when applying the model. However, it was found that none of the meteorological variables had a constant effect on the density throughout the year. This led to efforts to find a model where the influence of the variables on the density was allowed to differ for different seasons of the year. This assumption, with 24 seasons, 2 lags and 4 weather variables, implied 192 different combinations. It was decided to use stepwise regression to find such a model, due to lack of a theoretical basis for this type of model. The results obtained using stepwise regression must be regarded as tentative since this technique is an exploratory way of generating hypotheses. Further studies on the model obtained are desirable. The model was then tested separately on data from each year of the study.

2.2 Paper II. Variation in moisture content of Norway spruce and its consequences for sampling to determine the dry matter content

Norway spruce logs were sampled at three different times at Braviken pulp and paper mill in Norrköping in southern Sweden. Two discs were cut from each log and the discs were then divided into eight sections to imitate a sample taken with the chain sampler. The MC was then determined for each section using the gravimetric method. The MC within and between the logs could then be described.

In December 2010 six Norway spruce logs were collected 50 km north of Skellefteå in Northern Sweden. Each log was scanned with computed tomography at five different cross sections. The logs were kept indoors and scanned again at the same places after 14 and 27 days. After the cross sections were scanned the third time they were cut and dried in an oven. This allowed MC determination of the scanned cross sections. Through this, the variation in MC inside the Norway spruce logs could be further described

With the variation of the MC used as a starting point, the precision when sampling in different ways with hypothetical sampling equipment the MC was simulated. The simulations aimed to provide a theoretical background to be able to optimize the sampling procedure.

2.3 Paper III. Methods for the determination of the dry matter content of roundwood deliveries

The article was performed as a literature review. Different techniques that could be used to determine the dry matter content (which is equal to the inverse MC) in wood were described and discussed.

2.4 Paper IV. Determination of MC in spruce woodchips by dual energy X-ray absorptiometry

Thirty samples of wood chips from Norway spruce were measured to determine the MC with a prototype of a commercial product based on dual energy X-ray absorptiometry. The samples were measured ten times each, where after the MC was determined with the gravimetric method. The results were used to create a calibration model for Norway spruce. This model was then applied to the measurement device (this calibration model is from here on referred to as “spruce”). Forty-five samples were used to validate the calibration model. The validation part of the study consisted of 450 measurements with the gravimetric method used as a reference.

2.5 Paper V. Determination of the moisture content in wood chips of Scots pine and Norway spruce using Mantex Desktop Scanner based on dual energy X-ray absorptiometry

To determine the possibility to use the calibration model developed for Norway spruce (used in Paper IV) to determine the MC in Scots pine woodchips, seventy samples of Scots pine were measured with the Mantex Desktop Scanner (MDS) (the prototype in the previous paper had since been developed into a commercial product) based on dual energy X-ray absorptiometry. The gravimetric method was used to obtain a reference value for the samples.

Next, a calibration model developed for Scots pine was applied (this calibration model is from here on referred to as “pine”). Twelve samples of Scots pine chips aimed for pulp production were collected and measured six times each with the MDS to determine the MC. Reference values were obtained through gravimetric measurement of the samples.

A calibration model was developed to handle samples independent of whether they consisted of Scots pine, Norway spruce or different mixtures of Scots pine and Norway spruce. This calibration model was then evaluated (this calibration model is from here on referred to as “softwood”). Twenty-nine samples constituting Scots pine, Norway spruce and different mixtures thereof were then measured six times each with the MDS. Once again the gravimetric method was used as a reference for the MC achieved with the MDS.

Last, twenty samples of Norway spruce were measured, first frozen and then at room temperature, to determine if there were any differences in the results of the measurements when the samples were frozen or not.

2.6 Sampling techniques – modified chain sampler and chainsaw (additional study)

A modified chain sampler (Figure 5) based on an electrical chainsaw was constructed to take samples from roundwood. The starting point for the modified chain sampler was an electric chainsaw and a v-shaped sword that was manufactured separately; all to imitate the original chain sampler described earlier (Figure 1) and use the same concept of taking representative samples from a log (Braathe and Okstad, 1964, Okstad, 1971, Björklund, 1988, 1989).

Figure 5. A modified chain sampler based on an electric chainsaw. Photo: Hans Fryk

At three times, in April, June and October 2008, pulpwood from Norway spruce logs was sampled with the modified chain sampler and a regular chainsaw (Figure 3, left) at Braviken pulp and paper mill. The logs were taken randomly from the first truck carrying roundwood that arrived at the mill after a pre-set time. In April and June thirty logs were sampled each time, while in October, twenty-two logs were sampled.

Each log was sampled at five different places always starting at the butt end of the log. At each sampling point, two samples were taken with the modified chain sampler, and two samples were taken with the regular chainsaw. With the modified chain sampler, samples were taken using the same technique as for the original chain sampler that was described earlier (Figure 1 right). With the chainsaw, the log was sawn through half of its diameter also described earlier (Figure 3 right). The two samples from each sampler were collected in the same bag and were considered one sample. In the middle of each sampling location a disc was taken and used as a reference to the samples (Figure 6).

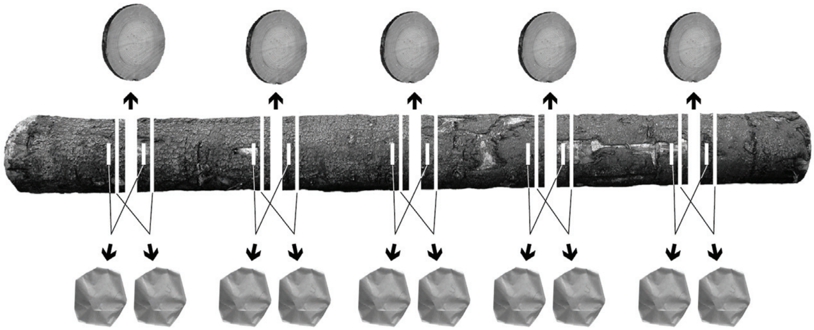

Figure 6. A log where five samples were taken with the modified chain sampler (bags to the left), and five samples were taken with a chainsaw (bags to the right). In the middle a disc was taken and used as reference value for the MC that was determined gravimetrically for all samples. Illustration: Hans Fryk

The samples were weighed immediately and were later transported to the laboratory where the MC was determined for each of the samples using the gravimetric method.

The precision of the chain sampler and the chainsaw were defined as the standard deviation of the differences in MC between the samples from the sampler (chain sampler or chainsaw) and the corresponding discs.

2.7 The precision of the different measurement methods to quantify pulpwood

As a measure of the precision when the volume was obtained using the green density and when the dry weight was determined, the standard error (SE) was used. The SE is a commonly used measure in traditional volume measurement of pulpwood and can also be used for weight scaling. The choice of SE allows one to make comparisons between the different measurements. Simulations of SE were made when the volume was obtained by using the weight and predictions of the green density and when the dry weight of a delivery of wood was to be decided.

As a way to improve the accuracy of the predictions of the green density, random samples (piles) would be taken for which the density would be manually measured. The result of the density measurements would be used to level the prediction made by the model in paper I, this procedure would also allow a direct comparison of SE to the traditional volume measurement. Traditional volume measurement is normally performed for each pile. In the model in paper I, the density was predicted for each truck. It was desirable to have the same level of SE regardless of whether the volume was obtained by the green density or traditional volume measurement; this to allow a fair comparison between the two methods. Using Equation 1, the prediction of the density was recalculated from truck level to pile level. By introducing the factor a, into Equation 1, the SE of the density measurement will be comparable to SE of the traditional volume measurement.

$$SE = \frac{\sqrt{\frac{s^2}{nt} + a^2 + \frac{s^2}{nt} * a^2}}{\sqrt{n}} \qquad \textit{Equation 1}$$

s was the standard deviation for the quotient between the measured and predicted density[3] (paper I). a was the standard deviation for the quotient between the log-by-log measurement and the pilewise measurement, when the pulpwood was traditionally measured according to volume. nt was the number of piles on each truck. n was the number of piles randomly sampled for which the green density would be measured pilewise. The values of a were taken from the literature (Wilhelmsson and Moberg, 2004).

The SE for traditional volume measurement was calculated with Equation 2.

$$SE = \frac{a}{\sqrt{n}} \qquad \textit{Equation 2}$$

a was the standard deviation of the quotient between the log-by-log measurement and the pile measurement and n was the number of sampled piles. The standard deviations (a) were 5.3 % for Norway spruce pulpwood, 5.9 % for softwood and 6.6 % for birch (Wilhelmsson and Moberg, 2004).

To simulate SE, when the dry weight of logs was determined for a simulated delivery of Norway spruce pulpwood, Equation 3, derived from Björklund (1988), was used. SE was simulated for three different times, April, June and October. For the parameters; variation inside a disc (VID), variation between discs in the same log (VBD) and variation between logs in the same pile (VBL), the material from paper II concerning the variation of the MC was

3. It is assumed that the error in the weight determination in the density measurement is negligible and that the error in the density determination derives from the volume measurement.

used. Results from papers IV and V, concerning the precision of the determination of the MC were used for the error parameter (ME) while simulating the determination of the MC in the samples. The precision of the modified chain sampler and the chainsaw, presented in the additional study, were used for the parameter, variation for the sampling technique (ST). For those parameters that were not collected within the scope of this thesis (variation between trucks from the same harvest area, (VBT), variation between harvest areas (VBH) and variation between piles on the same truck (VBP)), numbers were taken from Björklund (1988).

$$SE = \sqrt{\frac{VBT^2+VBH^2}{n} * \left(1-\frac{n}{N}\right) + \frac{VBP^2}{n} * \left(1-\frac{1}{3}\right) + \frac{VBL^2}{n*s} * \left(1-\frac{s}{200}\right) + \frac{VBD^2}{n*s} + \frac{ME^2}{n*s} + \frac{ST^2}{n*s} * K + \frac{VID^2}{n*s*p} * K}$$

Equation 3

VID = Variation inside a disc
ST_{cs} = Variation for the sampling technique, chain sampler
ST_{saw}= Variation for the sampling technique, chainsaw
ME = Error while determining the MC
VBD = Variation between discs in the same log
VBL = Variation between logs in the same pile
VBP =Variation between piles on the same truck
VBT = Variation between trucks from the same harvest area
VBH = Variation between harvest areas
N = Total number of trucks
n = Number of trucks sampled
s = Number of samples per pile
p = Pieces of disc that were taken (one for chain sampler and four for chainsaw)
K = Correction factor for the spread of log diameters

When SE was calculated for the modified chain sampler, the term ST_{cs}^2 replaced the term ST^2 in Equation 3, and when SE was calculated for the chainsaw, the term ST_{saw}^2 replaced the SE^2 parameter. K, was a correction factor for the likelihood that logs in a pile of wood would be hit with the chain sampler. Normally, K varies with the variation of log diameters. For a normal variation of the diameters in a pile the value of K would be 1.1, which was the value used in these calculations (Björklund, 1988). It was assumed when the SE was calculated, that a pile of wood contained 200 logs. Further, it was assumed that only one sample per log was taken. The numbers for all parameters used in Equation 3 are presented in Table 2.

Table 2. *The parameters used to simulate the standard error (SE) of delivery of wood when the dry weight was determined.VBP, VBH, VBTH and VBPH taken from Björklund (1988). All numbers are percentage units.*

	VID	SE_{CS}	SE_{SAW}	ME	VBD	VBL	VBP	VBT	VBH
April	2.5	3.1	2.0	0.75	2.3	4.9	2.0	2.0	4.0
June	3.5	4.5	2.5	0.75	2.0	7.2	2.0	2.0	4.0
October	2.0	4.0	0.7	0.75	1.6	3.6	2.0	2.0	4.0

VID = Variation inside a disc, SE_{CS} = Sampling error chain sampler, SE_{SAW} = Sampling error chainsaw, ME = error while determining the MC, VBD = Variation between discs in the same log, VBL = Variation between logs in the same pile, VBP = Variation between piles on the same truck, VBT = Variation between trucks from the same harvest area, VBH = Variation between harvest areas

The relative SE dependent on the MC was calculated by Equation 4.

$$Relative\ SE = \frac{Standard\ error}{Moisture\ content} \qquad Equation\ 4$$

3 Results

3.1 Predicting the green density as a means to achieve the volume of Norway spruce (*Picea abies*) (paper I)

The material analyzed to obtain the green density of the pulpwood that arrived at Braviken pulp and paper mill during the years 2003 – 2007 showed a distinct seasonal variation. The variation of the green density expressed as standard deviation varied significantly during and between the years, with the highest variation during summer.

The best fitting model predicted the green density at an explanation rate of 88.9 %. This model indicated that meteorological variables should only be included during the spring and summer months with the exception of the second part of November when humidity contributed significantly to the model.

To evaluate the model, the green densities for each year were predicted separately to the model. The evaluation showed that there were no systematic errors between predicted values and measured observations of the green density.

In general, the accuracy and precision of the density predictions were better during autumn and winter months compared to the spring and summer months. The precision of the predictions was better for the first years studied and then steadily decreased.

The SE for prediction of green density was simulated for all wood delivered during each period of half a month and as if 1, 10, 25, 50 or 100 piles of wood were sampled during the same period. The volume part of the density measurement was originally measured pilewise for the entire truck. Using Equation 1, the precision of the measurement was simulated to be at the same level as if the volume was measured log-by-log for each pile. The results are presented as the minimum and maximum values of SE for spring, summer, autumn and winter during the five years included in the study (Table 3).

Table 3. *SE (%) for a simulated delivery of wood when the green density was predicted with the model in paper I and when 1, 10, 25, 50 or 100 piles were randomly sampled during each period of half a month. SE is shown as the min and max values for, winter, spring, summer and autumn for the years 2003 – 2007.*

Month	Number of sampled piles									
	1		10		25		50		100	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Winter	6.1	6.4	1.9	2.0	1.2	1.3	0.9	0.9	0.6	0.6
Spring	6.2	6.7	2.0	2.1	1.2	1.3	0.9	0.9	0.6	0.7
Summer	6.5	8.0	2.0	2.5	1.3	1.6	0.9	1.1	0.6	0.8
Autumn	6.3	6.7	2.0	2.1	1.3	1.3	0.9	1.0	0.6	0.7

There was some seasonal variation of SE with the highest SE during summer. The variation of SE decreased with increased number of samples. There were differences in SE between the years for specific periods.

Table 4 presents the SE for traditional volume measurement of different assortments of pulpwood when 1, 10, 25, 50 or 100 piles were sampled and measured log-by-log.

Table 4. *SE (%) for the volume measurement when 1, 10, 25, 50 or 100 piles were randomly sampled and measured log-by-log.*

Number of samples	Norway spruce	Softwood	Hardwood
1	5.3	5.9	6.6
10	1.7	1.9	2.1
25	1.1	1.2	1.3
50	0.7	0.8	0.9
100	0.5	0.6	0.7

SE of the traditional volume measurement varied between assortments. Norway spruce pulpwood had the best precision for a given number of samples. For the volume measurement there was no seasonal variation of SE. SE was slightly lower for a certain number of samples compared to when the volume was obtained by the green density.

3.2 Dry weight as a basis to trade roundwood (paper II - V)

3.2.1 Moisture variation and its impact on sampling (paper II)

The study showed that there were high differences in the MC within single discs. The variation in the MC within and between logs, expressed as standard deviations, appeared to be greatest between the logs and least between discs from the same log. These findings were supported by the computed tomography scans of the newly harvested logs.

With the variation in the MC used as a starting point, simulations concerning how the precision was affected when samples were taken in different ways in a pile of pulpwood were undertaken to determine the MC. The results showed that if the aim was to reduce SE, one should focus on taking samples from several different logs. If samples were taken from the same log SE was reduced, but not as much as if samples had been taken from different logs. If several samples were taken from the same disc (i.e. if half or the entire disc was taken), the SE decreased only slightly compared to a one-section sample.

3.2.2 Determination of the MC (paper III - V)

The literature review demonstrated that many techniques have been tested during the past decades. Several techniques were shown to have problems when the samples were frozen or semi frozen. Three techniques were identified that have potential for further investigation, namely, NIR, RF and dual energy X-ray absorptiometry on which further studies were conducted within the scope of this doctoral thesis (paper III).

The result of the measurements with the MDS, based on dual energy X-ray absorptiometry, showed that the measurements to determine MC were dependent on the calibration model used (papers IV and V). When Scots pine was measured with a calibration model developed for Norway spruce the accuracy and precision of the measurements were worse compared to when the same calibration model was used to measure the MC in Norway spruce. When the calibration model ‘softwood’ was used, the accuracy and precision of the measurements were worse compared to when one tree species at a time was measured with its designated calibration model. However, the result was better than when samples of Scots pine were measured with the calibration model developed for Norway spruce. The results of the measurements were not affected if the material was frozen or not. Table 5 shows a summary of the statistics for the different calibration models.

Table 5. *Results from the measurements of moisture content (MC) with the Mantex Desktop Scanner (MDS). MC was determined by the gravimetric method. The standard deviation represents repeatable measurements on the same sample (results from papers IV and V).*

Material	Calibration model	Number of samples	Number of measurement per sample	MC (%)	Standard deviation (% unit)	Standard error of estimate (% unit)	R^2 (%)
Spruce	Spruce	45	10	21 - 56	0.53	1.83	98
Pine	Spruce	70	10	9 - 55	0.45	2.01	98
Pine	Pine	12	6	8 - 55	0.45	1.81	99
Pine and spruce (50/50)	Softwood	6	6	12 - 59	0.77	1.39	99
Pine and spruce (30/70)	Softwood	7	6	8 - 57	0.69	2.30	99
Pine	Softwood	9	6	9 - 56	0.80	2.57	98
Spruce	Softwood	7	6	13 - 59	0.73	1.51	99
All samples	Softwood	29	6	8 - 59	0.75	2.24	99
Spruce (frozen)	Spruce	20	6	12 - 57	0.51	1.46	99
Spruce (unfrozen)	Spruce	20	6	12 - 57	0.66	1.61	99
Total (frozen and unfrozen)	Spruce	40	6	12 - 57	0.59	0.91	99

Figure 7, shows regression lines for the three different calibration models (‘spruce’, ‘pine’ and ‘softwood’) used to measure the MC in the tree species for which they were intended (graph derived from papers IV and V).

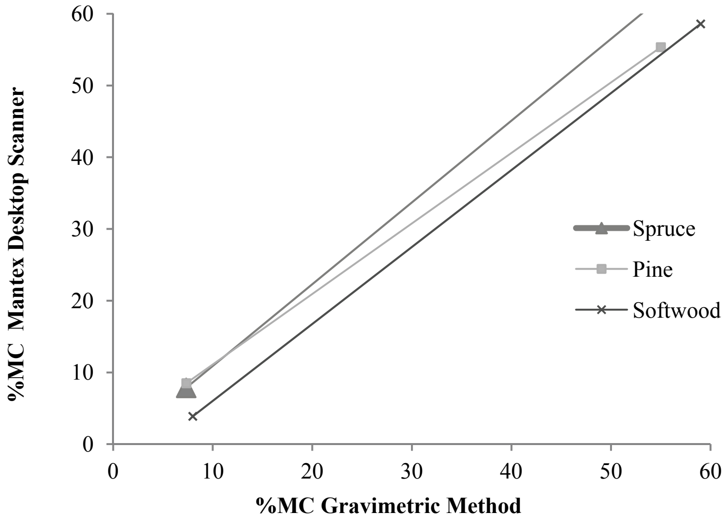

Figure 7. The regression lines for the three different calibration models used by MDS.

The lines differed slightly from a perfect correlation (y = x) for the different calibration models. There were also some differences in the regression lines between the calibration models.

3.3 Sampling techniques (additional study)

Results from the additional study where samples were taken with a modified chain sampler and a chainsaw are presented in Table 6.

Table 6. *The MC from the modified chain sampler, the chainsaw and the corresponding disc that was taken as a reference. Standard deviations for the sampling methods were defined as the standard deviation for the differences in MC between the disc and the sample.*

	MC (%)	Deviation in MC compared to disc (percentage units)	Standard deviation (%) sample	Standard deviation sampling method (%)
		April		
Chain sampler	45.3	- 5.2	6.3	3.3
Chainsaw	49.9	- 0.6	5.9	3.1
Disc	50.5		5.5	
		June		
Chain sampler	41.8	- 2.2	8.8	4.2
Chainsaw	43.0	- 1.0	8.3	3.5
Disc	44.0		5.5	
		October		
Chain sampler	59.8	- 3.0	6.1	2.8
Chainsaw	59.1	- 2.7	4.6	2.0
Disc	61.8		4.6	

The modified chain sampler as well as the chainsaw consistently underestimated the MC compared to the corresponding disc. The deviation between the modified chain sampler and the disc were larger than the deviation for the chainsaw compared to the disc. The standard deviation was larger for the modified chain sampler than for the regular chainsaw.

3.3.1 Precision of the dry weight for a simulated delivery of pulpwood

Values of SE when the dry weight of a delivery of wood was simulated are presented in Tables 7 and 8. The precision was simulated as if samples were taken with the modified chain sampler or with the chainsaw. In both cases the simulation of the precision was performed as if the MC of the samples was determined with the MDS. In Table 7, the precision for a simulated delivery of wood and as if the samples were taken with a modified chain sampler are presented.

Table 7. *SE of a simulated delivery of wood and as if samples were taken with the modified chain sampler. SE is displayed for the three different sampling times, April, June and October, when one sample per log was taken from 1, 5, 10 and 15 different logs from 1, 5, 10 or 15 trucks in a delivery of wood that constituted of 100 trucks in total. The relative SE for June at three different MCs are shown.*

Numbers of trucks sampled	Numbers of samples per truck	SE (% units) April	SE (% units) June	SE (% units) October	Relative SE (%) at different MC, June		
					40	50	60
1	1	8.4	10.6	7.2	17.6	21.1	26.4
1	5	5.7	6.3	5.3	15.8	12.7	15.8
1	10	5.2	5.6	5.0	9.3	11.2	13.9
1	15	5.1	5.3	4.9	8.8	10.6	13.3
5	1	3.7	4.7	3.2	7.8	9.4	11.8
5	5	2.5	2.8	2.3	4.7	5.6	7.0
5	10	2.3	2.5	2.2	4.1	4.9	6.2
5	15	2.2	2.3	2.2	5.8	4.7	5.8
10	1	2.6	3.3	2.2	5.5	6.6	8.3
10	5	1.7	2.0	1.6	3.3	3.9	4.9
10	10	1.6	1.7	1.5	2.9	3.4	4.3
10	15	1.5	1.6	1.5	2.7	3.2	4.1
15	1	2.1	2.7	1.8	4.5	5.4	6.7
15	5	1.4	1.6	1.3	2.6	3.2	3.9
15	10	1.3	1.4	1.2	2.3	2.7	3.4
15	15	1.2	1.3	1.2	2.2	2.6	3.3

June showed the highest values of SE for the different sampling times. Because of that, relative SE at three different MCs (40, 50 and 60 %) was simulated for the month of June with Equation 4. The relative SE increased with increased MC.

In Table 8, the SE for a simulated delivery of wood (100 trucks) when samples were taken with a chainsaw are presented.

Table 8. *SE of a simulated delivery of wood and as if samples were taken with the chainsaw. SE is displayed for the three different sampling times, April, June and October, when one sample per log was taken from 1,5,10 and 15 different logs from 1, 5, 10 or 15 trucks in a delivery of wood that consisted of 100 trucks in total. The relative SE for June at three different MCs are shown.*

Numbers of trucks sampled	Numbers of samples per truck	SE (% units) April	SE (% units) June	SE (% units) October	Relative SE (%) at different MC, June		
					40	50	60
1	1	8.0	9.7	6.6	16.2	19.4	24.2
1	5	5.5	6.0	5.2	10.1	12.1	15.1
1	10	5.1	5.4	5.1	9.0	10.8	13.6
1	15	5.0	5.2	4.9	8.7	10.4	13.0
5	1	3.5	4.3	2.9	7.2	8.6	10.8
5	5	2.4	2.7	2.3	4.5	5.3	6.7
5	10	2.3	2.4	2.2	4.0	4.8	6.0
5	15	2.2	2.3	2.1	3.8	4.6	5.7
10	1	2.5	3.0	2.0	5.1	6.1	7.6
10	5	1.7	1.9	1.6	3.1	3.7	4.7
10	10	1.6	1.7	1.5	2.8	3.3	4.2
10	15	1.5	1.6	1.5	2.6	3.2	4.0
15	1	2.0	2.5	1.6	4.1	4.9	6.2
15	5	1.4	1.5	1.2	2.5	3.0	3.8
15	10	1.3	1.3	1.2	2.2	2.7	3.3
15	15	1.2	1.3	1.2	2.1	2.5	3.2

June showed the highest values of SE for the different sampling times. Because of that, the relative SE at three different MC (40, 50 and 60 %) was simulated for June with Equation 4. As above, the relative SE increased with increased MC. The SE was lower when samples were taken with the chainsaw than with the modified chain sampler. The results from Tables 7 and 8 demonstrate that the reduction in SE was faster if the number of sampled trucks was increased compared to when the numbers of samples per truck was increased.

4 Discussion

4.1 Predicting the green density as a means to achieve the volume of Norway spruce (*Picea abies*) (paper I)

A model was developed to predict the green density of Norway spruce deliveries arriving at Braviken pulp and paper mill. Since the casual model approach didn't give satisfactory results, stepwise regression was chosen as a method. The method could be questioned e.g. that the results are of a tentative nature and the results needs to be confirmed by further studies before using the model in a practical application.

The values predicted by the model showed a good level of concurrence with the measured density values. This was reflected by the low root mean square error (RMSE) for the different years, and for the ratio between measured and predicted values of the density, which was close to 1 for all years.

Norway spruce pulpwood is known to be a homogenous assortment of pulpwood considering the MC, since it has a very strict criterion for freshness (Anon, 2006) due to mechanical pulping processes requiring fresh wood (Nylinder et al., 1995, Sundholm, 1999). If the model was developed or tested for a different assortment of pulpwood it is likely that the result would be less accurate. For a chemical pulp mill that commonly doesn't have the same criteria for freshness, and uses a broader range of species in its production, the variation in green density would increase. The accuracy and precision of a model as presented in Paper I at a chemical pulp mill would probably be lower compared to what was obtained here.

It is claimed by various authors that the variation in the basic density in Sweden increases with decreased latitude (Wilhelmsson et al., 2002, Moberg and Wilhelmsson, 2003, Enger 2005). The increased variation in the basic density would decrease the correlation between green density and volume. This opinion is strengthened by studies performed by Orvér (2001) where he concluded that using green density to obtain the volume only works satisfactorily in the northern part of Sweden. The findings in this thesis were, however, contradictory to Orvér (2001). The results of the model were comparable to those achieved using volume measurement. It is likely that the shortened times between harvesting of the wood and its transportation to the mill and the strict criterion for freshness contributed to the improved results shown here.

In January 2005, the storm Gudrun struck Sweden, and felled 75 million m^3 of forest in the southern parts of the country (Jonsson, 2008). The forest industry was unable to processes all the wood immediately, so the wood was stored and successively processed in following years. Normally, storage increases the variation of the MC in wood (Nylinder, et al., 1995, Filipsson et al., 2002, Ekenstedt et al., 2002). An increase in the standard deviation between measured and the predicted density were seen during 2006 and 2007 compared to the rest of the years analyzed. This was probably a result of storage.

The simulated SE when the green density was used to obtain the volume showed some seasonal variation, with a higher SE during the summer months compared to winter. The variation in SE decreased when the simulated sampling intensity increased. If one hundred samples were simulated, there were no significant seasonal variations to be seen in the SE.

As a rule of thumb, a wood delivery that exceeds 15 000 m^3 volume should be measured with a SE of ≤ 1 % (Orvér, 2001). By using the model to predict the green density, the SE can be determined within ≤ 1 % if 50 – 60 piles were sampled during each period of half a month. In comparison, to reach a SE that was ≤ 1 % for the traditional volume measurement, 30 – 40 piles needs to be sampled and be manually measured. The results showed that using the green density to obtain the volume was almost comparable to the volume measurement with respect to required sampling intensity.

4.2 Dry weight as a basis to trade roundwood

4.2.1 Moisture variation and its impact on sampling (paper II)

The results of the study in paper II demonstrated significant variation of the MC inside single discs, both for the wood upon arrival at the pulp mill and for wood that was newly harvested. The variation of MC, expressed as standard deviation, was greatest between logs, and smallest between discs in the same log. These results were consistent with the findings of Björklund (1988). These results were also supported by the results obtained using logs that were scanned with computed tomography. Further, the scans showed that dehydration of the logs tended to be uneven, thereby increasing the variation already occurring in the living tree. This finding was supported by e.g. (Nylinder, et al., 1995, Filipsson et al., 2002, Ekenstedt et al., 2002). The size of the variation and how the variation of MC occurred within and between logs is of importance for determining how to take samples to determine MC in logs (Marcuse, 1949).

In earlier studies on sampling of wood, one sample per log was taken (Braathe and Okstad, 1964, Okstad, 1971, Björklund, 1988, 1989). One goal in this study was to theoretically calculate how samples should be taken to achieve the greatest precision when sampling to determine MC, with the starting point in MC variations found within and between logs. The result of the study confirmed the sampling procedure used in earlier studies; that the focus should be on taking samples from as many different logs possible rather than taking several samples from the same log (Braathe and Okstad, 1964, Okstad, 1971, Björklund, 1988, 1989). The results further showed that there were rather small differences in SE if one, four or eight sections of a disc were included in each sample. One section of a disc was to represent a sample taken with the chain sampler and four and eight sections were to represent a sample taken with a chainsaw. If the choice of sampling technique was only based on SE caused by the variation of wood, no certain conclusions could be drawn whether to use the chain sampler or a chainsaw.

The study in paper II only included Norway spruce pulpwood. Scots pine and Norway spruce are very similar in their chemical composition and internal structure, while birch deviates in both matters compared to Scots pine and Norway spruce (Bjurulf, 2006). It is likely that the level of MC would differ between species (Björklund, 1988). Since there are chemical and structural differences (e.g. that birch lacks heartwood) one cannot expect that the variation within and between logs are the same for the different species. This suggests that there will be different levels of SE in a certain number of samples dependent on which tree species are sampled.

4.2.2 Determination of the MC (papers III - V)

The results from the literature review suggest that no method fulfilled the requirements of being fast, accurate and able to handle samples that were frozen at the moment. Three methods, RF, NIR and dual energy X-absorptiometry were indicated as being interesting in the future. There is already ongoing research for RF and NIR, and because of that, dual energy X-ray absorptiometry was chosen to undergo further studies (Berg et al., 2005, Duarte da Paz, 2008).

The results from papers IV and V concerning dual energy X-ray absorptiometry showed that it was possible to determine MC in a sample of wood chips with an accuracy of 1.4 – 2.6 % and a precision that ranged between 0.45 – 0.83 %. These results were comparable to what was found by Kullenberg et al. (2010) using the same technique. In comparison, NIR showed an accuracy of 2.0 % and a precision of 2.7 % for a sample of wood chips i.e. similar accuracy but less precision compared to the tested technique (Aulin et al., 2008). The results of the measurements were dependent on which calibration model was used. Table 5, and as can be seen from Figure 7, the regression lines looked slightly different for the different calibration models. Calibration models developed for single tree species (i.e. Scots pine and Norway spruce) showed, in general, better accuracy and precision, than if the calibration model was developed to handle both Scots pine and Norway spruce (calibration model ‘softwood’) simultaneously.

The temperature did not appear to have any effect on measurement of the MC. This is an important feature in the Nordic region, where the wood can be frozen during several months each year. These results are also consistent with what was found by Kullenberg et al. (2010). Studies with other techniques have shown that frozen and partly frozen material might cause problems when determining MC (Blomqvist, 1986, Thygesen, 1996).

Each measurement with MDS took one minute to perform. The benefit of a technique that almost instantaneously gives results is that it provides a more transparent system of wood measurement since the result of the measurement can be completed while the truck is still at the measuring station. Another factor to consider is that MC is an important process parameter in pulp production (Nylinder et al., 1995, Sundholm, 1999). It would therefore be beneficial to be able to sort pulpwood with different MC as it arrives at the pulp mill.

The dual energy X-ray technique can be used to determine the MC in the samples to determine the dry weight of a delivery of pulpwood. However, its biggest potential at the moment is probably to determine MC in chips from sawmills where they are already traded by their dry weight.

4.2.3 Sampling techniques (additional study)

The modified chain sampler that was used in this study was based on the same concept as the original chain sampler used in Germany and earlier studied by Braathe and Okstad (1967) and Björklund (1988; 1989). However, the modified chain sampler was based on an electric chainsaw making it considerably lighter and easier to handle compared to the original chain sampler.

Both the modified chain sampler and the chainsaw consistently underestimated the MC compared to the corresponding disc. The modified chain sampler gave a higher deviation than the chainsaw, (3.6 and 1.7 percentage units respectively); this was the case for all three sampling times. The deviation for the modified chain sampler was higher than what was earlier found (Braathe and Okstad 1967, Björklund, 1988). There might be several reasons for the deviation between samples and the corresponding disc (Braathe and Okstad 1967):

- Samples were drying while sampled due to heating from friction
- An imperfect v-shape of the sword leading to misrepresentative samples
- The tip of the sword was not perfectly placed into the pit of the log

Some further tests were performed to explain the deviations, but no unequivocal explanation was found. Since the regular chainsaw gave a smaller deviation compared to the chain sampler, it is likely that the shape of the sword and the smaller samples that were taken with the modified chain sampler 1/8 of a disc compared to 4/8 of a disc with the chainsaw influenced the results. The smaller deviation for the chainsaw compared to the chain sampler, were also found in an earlier study (Björklund, 1989). The systematic underestimation of the MC that occurred suggests the need for a correction factor, if the equipment is to be used in practice. The size of the correction factor needs to be further studied, since the error varied between the different sampling times.

There was variation in the precision for both sampling techniques during the three different sampling times. The precision of the modified chain sampler was worse than what was earlier reported (Braathe and Okstad 1967, Okstad, 1971, Björklund, 1988, 1989). The result might be explained by the fact that this study consisted of smaller sample size and unfamiliarity with the equipment, which made it difficult to correctly place the sword, which could lead to misrepresentative samples.

Only handheld samplers were included in this study. As presented earlier, there were other techniques to take samples available, e.g. the truck mounted drill. However, since pulpwood is a low value assortment, a solution for a sampler that involves a truck is unrealistic due to the cost and the project with the truck mounted drill is finished.

Precision when pulpwood is scaled according to its dry weight

In earlier studies, common practice has been to take ten samples from each truck (Braathe and Okstad 1967, Okstad, 1971, Björklund, 1988, 1989). In the simulations of the SE in this thesis it was assumed that one, five, ten or fifteen samples from each truck were taken and that one, five, ten or fifteen different trucks were sampled. The results showed that SE decreased faster if the numbers of trucks sampled were increased instead of number of samples per truck. However, if the numbers of sampled trucks were increased, the total time consumption for sampling would probably increase, and the overall cost would therefore increase. The decision whether one should increase the number of samples taken per truck or increase the number of sampled trucks to reach a certain SE must be based on economic calculations.

The Wood Measurement Act and the Swedish Forest Agency state in their regulation that the dry weight of the wood should be determined within 6 % of the true weight (Anon, 1966, Anon, 1999). The required number of trucks that need to be sampled to reach 6 % of the dry weight is shown in Table 9. The SE was calculated as if five or ten samples per truck were taken with the modified chain sampler and the chainsaw. Furthermore, the samples were supposed to be taken from different logs on each truck.

Table 9. *The number of trucks that needs to be sampled if 5 or 10 samples were taken from each truck using either the modified chainsampler or the regular chainsaw, at different MCs to reach a SE of 6%, the requirements of the Swedish Forest Agency (Anon, 1966, Anon, 1999).*

Number of samples per truck	5			10		
MC (%)	40	50	60	40	50	60
Modified chainsampler	4	5	7	3	4	5
Chainsaw	3	4	6	3	4	5

The need for sampling increased with increased MC of the logs. For an entire delivery of pulpwood, there were only small differences between the modified chainsampler and the regular chainsaw, favoring the chainsaw.

Since a delivery of wood in the calculations was assumed to consist of 100 trucks, the results in Table 9 cannot only be expressed as number of trucks but also as percentage and can thereby be applied to any delivery of wood, no matter the size of the delivery.

The SE levels for a given number of samples were similar to earlier studies (Björklund, 1988). Considering that the time between felling and transport to the mill has decreased substantially during the last twenty years (Wilhelmsson and Moberg, 2004), the logical result would have been a reduced variation in the MC and a reduced level of SE. However, the precision of the modified chain sampler was worse than in the previous studies (Braathe and Okstad 1967, Okstad, 1971, Björklund, 1988). Further, the calculations in this study were based on quite a small data set, making the levels rather uncertain. Another possible reason why SE did not decrease as expected compared to earlier studies, is that since not all parameters for Equation 3 were collected in this study, data from Björklund (1988) were used instead of the missing parameters.

It can be found in the literature that the precision is very much dependent on tree species, where birch unquestionable gives the lowest SE for a certain number of samples (Björklund, 1988). If weight scaling with determination of the dry weight is to be used practically at any pulp mill, it is important to have knowledge about the actual conditions concerning the pulpwood used at the specific mill. Attention is to be paid to species used, their level of MC, the level of variation of MC and the variation of MC over the year. A higher variation in MC calls for an increased level of sampling while, a decreased level of variation in MC would result in a decrease of the sampling intensity.

4.3 Concluding discussion

4.3.1 Weight scaling instead of volume measurement: Why now?

There are several reasons why weight scaling should be introduced for pulpwood. At the time of the studies by Björklund (1988, 1989), not all pulp and paper mills were equipped with weighbridges; this has, with time, changed and all mills now have them. Further, no sufficient sampling techniques were available then. The original chain sampler, which is commonly used in Germany, is very heavy and hard to handle. In recent years a regular chainsaw is increasingly considered a realistic alternative to use as a sampler. Another reason is the increased competition for wood from the bioenergy sector. The bioenergy plants are only interested in the dry weight and the MC (to calculate the energy value) of the wood in order to optimize their production. With tightened competition for raw material, uniform scaling methods between the different industries, would not only be preferable from a customer (wood seller) perspective, but also from a process perspective, planning and pricing of the wood. The development of techniques to determine MC makes it now possible to simultaneously determine MC in wood, opening new possibilities to sort the wood upon arrival depending on its MC. Further, awareness of the negative influence a low MC has on the mechanical pulping processes has increased the demand on wood freshness. This increases the likelihood that variation in green density has decreased. Decreased variation increases the possibility of using green density to obtain the volume of the pulpwood with high accuracy and precision.

4.3.2 Benefits of using weight scaling

The general benefit of using weight to scale pulpwood is that it is fast. The weighbridges are considered to be very reliable with high accuracy and precision. The method of weight scaling is considered objective compared to the volume measurement in the sense that the subjective part of determining the solid volume percentage of each pile of wood is not present, also the human interaction in the measurement decreases.

In the performance of traditional volume measurement for pulpwood quality control is present. Deduction from the volume is made for e.g. decay, wrong dimensions etc. Questions could be raised, as to whether quality control is necessary? A parameter such as decay, leads to reduction of the weight and would not need any additional quality control if weight scaling were used (Nilsson, 1990). If the quality control were removed, the time it takes to measure the wood would be significantly reduced and the necessity of measuring station personnel at the mill would be reduced.

The green density

The particular benefits of predicting the green density are that the results of weight scaling can be easily used to obtain the volume of the wood. The volume is commonly used and has a strong tradition in forestry. The trading unit of pulpwood is expressed as m^3ub, and an adaption of all data systems for a new trading unit would not be necessary.

To achieve a high level of accuracy, precision and transparency in green density scaling, samples need to be volume measured. If the measurement is performed as a log-by-log measurement of the sample, this could be done at a time independent of the arrival of the wood. The truck driver is notified that the truck has been chosen for sampling and is directed to unload the wood at a designated area for sampling. The samples could then be measured at any suitable time.

For prompt delivery of the wood after harvest, the forest owner is “rewarded” with a higher weight and the pulp mill would get fresher wood causing fewer problems in the processes (Berg et al., 1995).

Further, the density is an important process parameter in the mechanical pulping process, where the density of the wood has a direct effect on the refining intensity on the fibers (Miles and May, 1990).

The dry weight

The benefits from scaling pulpwood according to its dry weight are that the dry weight is directly correlated with the yield of pulp from the pulping process and this is the method the pulping industry asked for. The method is comparably easy to understand and is less sensitive to variation in the MC (increased variation is overcome with an increased number of samples).

There are now techniques available that can determine the MC in wood quickly and accurately. This also opens new possibilities to e.g. sort wood when it arrives at the mill.

Further, energy assortments are traded according to dry weight. The increased competition for raw material makes the bioenergy companies turn to the pulpwood market. For all parties in the wood market it is of interest to be able to make fair comparisons between the offers from different pulpwood consumers.

4.3.3 Drawbacks with using weight scaling

A common drawback that is indifferent to whether pulpwood is scaled according to its green or dry weight is the presence of quality control. If quality control of the arriving wood is to be performed, benefits such as the reduced need of labor when using weight scaling would be lost to some extent. If quality control was removed, it is believed likely that quality defects such as logs with undersized dimensions would increase. This would lead to e.g. increased breakage in the debarking drum and other process problems. Lack of quality control increases the risk of receiving dirt, soot and other non wanted parameters entering the mill.

Another issue common for both types of weight scaling is the presence of snow and ice during winter time. In the literature it has been reported that ice and snow can contribute as much as 15 % of the total weight of the wood (Björklund, 1989). If dry weight is used it is important that the sample contains a representative amount of the snow and ice that occurs in the load with wood.

The green density

The main drawback with using prediction of the green density to calculate the volume of the wood is that it is less correlated with the yield of pulp from the pulping processes than the dry weight. Further, the model in paper I was developed for Norway spruce pulpwood; as stated earlier, this assortment of pulpwood has very strict rules for freshness, which other assortments lack (Anon 2006). This might result in decreased accuracy and precision for the model when used on other assortments. It is likely that a single model needs to be developed for each assortment and each mill, due to differences in the basic density, logistic solutions etc. For mills having a large import of wood, or using a broader range of species such a model would probably not work.

The model presented in paper I can be hard to understand. The system of wood measurement and independent wood measurement associations is based on credibility of the measurement and its transparency. If the measurement doesn't meet the expectations of the sellers and buyers and they don't understand how the measurement was performed, they will be less likely to trust it.

The dry weight

The drawbacks with using the dry weight to determine the quantity of pulpwood is that the dry weight of an entire load of pulpwood cannot be determined directly, resulting in the need for sampling.

Further, no technique to take samples of roundwood has so far shown to be optimal; further development is needed.

To decide the dry weight of a truck load of wood, the gravimetric method is used, as explained before this is a very tedious process, taking at least twenty four hours. For several reasons, such as transparency and the possibility to sort the wood when it arrives at the pulp mill, it would be preferable to have a method that quickly determines MC in the samples. This would allow the deliverer of the wood to discover potential errors in measurement and a new measurement could be taken. By using the gravimetric method such direct control of measurement is impossible.

It is likely that samples to determine the dry weight of the wood will be taken at the time of arrival of the wood at the mill. This would require staffing during all opening hours of the mill. This would decrease the benefit of a reduced need for personal compared to volume measurement.

Currently volume is used for measuring timber assortment; a change to trading pulpwood according to its dry weight, would result in using two different ways of quantifying wood from the same stand and would result in confusion.

Last, the trading unit for pulpwood is today m^3ub. The weight of the wood includes bark, and so does the determination of the dry weight. Either the trading unit for pulpwood needs to be changed or a conversion factor between dry weight and volume needs to be used. If a conversion factor were to be introduced, this would further decrease the precision of the measurement.

In Table 10, the benefits and drawbacks with quantifying pulpwood according to its green and dry weight are summarized.

Table 10. *Benefits and drawbacks with scaling pulpwood with the help of its weight.*

Method	Benefits	Drawbacks
Volume obtained by the green density	The volume is easily achieved	Volume has weaker connection to with the yield of pulp than the dry weight
	Objective	Might not work for all assortments due to greater variations in the green density
	Volume is commonly used in the forest sector	The model not fully developed yet
	Fast measurement, the truck is weighed and the measurement is done.	Hard to understand the model and the development of it outside wood measurement profession
	Labor extensive	No quality control
	No quality control	
	The density is an important process parameter	Snow and ice
	The trading unit m^3ub is directly obtained	
	Samples can be measured at any time	
	Fast delivery is rewarded	
Dry weight	Requested by industry	MC cannot (yet) be determined for the entire load of wood, samples are needed
	Objective	Further research needed to find a suitable sampling method.
	Strong correlation between yield of pulp and dry weight of wood	Gravimetric method installed, takes long time to determine the MC in samples
	Easy to understand the measuring method	If MC is to be determined simultaneously, investments in an relatively virgin method need to be done
	Fits all assortments	Labor intensive compared to green density
	Technique available to determine the MC on samples simultaneously	No quality control
	No quality control	Trading unit is today m^3ub
	Energy assortments are traded according to its dry weight	Snow and ice Timber is traded according to its volume

4.4 Final remarks

As discussed earlier, the predictions of the green density and by that calculating the volume is likely best suited for mechanical pulp mills using Norway spruce as their raw material. To quantify the wood according to its dry weight would be suitable for both mechanical and chemical pulp mills, regardless of the assortment of pulpwood used. For both weight scaling methods, there are advantages and disadvantages discussed in this thesis. The thesis is not comprehensive in that economic aspects were omitted. The economic aspects are likely to be the deciding factors whether to choose one method instead of another.

The thesis was limited to weight scaling performed at the pulp mill. However, considerable efforts are being made to develop other types of measurements for pulpwood. To measure the volume of the wood already in the forest with the harvester, is one way (Möller, 1998, Karlsson, 2010). To decide the volume of trucks with laser technique is yet another way to quantify pulpwood (Nylinder et al., 2010).

The thesis only focused on determining the quantity of wood, while the quality aspects where left out. If quality control is considered necessary, either each truck is controlled as is done today or a second option is to make a general deduction, where the level of the deduction would be decided from sampling. With this routine, all trucks won´t need to be controlled and the time taken for measurement would be reduced.

In the calculations of the SE, no concern was placed on the error caused by the weighbridges. In paper IV, the greatest acceptable deviation for a weighbridge, was listed at ± 60 Kg if the load were 40 tons or more (Högberg, 2008). In practice, the error of the weighbridge is negligible compared to the error derived from sampling to determine the dry weight of the load or the error caused by the prediction of the green density.

5 Conclusions

The main conclusions from this doctoral thesis are that it is possible to build a statistical model that can predict the green density of Norway spruce with the help of meteorological data at a certain pulp mill. It was shown that the quantity of wood could be determined well within the limits set by the Swedish Forest Agency and gave comparable results with the volume measurement performed today by using such a model.

To scale the wood according to its dry weight also fulfilled the requirements from the Swedish Forest Agency. This method is less sensitive to the freshness of the wood and would be suitable for all assortments of pulpwood.

The thesis showed that the variation of MC can be substantial inside a single disc and between pulpwood logs. The variation affected how many samples are to be taken and how they were to be taken to reach a certain SE for the determination of the dry weight.

Further, it was shown that determination of MC with dual energy X-ray absorptiometry showed good concurrence with the gravimetric method that is commonly used today. Each measurement took one minute to perform and the results were unaffected whether the samples were frozen or not. The precision and accuracy of the technique varied with the different calibration models used. A calibration model developed for a specific tree species provided better accuracy and precision than a calibration model developed to handle both Scots pine and Norway spruce. The greatest use of this application would, at the moment in Sweden, be for sawmill chips.

The different techniques to take samples showed that it was a slight improvement to use a regular chainsaw compared to a modified chain sampler. However, both techniques were associated with systematic errors.

6 Further research

The model was created by using stepwise regression. Normally the results achieved by this method are of a tentative nature and need to be further studied. The study to obtain volume by using the weight and green density was made on a relatively small data set in the sense that only one pulp mill was represented. It would be of interest to apply the models created to material from other pulp mills and other assortments of pulpwood, not only Norway spruce.

Even though dry weight is commonly used in several countries, there is no practical, well studied method to take samples from roundwood. The original chain sampler that is used in many places, such as in Germany, poses problems - the studies available are quite old and furthermore the equipment is heavy and hard to handle. Research to develop new equipment that is accurate and easy to handle is of great interest if dry weight is to be a practical option. The chainsaw gave slightly better results as compared to the modified chain sampler. However, there was a systematic error that needs to be further studied and quantified. Also, a regular chainsaw, as it has been used in this thesis, is probably not consistent with Swedish work and environmental laws, and would need some kind of suspension, such as for the original chain sampler in Figure 1.

The variation in MC within and between logs was shown to be substantial, this suggests that the MC needs to be further studied for all assortments of pulpwood and for a larger sample of material.

A suggestion for further research regarding the dual X-ray energy absorptiometry device would be to set up a mill trial where the technique is used in parallel with the gravimetric method for some time on sawmill chips that arrive.

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