The impact of mechanical log surface damage on fibre loss and chip quality when processing *Eucalyptus* pulpwood using a single-grip harvester

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DECLARATION

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Abstract

Mechanised harvesting operations are growing in popularity in South Africa, as motor-manual and manual harvesting operations pose significant health and safety risks to workers. Potential damage inflicted by single grip harvester feed rollers and delimbing knives on the log surface during debranching and debarking eucalypts, may affect fibre recovery and chip quality. Chip quality is important as it influences pulp quality and recovery in the kraft pulping process. The study investigated the influence of two mechanised debarking treatments in eucalypts (three feed roller passes and five feed roller passes along the stem surface) with feed roller induced log surface damage on chip uniformity, size, purity and wood fibre loss. The two mechanised treatments were compared against chips produced from manually debarked logs. In addition, the effect of two log drying periods (one week and two weeks) and three log sections (base, middle and top logs) on chip quality were also analysed. An economic evaluation was conducted to quantify potential recoverable pulp value losses associated with debarking treatments and log drying periods.

Logs subject to manual debarking produced significantly less undesired sized chips than both three pass and five pass mechanically debarked logs. Potential recoverable pulp revenue for chips produced from five pass and three pass mechanically debarked logs were valued at R 60.54 BDt^{-1} and R 50.90 BDt^{-1} less than wood chips produced from manually debarked logs. Two week dried logs produced significantly less under-sized chips than chips produced from one week dried logs. However, two week dried logs produced wood chips with significantly more over-thick chips than logs dried for one week. The volume of undesirable sized chips produced during chipping increased with decreasing log size. Potential recoverable pulp revenue for chips produced from one week dried logs were valued at R 137.90 BDt^{-1} less than chips produced from two week dried logs.

Manually debarked logs produced chips with significantly less bark content than three pass mechanically debarked logs (0.008 % vs 0.062 %). Five pass mechanically debarked logs produced chips with significantly less bark content than three pass mechanically debarked logs (0.018 % vs 0.062 %). Middle logs also produced chips with significantly less bark content than base logs (0.016 % vs 0.056 %). Top logs produced chips with significant less bark content than base logs (0.017 % vs 0.056 %). In all cases the bark content was considerably less than the maximum of 1.0 % generally specified by kraft pulp mills.

Both three pass and five pass mechanically debarked trees caused significant fibre losses of 2.6 m^3 ha^{-1} and 5.1 m^3 ha^{-1} respectively. Wood fibre losses in terms of total extractable wood volume for three and five pass mechanically debarked trees were 0.8 % and 1.6 % respectively.

Opsomming

Meganiese-houtontginningsoperasies is besig om te groei in populariteit omdat ontginnings operasies (waar ontginning en ontbassing met die hand toegepas word) geweldige gesondheids-en veligheidsrisiko's tot gevolg het. Potensiële skade aan die oppervlakte van stompe, veroorsaak deur enkelgreepontginnerdeurvoeringsrollers en onttakkingsmesse tydens onttakking en ontbassing van eucalypts, mag 'n invloed hê op die hoeveelheid houtvesel wat verlore gaan sowel as aan die kwaliteit van die houtskyfies. Die produksie van goeie kwaliteit houtskyfies is belangrik, omdat dit die kwaliteit en omset van die pulp tydens die "kraft" pulpproses sal beïnvloed. Die studie het die invloed van twee meganiese ontginningbehandelings van die eucalypts (waar die deurvoeringsrollers drie keer oor die stomp oppervlakte beweeg het en waar die deurvoeringsrollers vyf keer oor die stomp oppervlakte beweeg het), en die skade wat aan stompoppervlaktes aangerig is deur die ontginnerdeurvoeringsrollers, ondersoek. Die studie ondersoek hoe die ontginningbehandelings die grootte, uniformiteit en suiwerheid van houtskyfies beïnvloed asook die hoeveelheid houtvesel wat verlore gaan tydens hierdie behandeling(e). Die houtskyfies wat geproduseer is tydens die meganiese-ontginde stompe is vergelyk met die houtskyfies wat geproduseer is van stompe wat met die hand ontbas is. Die studie ondersoek ook twee afsonderlike stompdrogingsperiodes (stompe wat afsonderlik gedroog is vir een en twee weke) en drie verkillende stompporsies van die boom (basis-, middel-en topstompe) en hoe dit die kwaliteit van die geproduseerde houtskyfies beïnvloed. 'n Ekonomiese analise is toegepas op die potensiële finasiële waarde van pulp wat verlore gaan a.g.v. verskillende ontbassingstegnieke en stompdrogingsperiodes.

Stompe wat met die hand ontbas is, het opmerklik minder onder-grootte houtskyfies (te klein vir pulpproduksie) geproduseer in vergelyking met die stompe wat meganies ontbas is (waar die deurvoeringsroller buide drie en vyf keer oor die stomp oppervlakte beweeg het). Potensiële finansiële inkomste deur die ontginbare pulp van houtskyfies geproduseer deur die meganiese ontbaste stompe (waar deurvoerings rollers beide vyf en drie keer oor die stomp se oppervlakte beweeg het), het 'n waarde van R 60.54 BDt^{-1} en R 50.90 BDt^{-1} onderskeidelik gelewer. Stompe wat gedroog is vir twee weke het opmerklik minder houtskyfies (te klein vir pulpproduksie) geproduseer as stompe wat vir een week gedroog is. Die hoeveelheid van ongewensde grootte houtskyfies wat geproduseer is, het toegeneem met 'n afname in stompgrootte. Potensiële finansiële inkomste deur die ontginbare pulp van houtskyfies geproduseer deur die stompe wat vir een week gedroog is, beloop R 137.90 BDt^{-1} minder as houtskyfies wat geproduseer is van stompe wat vir twee weke gedroog is.

Stompe wat met die hand ontbas is, het houtskyfies geproduseer met opmerklik minder basinhoud as houtskyfies wat geproduseer is van stompe wat meganies ontbas is (was waar die deurvoerings rollers drie keer oor die stomp oppervlakte beweeg het)(0.008 % teenoor 0.062 %). Houtskyfies wat geproduseer is van meganiese ontbaste stompe (waar

die deurvoerings rollers vyf keer oor die stomp oppervlakte beweeg het), het ook opmerklik minder basinhoud gehad as houtskyfies wat geproduseer is van meganiese ontbaste stompe (waar die deurvoeringsrollers drie keer oor die stompoppervlakte beweeg het)(0.018 % teenoor 0.062 %). Houtskyfies geproduseer van middelporsiestompe het minder basinhoud gehad as houtskyfies geproduseer van basisporsiestompe (0.016 % teenoor 0.056 %). Topporsiestompe het ook houtskyfies geproduseer met minder basinhoud as basisporsiestompe (0.017 % teenoor 0.056 %). In al die bogenoemde gevalle is die houtskyfiebasinhoud geweldig laer as die houtskyfiebasinhoudspesifikasies van “kraft” pulp meule wat ‘n basinhoud van 1.0 % vereis.

Beide meganiese-ontbassingstegnieke (waar deurvoeringsrollers beide drie en vyf keer oor die stompoppervlakte beweeg het), het onderskeidelik 2.6 m^3 ha^{-1} en 5.1 m^3 ha^{-1} houtvesel verloor. In terme van die totale persentasie van ontginbare houtvesel wat per boom verlore gegaan het, het meganiese ontbaste bome (waar deurvoeringsrollers drie keer en vyf keer oor die stomp oppervlakte beweeg het) onderskeidelik 0.8 % en 1.6 % van die boom se houtvolume verlore laat gaan.

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1. Introduction

1.1. Background and Justification

Commercial forestry is practiced on 1.273 million ha or 1.1 % of South Africa's total surface area (FSA, 2013). South African commercial forests serve various wood based industries of which the pulp and paper industry is the largest (FES, 2011; FSA, 2013). During 2011 the industry produced a total18.5 million m^3 of roundwood, of which 12.6 million m^3 was harvested for pulp and paper production (FSA, 2013). Revenue for these roundwood sales amounted to R 4.5 billion and pulp product sales from primary processing plants was R 12.9 billion (FSA, 2013). Fast growing eucalypt hardwood species, produces 83 % of wood resources used for pulp and paper manufacturing (FES, 2011).

Mechanised harvesting operations show an increasing trend in South Africa, as motor-manual and manual harvesting operations pose significant health and safety risks (Wästerlund, 1998; Marras, 2000; Lilley *et al.,* 2002; Thelin, 2002; Scott and Christie, 2004; Christie, 2006; Çalışkan and Çağlar, 2010). In addition, elevated levels of HIV/Aids and malnutrition in rural forestry areas, has had an impact on the supply of a healthy and productive labour force for, manual and motor-manual timber harvesting operations (Bollinger and Stover, 1999; Bourne *et al.,* 2002; Drimie, 2002; Manyuchi and Pulkki, 2002; Shackleton *et al.,* 2007; Pogue, 2008).

Certain challenges are being faced by the pulpwood producers with regards to mechanisation. Amongst others the harvester head feed rollers and delimbing/debranching knives impact the log surface (Figure 1 and 2), and can effect fibre recovery and chip quality (i.e., thickness, size distribution and chip fracturing). Chip quality is important as it influences pulp recovery and quality in kraft pulping (Macleod, 2007).

Chip size distribution and moisture content (MC) uniformity are important for maximising pulp yield. Chip quality, size, uniformity and MC allow for uniform "cooking" conditions in pulping digesters as under-sized chips tend to be over-cooked, thus decreasing yield and fibre strength, while over-sized chips are under-cooked (Tikka *et al.,* 1993; Hartler, 1996; Broderick *et al.,* 1998; Svedman *et al.,* 1998; Tessier *et al.,* 1999; Ding *et al.,* 2005; MacLeod, 2007; Balakrishnan, 2008; Clarke *et al.,* 2008; Dang and Nguyen, 2008; Färlin, 2008; Hellström, 2010; Patt *et al.,* 2012). Under-cooked chips give rise to fibre bundles (shives) in the pulp mix. Shives need secondary processing, leading to decreased financial return (Tikka *et al.,* 1993; Hartler, 1996; Tessier *et al.,* 1999; Ding *et al.,* 2005; Bjurulf, 2006; MacLeod, 2007; Dang and Nguyen, 2008; Färlin, 2008; Hellström, 2010). The over-production of pins, fines and over-sized chips (which can however be re-chipped) represents wasted or lost fibre.

Figure 1: Log surface damage inflicted by harvester head feed rollers and delimbing knives.

Figure 1: Log surface damage in smaller diameter logs inflicted by harvester head feed rollers and delimbing knives.

1.2. Significance of study

Land use for forestry purposes is regulated by water licences and land reform policies. Water licences are aimed at limiting the influence of tree growth on stream flow reduction in catchment areas, while land reform policies place pressure on private forestry companies to transfer land subject to land claims to previously disadvantaged communities (van der Zel, 1995; Scott *et al.,* 1998; Kepe, 1999; Weiner and Harris, 1999; Le Maitre *et al.,* 2000; Wily and Mbaya, 2001; Le Maitre *et al.,* 2002; Görgens and van Wilgen, 2004; Hall, 2004; Nel *et al.,* 2004; Dye and Versfeld, 2007). For these reasons it is important to maximise timber recovery during timber harvesting, as there is little opportunity of new afforestation in South Africa.

Maximisation of timber recovery is directly related to the loss of wood fibre during timber harvesting and associated operations. Chip quality is expressed in terms of chip size distribution, thickness, fracturing, and contamination (e.g., bark, knots, rot), which influence the homogeneity of cooking conditions during kraft pulping. Wood fibre loss occurs during mechanised debarking operation of eucalypts, when the log surface is damage by feed rollers and delimbing/debarking knives, and wood fractions are separated from the log surface. These fibre losses during mechanised cut-to-length timber harvesting operations have not been quantified and therefore needs closer study.

1.3. Objectives

This study aims to investigate the influence of three debarking techniques, two log drying periods and three log size classes on industrial eucalypt chip production in relation to:

- Chip size distribution including any fracturing
- Log surface damage and fibre recovery
- Chip MC uniformity
- Chip bark content

In addition an economic evaluation was performed to quantify:

- How the log drying periods and debarking treatments affect chip size, uniformity and pulp yield revenues.
- How log drying periods and mechanical debarking treatments affect fibre loss and impact wood fibre revenues.

These variables influence pulp yield and quality, in pulp manufacturing. A Maskiner SP 591LX one-grip harvester head mounted on a tracked Hitachi IS200 is the mechanised component used in this study on the Zululand coastal plain of South Africa.

2. Literature review

2.1. Wood is a heterogeneous material

Wood is a heterogeneous material and its inherent characteristics do not only vary between individual trees, but also within a single tree. In addition the cell anatomy of hardwood is more diverse than that of softwood creating complex challenges in relation to pulp quality control (Cotterill and Macrae, 1997; Clarke, 2001; MacLeod, 2007; Clarke *et al.*, 2008; Magaton *et al*., 2009; Niedźwiecki, 2011). These variations include fibre properties, inherent MC, knot content due to branch frequency and size and basic wood density (Pulkki, 1991; Jorge *et al*., 2000; Clarke, 2001; Hicks and Clark, 2001; Ona *et al*., 2001; Pulkki, 2001; Malan, 2003, Jonsson *et al*., 2004; Ding *et al*., 2005; Bjurulf, 2006; Naidoo *et al*., 2007; Hellström, 2008; Retief and Stanger, 2009; Shashikala and Rao, 2009; Hellström, 2010; du Plessis, 2012).

2.1.1. Wood density and fibre properties

Tree species are separated by anatomical structures, which are concentrically banded throughout the tree. These structures include: the pith, heartwood, sapwood, vascular cambium, inner bark and outer bark (Wiedenhoeft, 2005; Niedźwiecki, 2011). Each structure is different in terms of fibre morphology, basic density and pulp recovery (Pulkki, 1991; Ona *et al*., 2001; Malan, 2003; Miranda *et al*., 2007; Naidoo *et al*., 2007). Differences in structural timber properties have been observed in the horizontal and vertical directions of the tree bole for eucalypt species (Ona *et al*., 2001; Githiomi and Kariuki, 2010). For hardwoods, including eucalypt species, wood density increases with height and from the pith outwards (Jorge *et al.,* 2000; Megown *et al.,* 2000; Naidoo *et al.,* 2007; Shashikala and Rao, 2009; Githiomi and Kariuki, 2010; du Plessis, 2012).

In eucalypts, sapwood is denser than heartwood, and has longer fibres (Bhat *et al.,* 1990; Jorge *et al.*, 2000; Shashikala and Rao, 2009). Eucalypt heartwood also has more chemical extractives and therefore has a lower pulp yield when compared to sapwood (Venter, 2003; Miranda *et al*., 2007; Magaton *et al*., 2009; Githiomi and Kariuki, 2010). Variations in the proportion of heartwood and sapwood have been observed with tree height (Pulkki, 1991; Miranda *et al.,* 2007; Raymond and Muneri, 2000; Githiomi and Kariuki, 2010).

Regarding eucalypt plantations, basic wood density varies in relation to stand structure, tree age, tree form, growing conditions and applied silviculture practices (Kibblewhite *et al*., 1991; Cotterill and Macrae, 1997; Raymond and Muneri, 2000; Malan, 2003; Venter, 2003; Jonsson *et al*., 2004; Drew and Pammenter, 2007; Gava *et al*., 2008; Magaton *et al*., 2009; du Plessis, 2012; Lottering and Mutanga, 2012). The mean weighted basic wood density for plantation grown eucalypts increases with stand age, at low stocking and fertilizer treatments, and decreases with an increase in water availability (Megown *et* *al.,*2000; du Toit *et al.,* 2001; Wimmer *et al.,* 2002; Little *et al.,* 2004; Naidoo *et al.,* 2007; Gava *et al.,* 2008; Santos *et al.,* 2008; du Plessis, 2012). Therefore it is no surprise that South African hardwood kraft pulp producers have pulp yields ranging between 42 - 50% (Nice, 2012). Pulp yields of up to 57.5 % have however been recorded for *Acacia mearnsii* chips (McEwan, 2004; Nice, 2012). Wood characteristics of chips produced can only be as uniform, as the raw timber resource allows (Twaddle, 1997). Therefore, it is important to control and regulate timber stocks, to obtain a raw timber resource which is as homogenous as possible (Hellström, 2010).

2.1.2. Bark properties

Bark can be divided into two parts: outer and inner bark. Outer bark protects the inner bark and vascular cambium, which in turn facilitates the transportation of photosynthetic produced sugars from the tree crown to growth regions throughout the tree (Retief and Stanger, 2009; Niedźwiecki, 2011). Bark represents a smaller portion of the total above ground tree biomass as trees grow older and larger (Dye *et al.,* 2004). Bark properties vary between individual trees and within single trees in terms of bark type and thickness (Burrows, 2002; Niedźwiecki, 2011). Bark thickness generally decreases with tree height and *E. grandis* × *urophylla* trees grown in the Kwambonambi region of South Africa have a bark thickness ranging from 15.5 mm at the base of the tree and 3.5 mm in the crown (Shashikala and Rao, 2009). Retief and Stanger (2009) mention that debarking efficiency is perceived to be more related to bark type and texture, than to bark thickness. However no studies have been done to support this statement and Retief and Stanger (2009) also do not qualify their finding with an analysis of bark type and bark textrure, and their influence on the debarking efficiency of eucalypts.

2.1.3. Knot content

Knot content is a function of branch frequency and size (Malan, 2003). For eucalypts, branch sizes increase with tree height (Dye *et al.,* 2004; Kearney *et al.,* 2007). Knot content will therefore proportionally increase with tree height and decrease with age (Dye *et al.,* 2004; Kearney *et al.* 2007). High planting densities and branch pruning can potentially reduce wood defects associated with branches (Malan, 2003; Kearney *et al*., 2007).

2.2. Log moisture loss

Log MC influences mechanical wood properties such as wood hardness, strength and processing ability (Niedźwiecki, 2011). Post harvesting log drying rates are influenced by inherent physical log properties, storage variables and climatic conditions.

2.2.1. Physical log properties

Physical log properties such as log size (length and diameter), degree of debarking required, and potential log surface damage, and wood density, influence moisture loss efficiency. Logs with bark experience slower moisture loss as opposed to debarked logs or tree sections (Connel, 2003; Defo and Brunette, 2007; Röser *et al*., 2011). Sapwood is more exposed to climatic elements after debarking and therefore has higher moisture loss rates when compared to heartwood (Defo and Brunette 2007; Färlin, 2008).

2.2.2. Log storage variables

Freshly harvested logs lose moisture while in storage either in the plantation, at roadside or at the mill (Röser *et al.,* 2011). Various storage practices such as stack geometry, orientation to sun and wind, locality and individual log exposure will either accelerate or inhibit log drying efficiency (Persson *et al.*, 2002; Defo and Brunette, 2007; Färlin, 2008; Gjerdrum and Salin, 2009; Röser *et al.,* 2011). Smaller log stacks dry quicker due to higher degrees of log surface exposure and log stacks sheltered from the wind and sun will have slower drying rates (Persson *et al.,* 2002; Defo and Brunette, 2007; Färlin, 2008).

2.2.3. Climatic conditions

Seasonal variations in temperature, precipitation, relative humidity, wind speed and wind direction will influence log drying rates (Gjerdrum and Salin, 2009; Defo and Brunette, 2007; Röser *et al*., 2011). Log moisture loss is greater at higher ambient temperatures, low atmospheric humidity and/or when logs are exposed to a prevailing wind (Persson *et al.*, 2002; Connel, 2003; Defo and Brunette, 2007; Gjerdrum and Salin, 2009; Röser *et al*., 2011). Precipitation replenishes log moisture and will reduce moisture loss (Defo and Brunette, 2007; Gjerdrum and Salin, 2009; Röser *et al*., 2011).

2.3. Log surface damage

Bark accounts for 10% - 20% of the tree bole volume (Patt *et al.,* 2012). Damage to the log surface can be caused by mechanical delimbing and debarking. This can potentially lead to fibre losses and inferior raw timber quality (Bjurulf, 2006). In South Africa eucalypts are debarked prior to pulping as bark interferes with the pulp digesting process and in turn reduces paper strength (Patt *et al.,* 2012). According to Biermann (1996) and Patt *et al*. (2012) the mean bark content value in wood chips should be limited to about 0.3% - 0.5% for pulp production. However, the kraft pulping process is more tolerant to higher bark content, than the mechanical, chemi-mechanical and semi-chemical pulping processes (Biermann, 1996 (b)). Although no exact value for maximum bark content could be found in the literature, kraft mills generally set a maximum bark content allowed at 0.8 % to 1.0 %.

A wide variety of mechanical debarking technologies have been developed to cater for diverse mill quality specifications, site conditions and physical tree properties. The most popular mechanical debarking technologies include: ring debarkers, drum debarkers, flail delimber-debarkers, mechanised processors and harvester heads. Each debarking technology has its own inherent strengths and weaknesses, and need to be aligned with challenges faced during debarking operations and for specific purposes. Factors influencing log surface damage during debarking operations have been investigated internationally and are discussed below.

2.3.1. Mechanised debarking technologies

2.3.1.1. Ring debarker

During ring debarking logs are debarked by means of debarking knives. A ring mounted with tool arms rotate around the log, cutting and scraping bark from the log surface (Bassler, 1987; Araki, 2002; Laganiére and Hernandéz, 2005; Laganiére and Bédard, 2009; Eggers, 2010). The amount of pressure exerted by the knives influences the amount of fibre loss that can be expected during the process.

Laganiére and Hernandéz (2005) investigated the influence of radial forces applied to the log surface and tool arm path overlap on ring debarking efficiency of frozen balsam fir logs. They found that log surface damage was more severe when increasing radial forces were applied to the log surface and tool arm tips overlapped during debarking. More surface damage was also recorded on the thin ends of the logs. They also found that debarking efficiency was lower for frozen logs.

Laganiére and Bédard (2009) studied the effect of log temperature on bark/wood bond strength (BWBS) when debarking balsam fir and black spruce logs with a ring debarker. With an increase in BWBS, debarking efficiency decreased.

2.3.1.2. Drum debarker

Drum debarkers are able to debark multiple logs simultaneously, and are usually located at processing plants due to their size and the infrastructure required to run them. Logs are loaded into the cylindrical rotating drum causing friction between the tumbling logs which in turn causes the bark to be dislodged from the log surface.

Öman (2000) studied the influence of individual log characteristics when exposed to drum debarking of mixed pine and spruce pulpwood logs in Sweden. A strong relationship was found between log MC and BWBS which increased with decreasing log MC. Other physical tree properties influencing debarking efficiency included log length and diameter, bark type, stem form, log straightness and inherent knot frequency. He advised to separate trees according to species and log MC prior to debarking to ensure more efficient debarking and less fibre loss due to the friction between the logs.

Baroth (2005) in an extensive literature review on the latest developments of wood debarking focused on how log MC, tree species and log size influence debarking quality during drum debarking. He concluded that the debarking efficiency of logs was strongly influenced by BWBS, which increased with decreasing log MC and temperature. Wood fibre losses associated with drum debarkers were also influenced by the position of the closing gate of the drum, drum rotation speed, drum capacity and the time logs spend in the drum being debarked.

Isokangas (2010) analysed how process parameters during drum debarking affect bark removal, wood loss and chip quality at a Finnish kraft mill. Pine, spruce, birch and aspen trees were studied. It was found that aggressive debarking by increasing the rotation speed of the drum increased wood fibre losses. Once again the interaction of drum capacity, log positioning and tree characteristics influenced debarking efficiency and fibre loss.

2.3.1.3. Flail delimber-debarker

Chain flail delimber-debarkers (CFDD) are more mobile and are normally located at the harvesting site. Multiple trees are normally simultaneously fed horizontally into the delimber-debarker, where they are delimbed and debarked by flails (chains) attached to rotating drums. Chain lengths and drum rotation speeds vary according to the product required by the manufacturer and the tree species being debarked.

Bassler (1987) quantified the influence of three mobile CFDD on chip quality for hemlock, lodge pole pine and Douglas-fir located in the Pacific Northwest of America. He found that chip quality was influenced by both log surface damage and tree size from operations of the CFDD. CFDD design and settings of the flail length, flail drum size, log feed platform, and the degree of flail contact with logs and flail drum rotating speeds affect the degree of log surface damage, debarking efficiency and fibre loss and hence chip quality. Bassler (1987) found that debarking logs of equal dimension reduced fibre loss and increased debarking efficiency, and that fresh logs (>MC) were debarked quicker and more efficiently and with less damage to the log surfaces.

2.3.1.4. Mechanical harvester and processor heads

Mechanical harvester heads when used for the harvesting of eucalypts fell, debranch, debark and cross-cut trees into log assortments, while processor heads are limited to just debranching, debarking and producing log assortments when and where required. Cutting knives on the feed rollers apply pressure to the log surface to loosen the bark from the log surface (Hartsough *et al.,* 1996). Delimbing/debarking knives then remove branches and scrape bark free from the log surface.

Connel (2003) characterised different types of log damage during mechanical harvesting and processing operations of eucalypt sawlogs in Australia. Log surface damage caused by feed rollers was classified as chatter in his publication. Chatter is caused when the harvester head feed rollers cutting knives cut into (penetrate) the log surface (Figures 1 and 2).

Previous studies have found that feed roller type, tree size and species have a significant impact on log surface damage and fibre loss, when debranching stems (Connel, 2003; Brunberg, 2006; Gerasimov & Seliverstov, 2010; Sveningsson, 2011; Nuutinen *et al.*, 2010). However no research was found regarding the influence of harvesters on log surface damage and fibre loss for eucalypt roundwood logs used in kraft pulping, as these logs are normally debarked at the stump site.

2.3.2. Common findings

Despite diverse approaches in debarking technological designs, similar conclusions have been drawn with regard to the factors influencing log surface damage, fibre loss and debarking efficiency. Findings include:

- Debarking efficiency vary between debarking technologies (Hartsough *et al.*, 1996; Araki, 2002; Eggers, 2010).
- Log surface damage and fibre losses are greater when debarking smaller sized logs and/or thin ends of trees (Bassler, 1987; Pulkki, 1991; Hartsough *et al.*, 2000; Öman, 2000; Araki, 2002; Baroth, 2005; Laganiére and Hernandéz, 2005; Bjurulf, 2006; Nuutinen *et al.*, 2010).
- With higher pressure settings and log friction, log surface damage and fibre loss increases (Bassler 1987; Pulkki, 1991; Myhrman, 2000; Araki, 2002; Baroth, 2005; Laganiére and Hernandéz, 2005; Gerasimov and Seliverstov, 2010; Isokangas, 2010; Nuutinen *et al.*, 2010).
- Log MC and climatic conditions influence BWBS (Pulkki, 1991; Twaddle and Watson, 1992 (c); Öman, 2000; Eggers, 2010; Isokangas, 2010; Araki, 2002; Persson *et al.*, 2002; Dye *et al.*, 2004; Chow and Obermajer, 2004; Baroth, 2005; Laganiére and Hernandéz, 2005; Bjurulf, 2006; Färlin, 2008; Laganiére and Bédard, 2009; Gerasimov and Seliverstov, 2010; Nuutinen *et al.*, 2010; Murphy and Pilkerton, 2011).
- Debarking efficiency is directly proportional to fibre loss and chip bark content (Bassler, 1987; Öman, 2000; Araki, 2002; Bjurulf, 2006; Laganiére and Bédard, 2009; Isokangas, 2010).
- Log debarking efficiency is directly proportional to BWBS (Öman, 2000; Araki, 2002; Persson *etal.*, 2002; Chow and Obermajer, 2004; Baroth, 2005; Laganiére and Hernandéz, 2005; Laganiére and Bédard, 2009; Isokangas, 2010; Nuutinen *et al.*, 2010; Murphy and Pilkerton, 2011; Sveningsson, 2011; Röser *et al.*, 2011).

2.4. Chipping technology

Chip size and uniformity during chip production is affected by individual log size and MC, the amount and extent of log surface damage during debarking, chipper specifications and design, and chipper knife maintenance (e.g., knife sharpness)(Bassler, 1987; Twaddle and Watson, 1992(a); Twaddle and Watson, 1992(b); Twaddle and Watson, 1992(d); Qian *et al.,* 1994; Araki, 2002; Bjurulf, 2006; Hellström, 2008; Isokangas, 2010). It is thus important to distinguish between chipping equipment used and their settings, which include log feeding angle, log feeding speeds, knife sharpness, knife angles, anvil clearance, anvil wear and disc rotation speeds as these variables will influence chip size and uniformity during chip production (Twaddle and Watson,1992(b); Twaddle and Watson, 1992(d); Uhmeier, 1995; Hartler, 1996; Twaddle, 1997; Uhmeier and Persson, 1997; Hartsough *et al.,* 2000; Laitinen, 2001; Spinelli and Hartsough, 2001; Bjurulf, 2006; Hellström, 2008; Hellström, 2010; Isokangas, 2010; Niedźwiecki, 2011; Isaksson *et al*., 2013). An understanding of chipping technology is important to ensure the production of wood chips with maximum accept chip content.

2.5. Chip quality and chip recovery rate

Processing efficiencies and pulp yield can be directly related to chip quality, as chip quality plays an important role in mill pulp recovery (MacLeod, 2007). The quality of chips derived from chippers are expressed in terms of chips size distribution; i.e., the percentage of accept chips, prime chips, over-size chips, over-thick chips, pins, fines and whether the chips contain any impurities in the form of bark, knots and rot (Pulkki, 1991; Twaddle and Watson, 1992(a); Twaddle and Watson, 1992(b); Twaddle and Watson, 1992(c); MacLeod *et al.,* 1995; Uhmeier, 1995; Hartler, 1996; Uhmeier and Persson, 1997; Broderick *et al.,* 1998; Tessier *et al*., 1999; Bjurulf, 2005; Ding *et al.,* 2005; Bjurulf, 2006; MacLeod, 2007; Balakrishnan, 2008; Färlin, 2008; Hellström, 2010; Mafia *et al.,* 2012; Patt *et al*., 2012). In kraft pulping, chemical penetration times vary in relation to chip size, thickness and uniformity. Uniform chips lead to more uniform pulping conditions and higher pulp recovery (Pulkki, 1991; Broderick *et al.,* 1998; Ding *et al.,* 2005; Färlin, 2008). Chip sizes and fractions are characterised as follow:

- Fines can fit through a 3 mm round hole (rh) screen, while pins fit through a 7 mm rh screen, but will be retained on the 3mm rh screen (Biermann, 1996 (a); Hartler, 1996; Färlin, 2008; Niedźwiecki, 2011). Both of these size classes cause processing difficulties in continuous digester kraft pulping (Clarke *et al*., 2008). The fibre strength and yield of pin chips and fines will also be inferior due to over-cooking (Tikka *et al.,* 1993; Hartler, 1996; Broderick *et al.,* 1998; Tessier *et al.,* 1999; Balakrishnan, 2008;Ding *et al.,* 2005;MacLeod, 2007; Färlin, 2008; Clarke *et al.,* 2008;Hellström, 2010; Patt *et al.,* 2012).

Chips used for kraft pulping in continuous digesters should be limited to a maximum pin chip and fines content of 8 - 11 % (Hartler, 1996).

- Small sized accept chips will fit through a 13 mm diameter rh screen and retained on the 7 mm rh screen (Biermann, 1996 (a); Hartler, 1996; Bjurulf, 2005; Färlin, 2008; Niedźwiecki, 2011). Although these chips are smaller than prime chips, they are similar in chip thickness, and of acceptable size for pulping.
- Prime sized (accept chips) will fit through an 8 - 10 mm chip thickness screen slot, but will be retained on a 13 mm diameter rh screen (Biermann, 1996 (a); Hartler, 1996; Bjurulf, 2005; Färlin, 2008; Niedźwiecki, 2011). Chips of this size are referred to as prime chips and are of optimal size for kraft pulping.
- Over-sized chips are retrained on a 45 mm diameter rh screen, while over-thick chips will be retained on an 8 mm screen slot (Biermann, 1996 (a); Hartler, 1996; Balakrishnan, 2008; Färlin, 2008; Niedźwiecki, 2011). These chip sizes will lead to fibre bundles (shives) in the pulping solution due to undercooking and retarded delignification (Svedman *et al.,* 1998; Dang and Nguyen, 2008). Secondary processing (crushing or slicing) will be needed to facilitate complete chemical penetration of over-sized and over-thick chips during pulping (Tikka *et al.,* 1993; Hartler, 1996; Tessier *et al.,* 1999; Ding *et al.,* 2005; Bjurulf, 2006; MacLeod, 2007; Dang and Nguyen, 2008; Färlin, 2008; Hellström, 2010). Chips used for kraft pulping by continuous digesters should be limited to a maximum over-thick chip content of 3 % (Hartler 1996).

2.6. Chipping and MC

Timber freshness is expressed in terms of the MC in the wood itself and will influence chip size distributions during chip production (Qian *et al.,* 1994; Hellström, 2008; Hellström, 2010; Isokangas, 2010; Niedźwiecki, 2011). An increase in chip thickness during chip production has been observed, with decreasing log MC (Watson and Stevenson, 2007). When log MC is very high or low, chip size and uniformity will be negatively affected (Pulkki, 1991; Persson *et al.*, 2002; Bjurulf, 2006). Logs with very low MC produce greater amounts of undesired smaller chips (fines and pins) and large chips (over-sized and over-thick chips) due to decreasing wood plasticity (Pulkki, 1991; Uhmeier and Persson, 1997; Färlin, 2008; Hellström, 2008). At higher MC the wood is softer and hence greater quantities of pins and fines will be produced (Watson and Stevenson, 2007; Niedźwiecki, 2011). No studies could be found to indicate optimal MC for chipping as wood processing is a function of the interactions between wood density and MC (Niedźwiecki, 2011).

Watson and Stevenson (2007) investigated the influence of seasonal variations in log MC of softwood and hardwood species on chip size and uniformity and their effect on kraft pulping. The authors found that over-sized chip production increased with decreasing seasonal log MC. The production of under-sized chips increased as MC increased.

No literature was found as to how log MC influence size and uniformity of eucalypt chips, nor have critical log moisture values been associated with eucalypt chip quality.

2.7. Sampling

For chip sampling purposes it is important to review the sampling method itself, the frequency in which samples are collected and the quantities obtained from each sample to ensure that samples are an accurate representation of the log population under investigation (Ding *et al.,* 2005). Chip pins and fines, tend to move down in chip piles, while larger chip fractions accumulate closer to the surface (Bjurulf, 2006). Therefore the point of sampling or pre-mixing is important to ensure an unbiased representation of the target populations is obtained.

3. Methodology

3.1. Site selection

The study was done near Kwambonambi of the Northern KwaZulu-Natal forestry region of South Africa. The coastal region is subject to sub-tropical climates, with mean annual temperature and precipitation of 22˚C and 1 196 mm respectively (Dovey 2012).

Eucalyptus grandis × *urophylla* clones of even age with relatively uniform tree size were selected (Table 1). Trees selected for the study were without form defects or growth stress and located on level terrain. Edge trees were excluded.

Table 1: Study site and tree details.

Species	E. *grandis* × *urophylla*
Age	8 years
Establishment Spacing	3m × 2.5m
SI	26.20
MAI (6 years)	31.4 m^3 ha^{-1} yr^{-1}
DBH	15cm-20cm
Slope	< 2 %

3.2. Research Design

A 3×2×3 factorial design was applied of factors A, B and C (Figure 3) and two-way and three-way main interactions between factors were analysed where applicable.

Factor A: Debarking treatment	**A1: Manual (60 trees)** • Motor-manual harvesting as control						**A2: Mech. 3 pass (60 trees)** • Three harvester head passes along the log surface						**A3: Mech. 5 pass (60 trees)** • Five harvester head passes along the log surface					
Factor B: Log drying Period	***One week*** (30 trees)			***Two weeks*** (30 trees)			***One week*** (30 trees)			***Two weeks*** (30 trees)			***One week*** (30 trees)			***Two weeks*** (30 trees)		
Factor C: Log section class	*Base*	*Middle*	*Top*	*Base*	*Middle*	*Top*	*Base*	*Middle*	*Top*	*Base*	*Middle*	*Top*	*Base*	*Middle*	*Top*	*Base*	*Middle*	*Top*

Figure 3: Research framework

3.2.1. Factor A: Debarking treatment

Factor A investigated the influence of log surface damage on chip purity, chip size distribution and fibre loss. Trees were subjected to three different debarking methods; A1 - manual debarking, A2 - a three pass mechanical debarking treatment where the harvester head moved over the length of the tree surface three times after felling, and A3 - a five pass mechanical debarking treatment where the harvester head moved over the length of the tree surface five times after felling (Figure 3). The manual debarked sample served as a control as it was accepted that little or no damage was inflicted on the log surface during debarking. For the mechanised debarking operations, the harvesting head was calibrated according to the inherent characteristics of the trees making up the study. Variations in harvester head settings were in this way limited as to their effect on debarking quality and also potential log surface damage. The same harvester and harvester operator was used throughout the study.

3.2.2. Factor B: Drying period

Factor B investigated the influence of log MC on chip purity and chip size distribution. Each treatment was subject to two drying (moisture loss) periods: period 1 - as fresh as possible (in this case one week drying – the time taken to transfer the logs from Kwambonambi to Worcester); and period 2 - two weeks of drying before chipping was initiated (Figure 3).

3.2.3. Factor C: Log section class

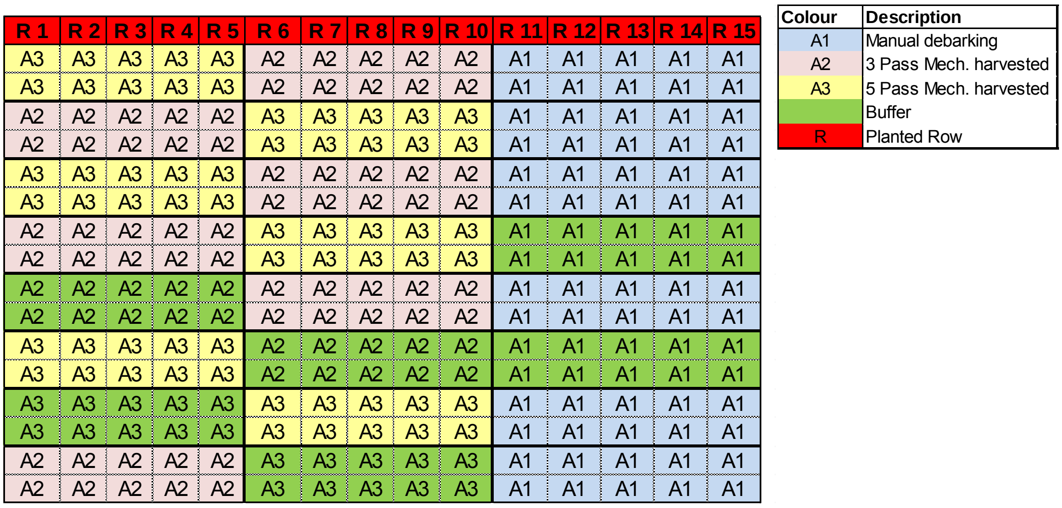
Factor C made a distinction between three log size classes and how these related to chip purity, size and uniformity by also taking factors A and B into account. Three logs were removed from every tree - base, middle and top logs (Figure 3). The top log was the third log up the tree and not necessarily the last possible log available from any specific tree.

3.3. Research instruments

3.3.1. Pre-harvesting

3.3.1.1. Trial layout

Trees subject to mechanical debarking (treatments A2 and A3) were felled by the harvester. Manually debarked trees (treatment A1) were felled motor-manually. Trees mechanically felled were felled in blocks of 10 trees (5 x 2 rows)(Table 4). These 10 trees are referred to as a harvester setting as the machine remained stationary during the felling and processing of the 10 identified trees. Hence the harvester had a number of settings in order to complete the felling and processing of trees selected for mechanised debarking. On the other hand manually debarked (A1) trees were felled and processed after the harvester had completed its work, in one continuous operation; not setting by setting as with mechanical felling (Figure4). The breast height diameters (DBH) of the sample trees ranged from 15 cm to 20 cm. Trees with growth deformities such as double leaders and butt sweep within the experimental layout were excluded and formed part of the buffer zones to maintain design continuity. Treatments A2 and A3 were randomly assigned within the harvesting layout and treatment A1 was assigned separately (Figure 4). Trees within each setting were colour coded, according to harvesting treatment and numbered to reflect tree position (Figure 4).



R 1	R 2	R 3	R 4	R 5	R 6	R 7	R 8	R 9	R 10	R 11	R 12	R 13	R 14	R 15
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A2	A2	A2	A2	A2	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A3	A3	A3	A3	A3	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1
A2	A2	A2	A2	A2	A3	A3	A3	A3	A3	A1	A1	A1	A1	A1

Colour	Description
A1	Manual debarking
A2	3 Pass Mech. harvested
A3	5 Pass Mech. harvested
🟩	Buffer
R	Planted Row

Figure 4: Harvesting layout.

3.3.1.2. Individual tree measurements

DBH and height of each of the 180 trees in the sample were measured and recorded. Tree heights were measured and recorded using a Haglöf Laser hypsometer Vertex VL402. DBH measurements were recorded using a Haglöf Digitech electronic calliper. DBH and height information was paired to individual trees by transponding tree height measurements from the laser hypsometer to the electronic calliper data files. Individual log volumes were calculated using Smalian's formula (Husch *et al.*, 2003)(Equation 1).

$$V_{log} = \frac{h}{2}(A_b + A_u) \qquad (1)$$

Where:

V_{log} = Log volume (m^3)

A_b = Cross sectional area at base (m)

A_u = Cross section area at upper end (m)

h = Log length (m)

The cumulative volumes of log assortments (per tree) were calculated using Equation 2.

$$V_t = \left(V_{base} + V_{middle} + V_{top}\right) \qquad (2)$$

Where:

V_{tree} = Total log volume extracted per tree (m^3)

V_{base} = Volume of base log (m^3)
V_{middle} = Volume of middle log (m^3)
V_{top} = Volume of top log (m^3)

The cumulative extracted log volumes (per harvester setting) were calculated using Equation 3.

$$V_{setting} = \left(\sum_{n=1}^{10} V_{t1} + V_{t2} + V_{t3} \dots V_{tn} \right) \tag{3}$$

$V_{setting}$ = Total extracted log volume (per harvester setting)(m^3)
V_{tx} = Volume of total log volume extracted per tree within treatment harvester setting (m^3)

3.3.2. Harvesting

3.3.2.1. Mechanised harvesting

A SP Maskiner 591LX harvesting head mounted on a tracked Hitachi IS200 excavator base was used for mechanised felling and debarking of treatments A2 and A3 (Figure 5). The feed roller pressures were calibrated according to tree size in order to minimise potential feed roller induced log surface damage. The trees were cross-cut into 5.5 m log lengths: i.e., three log assortments (base, middle and top logs).

Figure 5: SP Maskiner 591LX harvesting head mounted on a tracked Hitachi IS200 excavator.

3.3.2.2. Motor-manual harvesting and debarking

Manually debarked trees (treatment A1) were felled motor-manually. The trees were cross-cut into 5.5 m log lengths: i.e., three log assortments (base, middle and top logs).

An axe was used to cut a vertical incision into the bark across the length of the log. The back of the axe head was then used to apply force to the bark covered log surface and loosen bark. Loose bark was then removed from the log surface by hand. Manual debarking was executed by experienced forest workers.

3.3.3. Post-Harvesting

3.3.3.1. Log marking

Each of the 540 harvested logs was tagged with a plastic disc. Each tag displayed the information of the harvesting treatment applied and included the harvester setting where the tree was harvested, from which tree within the harvester setting the log was obtained and in which section of the tree the log was positioned (Figure 6).

Figure 6: Timber tags on logs.

3.3.3.2. Collection of surface fibre lost during debarking

At each of the harvester settings (Figure 4) surface fibre losses resulting from the mechanical debarking process were collected on a tarpaulin that was placed below the harvester head, as they were dislodged during debarking. Surface fibre dislodged during the final pass over the tree surface were not collected, as the harvester head was moved (away from the tarpaulin) to above the log stack for cross-cutting and stacking. The harvester head travelled over the entire length of the tree during the cross-cutting operation. The dislodged fibre including bark and wood fragments were collected in heavy duty plastic bags to limit moisture loss (Figure 7). Coded tags were placed in each bag to indicate which harvester setting the fibre was collected from. The bags were sealed and transported to the laboratory at Stellenbosch University for further processing.

Figure 7: Collection of surface fibre lost during debarking.

3.3.3.3. Log extraction

A Timberpro TF840-B forwarder extracted the log assortments to roadside and also loaded the logs directly onto a truck and trailer (Figure 8). The load was securely covered with a tarpaulin to limit moisture loss during transport to the Worcester based chipping facility.

Figure 8: Primary transport of logs by forwarder.

3.3.4. Sample processing

3.3.4.1. Log specific data collection

Once the logs reached the chipping facility both thick and thin end diameters and length for each log were recorded.

3.3.4.2. Chip production

Logs were chipped in a Bandit 250 XP mobile disc chipper (Table2). Chipper maintenance was done by a chipper technician prior to chipping of logs from the different drying periods. Chipper maintenance included knife change and anvil clearance adjustments. The chipper knife angles were fixed at 45˚.

Table 2: Chipper specifications.

Manufacturer	Bandit
Model	250 XP
Type	Disc chipper
Log Feed	Horizontal
Engine	106 kW
Capacity (Log diameter)	30.48 cm
Knife angle (fixed)	45˚
Feed rate	0.6096 m/sec

Logs were separated and stacked according to debarking method and drying period. Logs were manually fed into the chipper to avoid potential grapple induced log surface damage of a mechanical loader. An individual log was chipped from each debarking treatment in a repetitive cycle to avoid bias resulting from chipping conditions associated with chipper knife wear. Chips produced from individual logs were mixed thoroughly in a tumbler for one minute before a 12 l sample was extracted. Samples were immediately placed in plastic bags and sealed to avoid further moisture loss. Each log’s tag information was copied onto the bag containing the chips produced from it. The remainder of chips were emptied onto a tarpaulin and discarded. The sample bags were then transported to Stellenbosch University for further analysis.

3.3.4.3. Chip sample preservation

The green mass of each sample was recorded in the data register before being repacked into brown paper bags to facilitate moisture loss. Individual log information was replicated onto the paper bag. Samples were stored off the ground for one month to allow for air drying.

3.3.4.4. Chip screening

Chip samples were screened for five minutes according to SCAN-CM 90:94 standards into five chip size fractions (over-sized, over-thick, accepts, pins and fines) using a mechanical chip size screener. Each of the 2 700 individual fractioned chip sub-samples (five fractioned chip sub-samples per chip sample), were marked for identification and bagged separately. Fractioned chip sub-samples were dried at a temperature of 105 ˚C for 24 hours according to SCAN-CM 39:94 standards to determine dry matter content. Individual chip fraction sub-samples were expressed as a mass percentage of the total sample bone dry mass.

3.3.4.5. Chip purity calculation

Bark and knots were removed by hand from the over-sized, over-thick and accept chips from each chip fraction sub-sample after oven drying. There was no rot in the trees harvested.

The sum total of the extracted knots was expressed as a mass percentage of the total oven dried sample mass using Equation 4.

$$K_{total} = \frac{K_{oversize} + K_{Over-thick} + K_{Accepts}}{W_o} \cdot\times\cdot 100 \qquad (4)$$

Where:

K_{total} = Total chip knot content %

$K_{oversize}$ = Oven dried mass of knots removed from over-size chip size fraction (g)

$K_{Over-thick}$ = Oven dried mass of knots removed from over-thick chip size fraction (g)

$K_{Accepts}$ = Oven dried mass of knots removed from accept sized chip fraction (g)

W_o = Total oven dried mass of chip sample extracted from each log (g)

The sum total of the extracted bark was expressed as a mass percentage of the total oven dried sample mass using Equation 5.

$$B_{total} = \frac{B_{oversize} + B_{Over-thick} + B_{Accepts}}{W_o} \times 100 \qquad (5)$$

Where:

B_{total} = Total chip bark content %

$B_{oversize}$ = Oven dried mass of bark removed from over-size chip size fraction (g)

$B_{Over-thick}$ = Oven dried mass of bark removed from over-thick chip size fraction (g)

$B_{Accepts}$ = Oven dried mass of bark removed from the accept chip size fraction (g)

W_o = Total oven dried mass of chip sample extracted from each log (g)

3.3.4.6. Chip MC calculation

Chip MC was calculated for individual samples using Equation 6 (Govett *et al.*, 2010).

$$Chip\ MC\ (\%) = \left[\left(W_g - W_o\right)/W_g\right] \times 100 \qquad (6)$$

Where:

$Chip\ MC\ (\%)$ = Chip MC expressed as a percentage (green basis)

W_g = Chip sample green mass (g)

W_o = Chip sample oven dried mass (g)

3.3.4.7. Basic wood density calculation

From the accept chips for each sample 500 ml of chips were randomly selected. The oven dried mass (M_o) was recorded for the 500 ml of chips, before being transferred to net packaging bundles which facilitated the rehydration of chips during water immersion. Identification tags were attached to each of the chip net bundle samples and submerged in water for five weeks to determine the water saturated chip mass of each sample. The water containers in which the samples were immersed were disinfected beforehand with ethanol to limit biotic growth. Individual samples were emptied onto a moist towel, and excess water was removed by gently pressing down onto the chips with a moist cloth (Figure 9).

The saturated mass of each sample (M_m) was recorded and specific wood gravity was calculated by substituting values into the Smith formula (Smith 1954)(Equation 7). The average specific gravity of 1.53 for solid wood matter (G_{so}), was used for basic density calculations as stipulated in the Smith formula. The Smith formula was used in favour of the more conventional water displacement method (Seifert and Seifert, 2014) due to firstly the inherently small sizes of individual chip samples which made the water displacement method more difficult to deal with; and the laboratory weighing scales available were not precise enough to use this typical method.

$$G_f = \frac{1}{\frac{M_m - M_o}{M_o} + \frac{1}{G_{so}}} \times 1000 \tag{7}$$

Where:

G_f = Basic wood density (kg m^{-3})

M_m = Moisture saturated mass (g)

M_o = Oven dried mass (g)

G_{so} = Average specific gravity of wood matter (g cm^{-3})

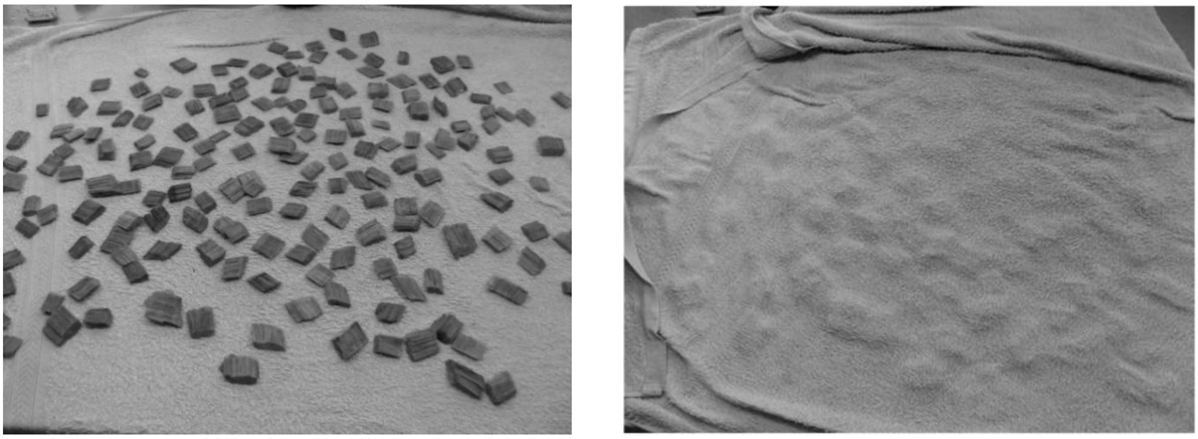


Figure 9: Removal of excess water.

3.3.4.8. Surface fibre dislodged during delimbing/debarking

To determine merchantable wood volume lost during mechanised debarking as well as the economic value associated with these losses, the bark contained in the dislodged wood fibre needed to be separated from the wood fibres. Both bark and wood fibre varied in size (from large to very fine) and therefore were screened as a first step to facilitate separation of the larger pieces of wood and bark. The separated larger wood fibres were collected in paper bags and oven dried for 48 hours at 105 ˚C and then weighed ($W_{\Delta \text{ total}}$).

The wood content of the smaller sized (pin and fines sized) bark and wood fibres samples were determined via Micro CT scanning (Table 3) after they had been oven dried as above. The individual samples were thoroughly mixed and a 50 ml secondary test tube sample (Figure 10) for each harvester setting used for woody fibre content estimations.

Table 3: Industrial micro CT scanner specifications.

Variable	**Specification**
Manufacturer	General Electric
Model	Phoenix V|Tome|X L240
Additional tubes	NF 180
Voltage setting	180 kV
Current	160 µA
Geometric resolution (voxel size)	160.797 µM
Number of images recorded	3200
Image rotation sector	360˚

CT-scanning is a tomographic imaging technology based on the x-ray absorption of materials, which are translated to grey values in an imaging procedure. These grey values can be calibrated with bodies of known density under the assumption that moisture content and material properties (atomic numbers) vary insignificantly (du Plessis *et al.,* 2012). Grey scale values are directly proportional to material densities and can be expressed as a volume for each scanned sample. CT scanning has been used successfully for the measurement of wood density and many other wood properties (see e.g. Castell *et al.,* 2005; Nikolova *et al.,* 2009; Seifert *et al.,* 2010). To determine the inherent grey scale range for wood fibre related to this study and the basic wood density of the dislodged surface wood fibres a 10 cm^3 sample of wood was taken from the pin sized fraction class of dislodged surface fibre. The sample was oven dried, weighed and scanned. The oven dried mass (W_o) and volume (V_o) of the sample were recorded. The oven dried density (P_{ow}) was calculated for log surface wood fibre using Equation 8.

$$P_{ow} = \frac{W_o}{V_o} \qquad (8)$$

Where:

P_{ow} = Oven dried density of surface wood fibre (g cm^{-3})

W_o = Oven dried mass of surface wood fibre (g)

V_o = Oven dried volume of surface wood fibre (cm^3)

A secondary sample containing the smaller (fines) sized fractions were placed into a polystyrene test tube holder and scanned (Figure 10). The reconstructed volume was segmented to allow individual sample analysis (Figure 10).

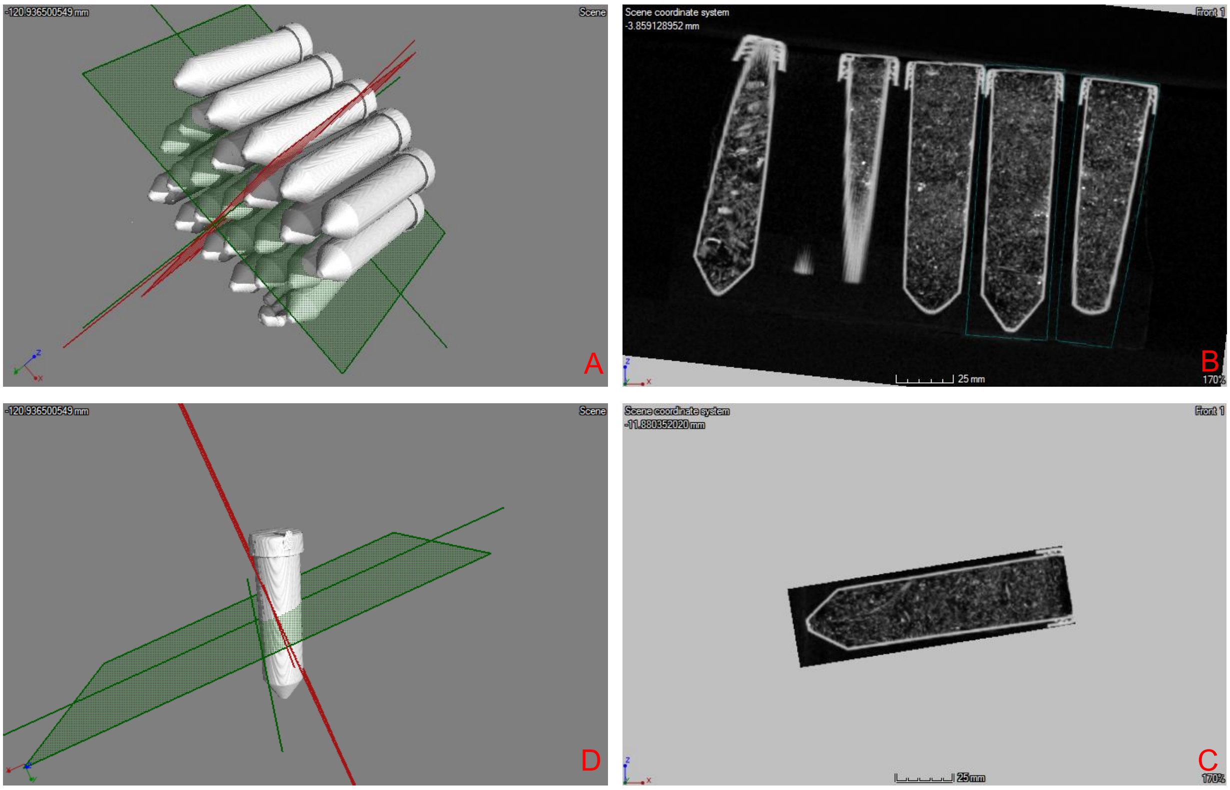


Figure 10: Micro CT scanner image analysis: A-Digital positioning of bulk sample for segment extraction; B-Cross section view of representative samples; C-Alignment of extracted sample segments for wood volume analysis; D-Cross section view of sample segment.

Wood volume ($V_{\Delta\, sub\, wood}$) was calculated for that volume falling in the pre-calculated grey scale range of 12 000 to 18 000 system units for each sample, while the grey value threshold distinguished wood fibre from air, polystyrene and bark fibre. The total surface fibre loss of each sample is calculated and expressed as a mass percentage using Equation 9.

$$Fibre\ loss\ \% = \frac{100(P_{ow}.V_{\Delta\, sub\, wood})}{W_{\Delta\, sub}} \qquad (9)$$

Where:

$Fibre\ loss\ \%$ = Total surface fibre loss %

P_{ow} = Oven dried wood density of surface wood fibre (g cm^{-3})

$V_{\Delta\, sub\, wood}$ = Wood volume of CT-scanned pin and fines sized surface wood fibre (cm^3)

$W_{\Delta\, sub}$ = Oven dried mass of CT-scanned pin and fines sized surface fibre (g)

The wood percentage calculated from the secondary samples was extrapolated to estimate wood content of pin and fines sized surface fibre per harvester setting using Equation 10. The sum total of fibre lost t^{-1} extracted and estimated by CT-scanning was calculated for each mechanically debarked experimental block.

$$W_{sum\ total} = \frac{Woody\ Residue\ \% \times W_{\Delta\ total}}{100 \times 10^6} \qquad (10)$$

Where:

$W_{sum\ total}$ = Estimated total oven dried mass of pin and fines sized fibre lost (t)

$Woody\ Residue\ \%$ = Wood fibre for pin and fines sized fibre lost (%)

$W_{\Delta\ total}$ = Total oven dried mass for pin and fines sized fibre loss samples (g^{-1})

Fibre lost during mechanical debarking was expressed as a percentage of the total extractable wood volume per harvester setting using Equation 11.

$$V_{setting\ \%} = \frac{W_{setting}/P_{ow}}{V_{setting}} \times 100 \qquad (11)$$

Where:

$V_{tree\ \%}$ = Fibre volume lost expressed as a % of the total extractable fibre volume per harvester setting

$W_{setting}$ = Total oven dried mass of fibre lost per harvester setting (kg)

P_{ow} = Specific gravity of wood fibre lost (kg m^{-3})

$V_{setting}$ = Total extracted log volume per harvester setting (m^3)

3.3.5. Economic evaluation

3.3.5.1. Pulp yield

Although pulp contains moisture at the point of sale of between 5 % - 10 %, depending on climatic conditions, this figure can be highly variable. Therefore pulp yields were expressed on a BDt basis. Pulp recovery for individual chip samples were estimated using relative pulp yield values ($PY_{Relative}$)(Table 4). Pulp yields for chip size fraction units ($PY_{size\ fraction}$), were adjusted for South African grown *E.grandis* × *urophylla* chips, according to published pulp yields, which were then expressed as a percentage ($PY_{Accepts}$) using Equation 12 and values from Table 12.

$$PY_{size\ fraction} = \frac{PY_{Accepts}}{100} \times PY_{Relative} \tag{12}$$

Where

$PY_{size\ fraction}$ = Estimated pulp yield for individual chip size fraction units

$PY_{Accepts}$ = Pulp yield of accept chip size fractions units

$PY_{Relative}$ = Relative pulp yield for size fraction units

Table 4: Pulp yield values for different chip size fraction units (McEwan 2004; True 2006).

	Fines	**Pins**	**Accepts**	**Over-thick**	**Over-size**
Relative pulp yield values	0.25	0.50	1.00	0.94	0.92
Pulp Yield % for *E.grandis* × *urophylla* (9 years)	12.85	25.70	51.40	48.32	47.29

Total pulp yield for individual chip samples are calculated using Equation 13.

$$PY_g = \sum_{i=n}^{n=a,b,c,d,e} W_i . PY_i \tag{13}$$

Where:

PY_g = Total pulp yield for extracted chip sample (g)

W_x = Oven dried mass of individual chip size fraction units (g)

PY_x = Relative pulp yield of individual chip size fractions units (g)

A conversion factor (SC_f) was calculated for each chip sample to facilitate the calculation of pulp yield per bone dry tonne (BDt^{-1}) of chips. The chip samples total oven dried mass (W_{total}) was substituted into Equation 14.

$$\boldsymbol{SC_f} = \frac{\mathbf{1 \times 10^6}}{\boldsymbol{W_{total}}} \tag{14}$$

Where:

SC_f = Conversion factor to pulp yield g t^{-1}

W_{total} = Total oven dried mass of chip sample (g)

Pulp yield for individual samples were extrapolated to a per BDt value (PY_t) by substituting the total pulp yield (PY_g) and conversion factor (SC_f) into Equation 15. Pulp yield was expressed in tonnes per BDt of chips.

$$\boldsymbol{PY_t = \frac{PY_g.SC_f}{1\times10^6}} \qquad (15)$$

Where:

PY_t = Pulp yield t BDt^{-1}

PY_g = Total pulp yield for extracted chip sample g g^{-1}

SC_f = Conversion factor from pulp yield g g^{-1} to pulp yield g t^{-1}

Pulp yield per BDt of chips (PY_t) for individual samples were expressed as a monetary pulp yield value (PY_{value}) using Equation 16. Bleached eucalypt kraft pulp (BEKP) prices for August 2013 (US dollar) of $ 792 were converted to a South African rand value of R 7 989.21 (P_{price}) according to the US dollar Rand exchange rate of R 10.087 for the same time period (KSH Consulting 2013).

$$\boldsymbol{PY_{value} = PY_t \times P_{price}} \qquad (16)$$

Where:

PY_{value} = Value of potential recoverable pulp (R t^{-1})

PY_t = Pulp yield (t $\text{BDt}^{-1)}$

P_{price} = Pulp price (R t^{-1})

3.3.5.2. Fibre loss

Economic values associated with fibre loss were assigned to individual mechanical debarked treatment harvester setting (Figure 5) according to mechanical debarking treatment. In South Africa pulp logs are sold in green tonnes (gt). Therefore oven dried dislodged surface fibre masses were adjusted according to mechanical debarking treatments and drying periods as MCs will have an effect on the economic values assigned per tonne fibre lost. MC correction factors used for the calculations are shown in Table 5.

Table 5: Least square mean (LSM) of log MC % according to mechanical debarking treatments and log drying periods.

	Drying Period	
Debarking Treatment	one week	two week
Mechanical (three pass)(LSM)	47.67	37.96
Mech. (five pass)(LSM)	47.23	37.94

The bone dry dislodged fibre mass was corrected for MC (for the MC of merchantable fibre lost after both one week and two week log drying periods) using Equation 17.

$$\boldsymbol{W_g = W_o + \frac{MC.W_o}{100}} \qquad (17)$$

Where:

W_g = the adjusted green mass of dislodged wood fibre per harvester setting (10 trees)(gt)

W_o = the actual oven dried mass of dislodged wood fibre per harvester setting (10 trees)(ODt)

MC = the estimated MC % according to mechanical debarking treatments used and log drying periods (%)

The value dislodged surface fibre was calculated using Equation 18. The eucalypt pulpwood price for 2012; R 299.28 gt^{-1}, were used for value calculations (Meyer, 2012). Extraction and transport costs were excluded from the pulpwood price used.

$$\boldsymbol{Value_{wood\,fibre} = W_g \times PW_{price}} \qquad (18)$$

Where:

$Value_{wood\,fibre}$	= Value of fibre lost (R gt^{-1})
W_g	= Estimated green mass (gt)
PW_{price}	= Pulpwood price per gt (R t^{-1})

The value of fibre lost during harvesting was extrapolated to a value for 1600 trees ha^{-1} as per normal planting density in South African grown eucalypt pulpwood plantations.

3.3.6. Statistics

One way, two way and three way multi factorial analysis of variance (ANOVA) were used to analyse the data using the STATISTICA 10 software package (StatSoft, 2012). Null hypothesis tested was for no treatment interaction effect. If the null hypothesis was rejected, individual treatment effects were compared. However if the null hypothesis was not rejected, treatment interactions are significant and only the interactions between treatments were analysed, as treatment effects were dependent of each other (Milton and Arnold 1999). When significant differences were found between treatment or treatment interaction effects ($\alpha = 0.05$), significant differences between individual means were determined using a post hoc Bonferroni test. When ANOVA residuals were normally distributed, a non-parametric Bootstrap test was used. The least square means (LSM) were used for the graphical representation of significant treatment interactions and Bootstrap means for non-normal distributed treatments. For secondary results Bootstrap tests were applied for moisture, bark and knot content values. For primary results bootstrap tests were applied for over-thick chips, fines and fibre loss values.

4. Results

4.1. Physical chip properties

4.1.1. Chip MC

Chip MC differed significantly in relation to debarking treatments, log drying periods and log sections. Significant interactions were also observed between: debarking treatment and log sections and log drying periods and log sections (Table 6).

Table 6: ANOVA table for chip MC three way factorial experiment.

Source of variation		**MC % (Green basis)**				
	Df	SS	MS	F	P	Prob.
Intercept	1	981501.9	981501.9	193233.2	0.000	***
Main effect						
Treatment	2	61.7	30.9	6.1	0.002	**
Drying period	1	11479.8	11479.8	2260.1	0.000	***
Log class	2	6960.4	3480.2	685.2	0.000	***
2 Factor interaction						
Treatment*Drying period	2	30.4	15.2	3.0	0.051	NS
Treatment*Log class	4	51.4	12.9	2.5	0.040	*
Drying period*Log class	2	1265.5	632.8	124.6	0.000	***
3 Factor interaction						
Treatment*Drying period*Log class	4	19.6	4.9	1.0	0.426	NS
Error	531	2697.1	5.1			
Total	548	23180.3				

*(From here on significant tabulated p-values will be referred to as *, highly significant tabulated p-values will be referred to as ** and very highly significant tabulated p-values will be referred to as ***)*

4.1.1.1. Debarking treatment × log class

Interactions between debarking treatment and log class had a significant effect on chip MC (p=0.040)(Table 6 and Figure 11).

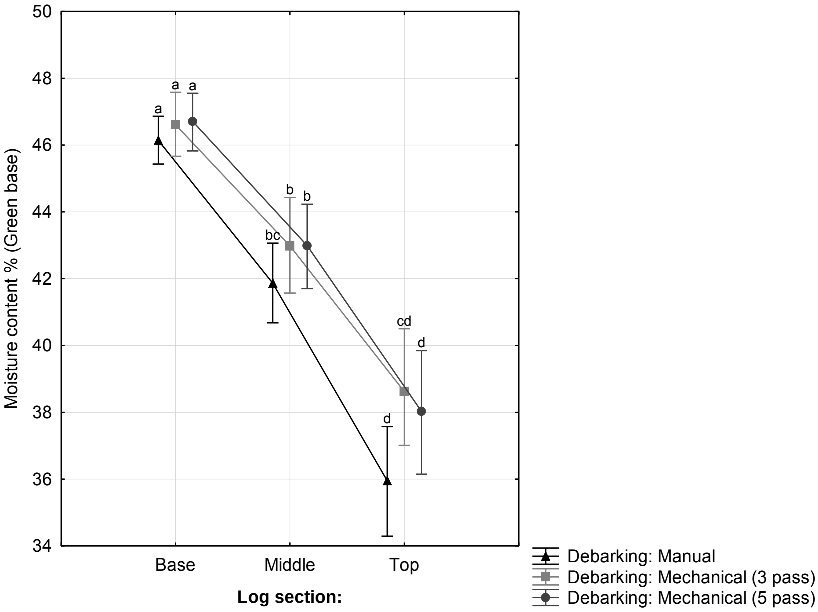


Figure11: Influence of debarking treatment and log sections on chip MC (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, etc.).

Manually debarked logs

Significant LSM MC differences were observed between manually debarked logs, three and five pass mechanical debarking treatments and log sections.

Table 7: Significant Bootstrap means MC differences: Manually debarked top logs vs respective debarking treatments and log sections.

Treatment	MC%	Treatment	MC%	Diff.
Manually debarked		***Manually debarked***		
Top logs	35.9	Base logs	46.2	- 10.3
		Middle logs	41.9	- 6.0
		Mech. debarked (three pass)		
		Base logs	46.6	- 10.7
		Middle logs	43.0	- 7.1
		Mech. debarked (five pass)		
		Base logs	46.7	- 10.8
		Middle logs	43.0	- 7.1

Manually debarked top logs with a MC of 35.9 % produced wood chips (from here on referred to as chips) of 10.3 % and 6.0 % lower in MC than manually debarked base and middle logs respectively. Manually debarked top logs also produced chips 10.7 % and 7.1 % lower in MC than three pass mechanically debarked (from here on referred to as three pass debarked) base and middle logs respectively, and 10.8 % and 7.1 % lower in MC than chips produce from five pass mechanically debarked (from here on referred to as five pass debarked) base and middle logs respectively. Significant MC differences in relation to respective debarking treatments and log sections are shown in Table 7.

Table 8: Significant Bootstrap means MC differences: Manually debarked middle logs vs respective debarking treatments and log sections.

Treatment	**MC%**	**Treatment**	**MC%**	**Diff.**
Manually debarked		***Manually debarked***		
Middle logs	41.9	Base logs	46.2	- 4.3
		Mech. debarked (three pass)		
		Base logs	46.6	- 4.7
		Mech. debarked (five pass)		
		Base logs	46.7	- 4.8

Manually debarked middle logs with a MC of 41.9 % produced chips 4.3 % lower in MC than manually debarked base logs. Manually debarked middle logs also produced chips 4.7 % and 4.8 % lower in MC than three pass and five pass debarked base logs respectively. Significant MC differences in relation to respective debarking treatments and log sections are shown in Table 8.

Mechanical debarked logs (three pass)

Significant LSM MC differences were observed between three pass debarked logs, respective debarking treatments and log sections.

Table 9: Significant Bootstrap means MC differences: Three pass debarked top logs vs respective debarking treatments and log sections.

Treatment	**MC%**	**Treatment**	**MC%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Top logs	38.6	Base logs	46.6	- 8.0
		Middle logs	43.0	- 4.4
		Manually debarked		
		Base logs	46.2	- 7.6
		Middle logs	41.9	- 3.3
		Mech. debarked (five pass)		
		Base logs	46.7	- 8.1
		Middle logs	43.0	- 4.4

Three pass debarked top logs with a MC of 38.6 % produced chips 8.0 % and 4.4 % lower in MC than three pass debarked base and middle logs respectively. Three pass debarked top logs also produced chips 7.6 % and 3.3 % lower in MC than manually debarked base and middle logs respectively, and 8.1 % and 4.4 % lower in MC than produced from five pass debarked base and middle logs respectively. Significant MC differences in relation to respective debarking treatments and log sections are shown in Table 9.

Table 10: Significant Bootstrap means MC differences: Three pass debarked middle logs vs respective debarking treatments and log sections.

Treatment	**MC%**	**Treatment**	**MC%**	**Diff. (MC%)**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Middle logs	43.0	Base logs	46.6	- 3.6
		Manually debarked		
		Base logs	46.2	- 3.2
		Mech. debarked (five pass)		
		Base logs	46.7	- 3.7

Three pass debarked middle logs with a MC of 43.0 % produced chips 3.6 % lower in MC than three pass debarked base logs. Three pass debarked middle logs also produced chips 3.2 % lower in MC than manually debarked base and 3.7 % lower in MC than five pass debarked base logs. Significant MC differences in relation to respective debarking treatments and log sections are shown in Table 10.

Mechanical debarked logs (five pass)

Significant LSM MC differences were observed between five pass debarked logs, respective debarking treatments and log sections.

Table 11: Significant Bootstrap means MC differences: Five pass debarked top logs vs respective debarking treatments and log sections.

Treatment	**MC%**	**Treatment**	**MC%**	**Diff. (MC%)**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Top logs	38.1	Base logs	46.7	- 8.6
		Middle logs	43.0	- 4.9
		Manually debarked		
		Base logs	46.2	- 8.1
		Middle logs	41.9	- 3.8
		Mech. debarked (three pass)		
		Base logs	46.6	- 8.5
		Middle logs	43.0	- 4.9

Five pass debarked top logs with a MC of 38.1 % produced chips 8.6 % and 4.9 % lower in MC than five pass debarked base and middle logs respectively. Five pass debarked top logs also produced chips 8.1 % and 3.8 % lower in MC than manually debarked base and middle logs respectively, and 8.5 % and 4.9 % lower in MC than three pass debarked base and middle logs. Significant MC differences in relation to respective debarking treatments and log sections are shown in Table 11.

Table 12: Significant Bootstrap means MC differences: Five pass debarked middle logs vs respective debarking treatments and log sections.

Treatment	MC%	Treatment	MC%	Diff.
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Middle logs	43.0	Base logs	46.7	- 3.7
		Manually debarked		
		Base logs	46.2	- 3.2
		Mech. debarked (three pass)		
		Base logs	46.6	- 3.6

Five pass debarked middle logs with a MC of 43.0 % logs produced chips 3.7 % lower in MC than five pass debarked base logs. Five pass debarked middle logs also produced chips 3.2 % lower in MC than manually debarked base logs and 3.6 % lower in MC than three pass debarked base logs. Significant moisture differences according to respective debarking treatments and log sections are shown in Table 12.

4.1.1.2. Drying period × Log sections

Interactions between drying period and log sections had a very highly significant influence on log MC (p<0.001)(Table 6 and Figure 12).

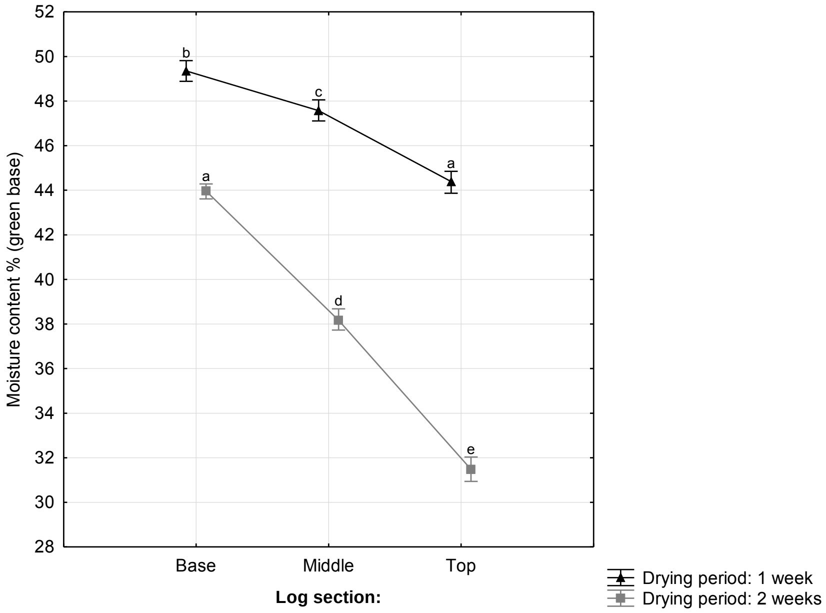


Figure 11: Influence of log drying period and log sections on chip MC (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, e, etc.).

Drying period A (two week)

Significant LSM MC differences were observed between two week dried logs, respective log drying periods and log sections.

Table 13: Significant Bootstrap means MC differences: Top two week dried logs vs respective log drying periods and log sections.

Log drying period	**MC%**	**Log drying period**	**MC%**	**Diff.**
Two week		***Two week***		
Top log	31.5	Base log	44.0	- 12.5
		Middle log	38.2	- 6.7
		One week		
		Base log	49.3	- 17.8
		Middle log	47.6	- 16.1
		Top log	44.4	- 12.9

Two week dried top logs with a chip MC of 31.5 % produced chips 12.5 % and 6.7 % lower in MC than base and middle logs dried for the same time period respectively. Two week dried top logs also produced chips 17.8 %, 16.1 % and 12.9 % lower in MC than base, middle and top logs dried one week respectively. Significant MC differences in relation to respective drying periods and log sections are shown in Table 13.

Table 14: Significant Bootstrap means MC differences: Middle two week dried logs vs respective log drying periods and log sections.

Log drying period	**MC%**	**Log drying period**	**MC%**	**Diff.**
Two week		***Two week***		
Middle log	38.2	Base log	44.0	- 5.8
		One week		
		Base log	49.3	- 11.1
		Middle log	47.6	- 9.4
		Top log	44.4	- 6.2

Two week dried middle logs with a MC of 38.2 % produced chips 5.8 % lower in MC than base logs dried for the same time period and 11.1 %, 9.4 % and 6.2 % lower in MC than one week dried base, middle and top logs respectively. Significant MC differences in relation to respective log drying periods and log sections are shown in Table 14.

Table 15: Significant Bootstrap means MC differences: Base two week dried logs vs respective log drying periods and log sections.

Log drying period	**MC%**	**Log drying period**	**MC%**	**Diff.**
Two week		***One week***		
Base log	44.0	Base log	49.3	- 5.3
		Middle log	47.6	- 3.6

Two week dried base logs with a MC of 44.0 % produced chips 5.3 % and 3.6 % lower in MC than one week dried base and middle logs respectively (Table 15).

Drying period B (one week)

Significant LSM MC differences were observed between one week dried logs, respective log drying periods and log sections.

Table 16: Significant Bootstrap means MC differences: Top logs dried for one week vs respective log drying periods and log sections.

Log drying period	**MC%**	**Log drying period**	**MC%**	**Diff.**
One week		***One week***		
Top logs	44.4	Base logs	49.3	- 4.9
		Middle logs	47.6	- 3.2

One week dried top logs with a MC of 44.4 % produced chips 4.9 % and 3.2 % lower in MC than base and middle logs dried for the same time period respectively (Table 16).

Table 17: Significant Bootstrap means MC differences: Middle logs dried for one week vs respective log drying periods and log sections.

Log drying period	**MC%**	**Log drying period**	**MC%**	**Diff.**
One week		***One week***		
Middle logs	47.6	Base logs	49.3	- 1.7

One week dried middle logs with a MC of 47.6 % produced chips 1.7 % lower in MC than base logs dried for the same time period (Table 17).

4.1.2. Basic wood density

Basic density significantly differed in relation to log sections (Table 18).

Table 18: ANOVA table for basic density one way factorial experiment.

Source of variation	Df	**Wood density (kg m^3)**				
		SS	MS	F	P	Prob.
Intercept	1	117675820.4	117675820.4	333023.9	0.000	***
Main effect						
Log class	2	102235.2	51117.6	144.7	0.000	***
Error	545	192578.7	353.4			
Total	547	294813.9				

4.1.2.1. Log class

Log class had a very highly significant effect on the basic density of chips produced ($p<0.001$)(Table 18 and Figure 13).

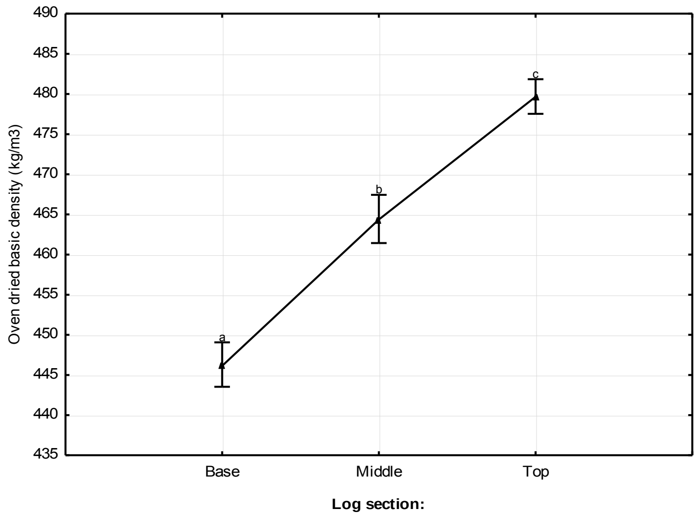


Figure 12: Influence of log class on basic density (significant differences in treatment mean are marked with different letters such as a, b, c, etc.).

Table 19: Significant Bootstrap means differences in basic density: Base logs vs respective log sections.

Log class	**kg m^{-3}**	**Log class**	**kg m^{-3}**	**Diff. (kg m^{-3})**
Base	446.3	Middle	464.3	- 18.0
		Top	479.6	- 33.3

Base logs with a basic density of 446.3 kg m^{-3} produced chips with 18.0 kg $m^{-3}$and 33.3 kg m^{-3} lower basic density than middle and top logs respectively (Table 19 and Figure 13).

Table 20: Significant Bootstrap means differences in basic density: Middle logs vs respective log sections.

Log class	**kg m^{-3}**	**Log class**	**kg m^{-3}**	**Diff. (kg m^{-3})**
Middle	464.3	Top	479.6	- 15.3

Middle logs with a basic density of 464.3 kg m^{-3} produced chips with 15.3 kg m^{-3} lower basic density than top logs (Table 20 and Figure 13).

4.2. Chip purity

4.2.1. Wood Knot content

Chip knot content differed significantly in relation to log sections (Table 21).

Table 21: ANOVA table for chip knot content one way factorial experiment.

Source of variation	Df	**Knot %**				
		SS	MS	F	P	Prob.
Intercept	1	4488.7	4488.7	925.9	0.000	***
Main effect Log class	2	444.7	222.4	45.9	0.000	***
Error	545	2642.2	4.9			
Total	547	3086.9				

4.2.1.1. Log class

Main effect log class had a very highly significant effect on the knot content of chips produced ($p<0.001$)(Table 21 and Figure 14).

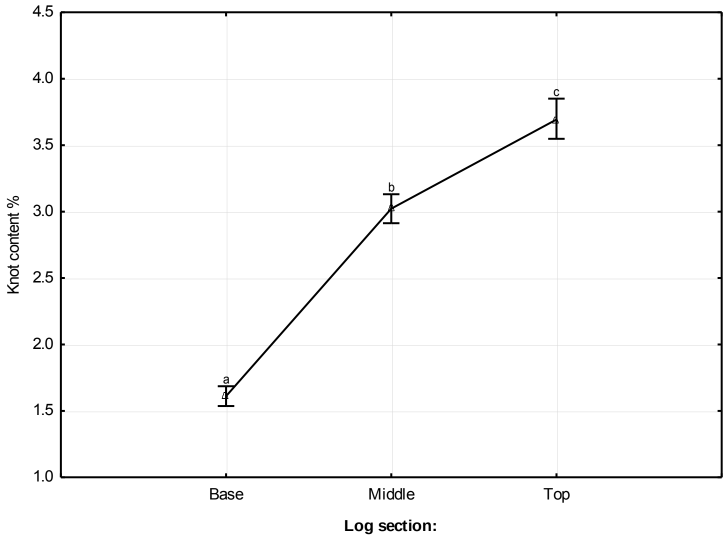


Figure 14: Influence of log class on knot content value (significant differences in treatment mean are marked with different letters such as a, b, c, etc.).

Table 22: Significant Bootstrap means differences in knot content: Base logs vs respective log sections.

Log class	**Knot %**	**Log class**	**Knot %**	**Diff.**
Base	1.6	Middle	3.0	- 1.4
		Top	3.7	- 2.1

Base logs produced chips 1.4 % and 2.1 % lower in knot content than middle and top logs respectively (Table 22 and Figure 14).

Table 23: Significant BM differences in knot content: Middle logs vs respective log sections.

Log class	**Knot %**	**Log class**	**Knot %**	**Diff.**
Middle	3.0	Top	3.7	- 0.7

Middle logs produced chips 0.7 % lower in knot content than top logs (Table 23 and Figure 14).

4.2.2. Chip bark content

Bark content significantly differed in relation to debarking treatment and log sections (Table 24).

Table 24: ANOVA table for bark content three way factorial experiment.

Source of variation		Bark content %				
	Df	SS	MS	F	P	Prob.
Intercept	1	0.5	0.5	28.8	0.000	***
Main effect						
Treatment	2	0.3	0.2	9.4	0.000	***
Drying period	1	0.0	0.0	0.1	0.809	NS
Log class	2	0.2	0.1	5.6	0.004	**
2 Factor interaction						
Treatment*Drying period	2	0.0	0.0	0.0	0.957	NS
Treatment*Log class	4	0.1	0.0	1.0	0.387	NS
Drying period*Log class	2	0.0	0.0	1.2	0.289	NS
3 Factor interaction						
Treatment*Drying period*Log class	4	0.1	0.0	1.3	0.263	NS
Error	531	8.7	0.0			
Total	548	9.4				

4.2.2.1. Debarking treatment

Main effect debarking treatment had a very highly significant effect on the bark content (p<0.001)(Table 24 and Figure 15).

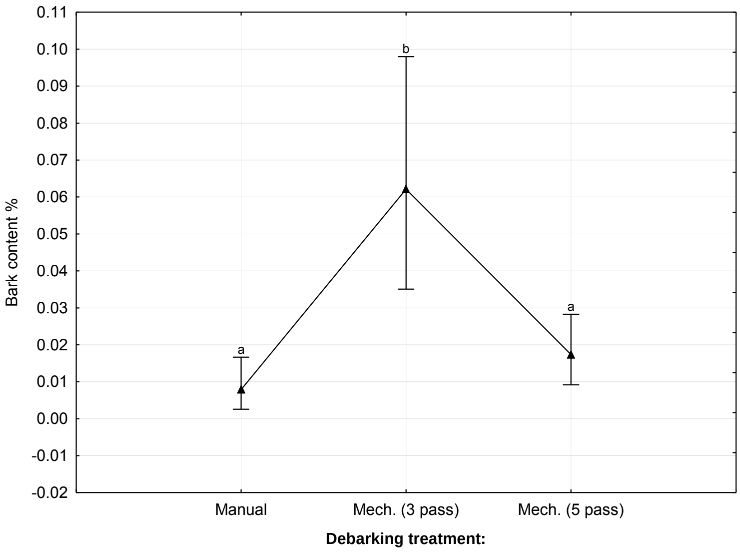


Figure 15: Influence of debarking treatment on bark content values (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, etc.).

Table 25: Significant Bootstrap means differences in bark content: Manually debarked logs vs respective debarking treatments.

Treatment	Bark %	Treatment	Bark %	Diff.
Manually debarked	0.008	Mech. debarked (three pass)	0.062	- 0.054

Manually debarked logs produced chips 0.054 % lower in bark content than three pass debarked logs (Table 25 and Figure 15).

Table 26: Significant Bootstrap means differences in bark content: Five pass debarked logs vs respective debarking treatments.

Treatment	Bark %	Treatment	Bark %	Diff.
Mech. debarked (five pass)	0.018	Mech. debarked (three pass)	0.062	- 0.044

Five pass debarked logs produced chips 0.044 % lower in bark content than three pass debarked logs (Table 26 and Figure 15).

4.2.2.2. Log class

Main effect log class had a highly significant effect on the bark content (p=0.004)(Table 24 and Figure 16).

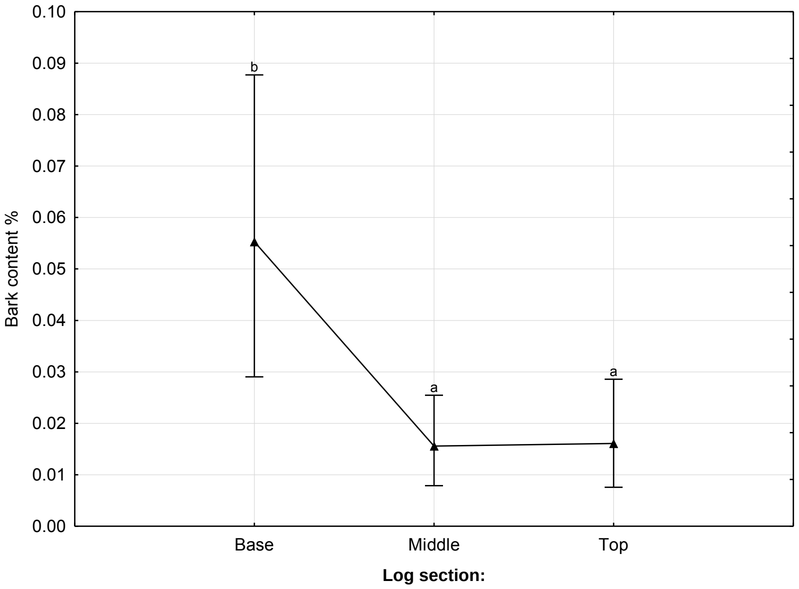


Figure 13: Influence of log class on bark content values (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, etc.).

Table 27: Significant Bootstrap means differences in bark content: Middle logs vs respective logs section classes.

Log class	Bark %	Log class	Bark %	Diff.
Middle	0.016	Base	0.056	- 0.040

Middle logs produced chips 0.040 % lower in bark content than base logs (Table 27 and Figure 16).

Table 28: Significant Bootstrap means differences in bark content: Top logs vs respective log sections.

Log class	**Bark %**	**Log class**	**Bark %**	**Diff.**
Top	0.017	Base	0.056	- 0.039

Top logs produced chips 0.039 % lower in bark content than base logs (Table 28 and Figure 16).

4.3. Chip size and uniformity

4.3.1. Chip size distribution

Chip size and uniformity differed significantly in relation to debarking treatments, log drying periods and log sections (Table 29).

Table 29: ANOVA table for over-sized chips, over-thick chips, accept chips, pin chips and fines three way factorial experiment.

Source of variation	Df	**Over-size**					**Over-thick**					**Accepts**					**Pins**					**Fines**				
		SS	MS	F	p	Prob.	SS	MS	F	p	Prob.	SS	MS	F	p	Prob.	SS	MS	F	p	Prob.	SS	MS	F	p	Prob.
Intercept	1	7	7.2	33.2	0.000	***	2213.5	2213.5	1791.6	0.000	***	3295007	3295007.2	515323.1	0.000	***	160894	160894.3	36322.1	0.000	***	4424	4424.0	24382.6	0.000	***
Main effects																										
Treatment	2	0	0.1	0.6	0.548	NS	0.7	0.4	0.3	0.752	NS	700	349.8	54.7	0.000	***	402	200.9	45.4	0.000	***	43	21.3	117.2	0.000	***
Drying period	1	0	0.2	0.8	0.375	NS	136.7	136.7	110.6	0.000	***	4050	4049.7	633.4	0.000	***	4392	4392.1	991.5	0.000	***	90	89.6	494.1	0.000	***
Log section	2	1	0.3	1.2	0.296	NS	58.4	29.2	23.6	0.000	***	5692	2846.1	445.1	0.000	***	3604	1802.2	406.8	0.000	***	54	27.1	149.1	0.000	***
2 Factor interaction																										
Treatment*Drying period	2	1	0.3	1.4	0.243	NS	8.2	4.1	3.3	0.037	*	21	10.3	1.6	0.200	NS	27	13.5	3.0	0.048	*	1	0.4	1.9	0.145	NS
Treatment*Log section	4	0	0.1	0.5	0.772	NS	13.2	3.3	2.7	0.032	*	41	10.2	1.6	0.174	NS	13	3.3	0.7	0.560	NS	6	1.5	8.2	0.000	***
Drying period*Log section	2	0	0.0	0.1	0.948	NS	2.0	1.0	0.8	0.442	NS	134	66.8	10.4	0.000	***	145	72.4	16.4	0.000	***	4	2.0	11.1	0.000	***
3 Factor interaction																										
Treatment*Drying period*Log section	4	2	0.4	2.0	0.094	NS	3.8	0.9	0.8	0.548	NS	48	11.9	1.9	0.116	NS	46	11.4	2.6	0.037	*	1	0.3	1.4	0.219	NS
Error	531	114	0.2				656.0	1.2				3395	6.4				2352	4.4				96	0.2			
Total	548	118					878.4					14325					11174					306				

4.3.1.1. Over-sized chips

No significant interactions were observed between debarking treatment and drying period (p=0.243), debarking treatment and log class (p=0.772), drying period and log class (p=0.948) or debarking treatment, drying period and log class (p=0.094) and the amount of over-sized chips produced. The individual main effects of debarking treatment, drying period and log class also had no significant effect, on the amount of over-sized chips produced (p=0.548, p=0.375 and p=0.296) (Table 29).

4.3.1.2. Over-thick chips

Treatment × Log drying period

Interactions between debarking treatment and drying period had a significant effect on the amount of over-thick chips produced during chip production (p=0.037)(Table 29 and Figure 17).

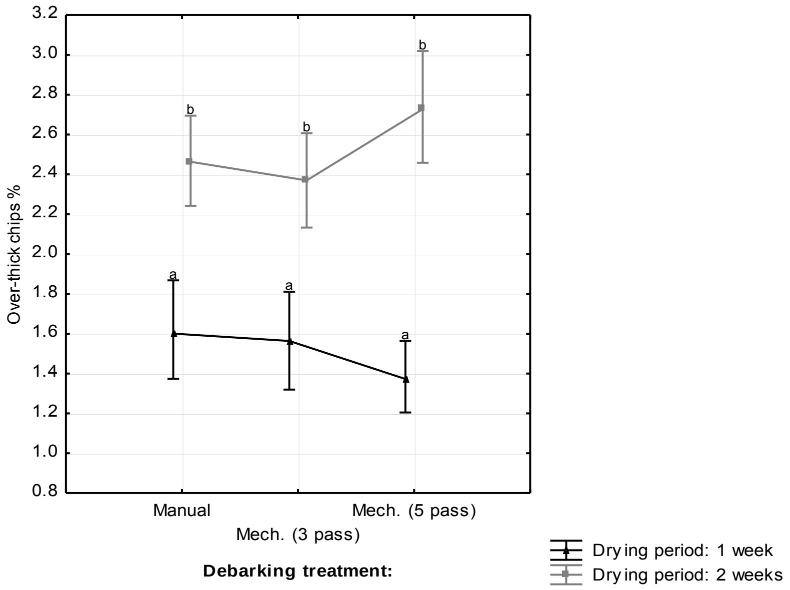


Figure 14: Influence of debarking treatment and log drying period on over-thick chip production (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, etc.).

Table 30: Significant Bootstrap means differences in over-thick chip production: Manually debarked logs dried for one week vs respective debarking treatments and log drying periods.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Manually debarked***		
One week drying	1.6	Two week drying	2.5	- 0.9
		Mech. debarked (three pass)		
		Two week drying	2.4	- 0.8
		Mech. debarked (five pass)		
		Two week drying	2.7	- 1.1

One week dried manually debarked logs produced chips with 0.9 %, 0.8 % and 1.1 % less over-thick chips than chips produced from two week dried manually, three pass and five pass debarked logs respectively (Table 30 and Figure 17).

Table 31: Significant Bootstrap means differences in over-thick chip production: Three pass debarked logs dried for one week vs respective debarking treatments and log drying periods.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Manually debarked***		
One week drying	1.6	Two week drying	2.5	- 0.9
		Mech. debarked (three pass)		
		Two week drying	2.4	- 0.8
		Mech. debarked (five pass)		
		Two week drying	2.7	- 1.1

One week dried three pass debarked logs produced chips with 0.9 %, 0.8 % and 1.1 % less over-thick chips than two week dried manually, three pass and five pass debarked logs respectively (Table 31 and Figure 17).

Table 32: Significant Bootstrap means differences in over-thick chip production: Five pass debarked logs dried for one week vs respective debarking treatments and log drying periods.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Manually debarked***		
One week drying	1.4	Two week drying	2.5	- 1.1
		Mech. debarked (three pass)		
		Two week drying	2.4	- 1.0
		Mech. debarked (five pass)		
		Two week drying	2.7	- 1.3

One week dried five pass debarked logs produced chips with 1.1 %, 1.0 % and 1.3 % less over-thick chips than two week dried manually, three pass mechanically and five pass debarked logs respectively. Significant differences in over-thick chip production in relation to respective debarking treatments and log drying periods are displayed in Table 32 and Figure 17.

Treatment ×Log class

Interactions between debarking treatment and log class had a significant effect on amount of over-thick chips produced (p=0.032)(Table 29 and Figure 18).

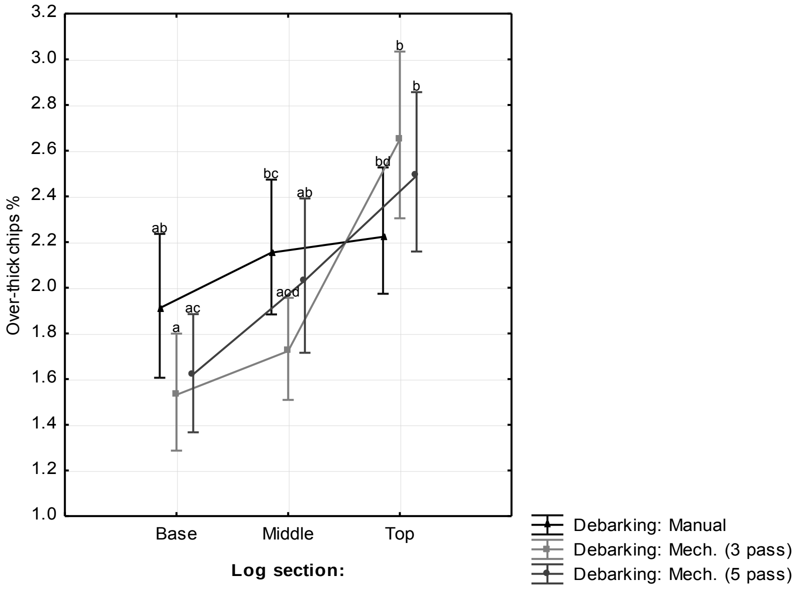


Figure 15: Influence of debarking treatment and log class on over-thick chip production (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, etc.).

Table 33: Significant Bootstrap means differences in over-thick chip production: Manually debarked base logs vs respective debarking treatments and log sections.

Treatment	%	Treatment	%	Diff.
Manually debarked		***Mech. debarked (three pass)***		
Base logs	1.9	Top logs	2.7	- 0.8

Manually debarked base logs produced chips with 0.8 % less over-thick chips than chips produced from three pass debarked top logs (Table 33 and Figure 18).

Table 34: Significant Bootstrap means differences in over-thick chip production: Three pass debarked base logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Base logs	1.5	Top logs	2.7	- 1.2
		Manually debarked		
		Middle logs	2.2	- 0.7
		Top logs	2.2	- 0.7
		Mech. debarked (five pass)		
		Top logs	2.5	- 1.0

Three pass debarked base logs produced chips with 1.2 % less over-thick chips than chips produced from three pass debarked top logs. Three pass debarked base logs also produced chips with 0.7 % and 0.7 % less over-thick chips than chips produced from manually debarked middle and top logs respectively, and 1.0 % less over-thick chips than chips produced from five pass debarked top logs. Significant differences in over-thick chip production in relation to the different debarking treatments and log sections are shown in Table 34 and Figure 18.

Table 35: Significant Bootstrap means differences in over-thick chip production: Three pass debarked middle logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Middle logs	1.7	Top logs	2.7	- 1.0
		Mech. debarked (five pass)		
		Top logs	2.5	- 0.8

Three pass debarked middle logs produced chips with 1.0 % less over-thick chips than three pass debarked top logs and 0.8 % less over-thick chips than five pass debarked top logs (Table 35 and Figure 18).

Table 36: Significant Bootstrap means differences in over-thick chip production: Five pass debarked base logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Base logs	1.6	Top logs	2.5	- 0.9
		Manually debarked		
		Top logs	2.2	- 0.6
		Mech. debarked (three pass)		
		Top logs	2.7	- 1.1

Five pass debarked base logs produced chips with 0.9 % less over-thick chips than five pass debarked top logs. Five pass debarked base logs also produced chips with 0.6 % less over-thick chips than manually debarked top logs and 1.1 % less over-thick chips than three pass debarked top logs (Table 36 and Figure 18).

4.3.1.3. Accept chips

Treatment

Debarking treatment had a very highly significant effect on the amount of accept chips produced (p<0.001)(Table 29 and Figure 19).

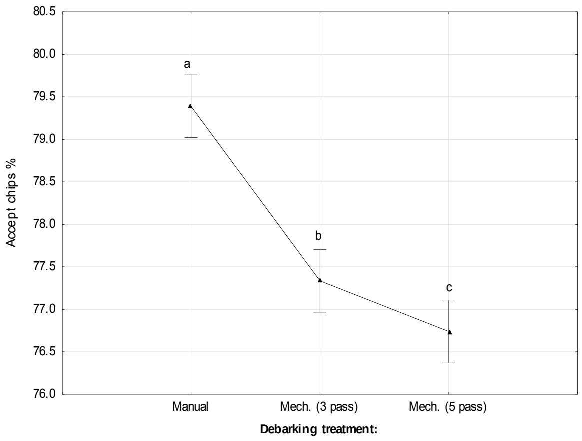


Figure 16: Influence of debarking treatment on the production of accept chips (significant differences in treatment mean are marked with different letters such as a, b, c, etc.).

Table 37: Significant LSM differences in accept chip production: Five pass debarked logs vs respective debarking treatments.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)	76.7	Manually debarked	79.4	- 2.7
		Mech. debarked (three pass)	77.3	- 0.6

Five pass debarked logs produced chips with 2.7 % and 0.6 % less accept chips than manually and three pass debarked logs respectively (Table 37 and Figure 19).

Table 38: Significant LSM differences in accept chip production: Three pass debarked logs vs manually debarked logs.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)	77.3	Manually debarked	79.4	- 2.1

Three pass debarked logs produced chips with 2.1 % less accept chips than manually debarked logs (Table 38 and Figure 4.9).

Drying period × Log class

Interactions between drying period and log class, had a very highly significant effect on the amount of accept chips produced (p<0.001)(Table 29 and Figure 20).

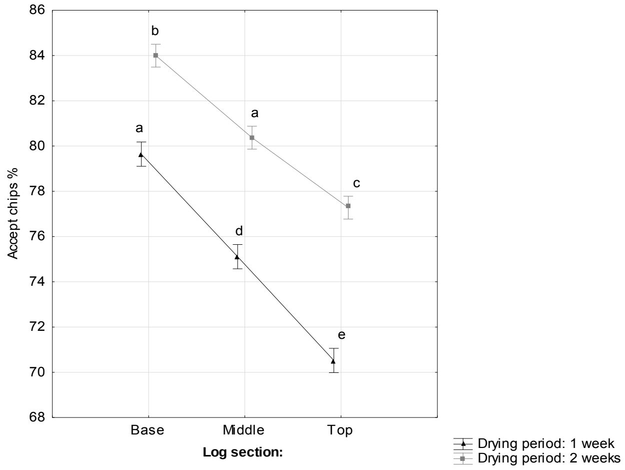


Figure 20: Influence of log drying period and log sections on the production of accept chips (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, e, etc.).

Table 39: Significant LSM differences in accept chip production: Top logs dried for one week vs respective log drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
One week drying		***One week drying***		
Top logs	70.5	Base logs	79.6	- 9.1
		Middle logs	75.1	- 4.6
		Two week drying		
		Base logs	84.0	- 13.5
		Middle logs	80.4	- 9.9
		Top logs	77.3	- 6.8

One week dried top logs produced chips with 9.1 % and 4.6 % less accept chips than base and middle logs dried for the same time period. One week dried top logs also produced chips with 13.5 %, 9.9 % and 6.8 % less accept chips than two week dried base, middle and top logs respectively. Significant differences in accept chip production in relation to respective log drying periods and log sections are shown in Table 39 and Figure 20.

Table 40: Significant LSM differences in accept chip production: Middle logs dried for one week vs respective log drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
One week drying		***One week drying***		
Middle logs	75.1	Base logs	79.6	- 4.5
		Two week drying		
		Base logs	84.0	- 8.9
		Middle logs	80.4	- 5.3
		Top logs	77.3	- 2.2

One week dried middle logs produced chips with 4.5 % less accept chips than base logs dried for the same time period. One week dried middle logs also produced chips with 8.9 %, 5.3 % and 2.2 % less accept chips than two week dried base, middle and top logs respectively. Significant differences in accept chip production in relation to respective log drying periods and log sections are shown in Table 40 and Figure 20.

Table 41: Significant LSM differences in accept chip production: Base logs dried for one week vs base two week dried logs.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
One week drying		***Two week drying***		
Base logs	79.6	Base logs	84.0	- 4.4

One week dried base logs produced chips with 4.4 % less accept chips than two week dried base logs (Table 41 and Figure 20).

Table 42: Significant LSM differences in accept chip production: Top two week dried logs vs respective log drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
Two week drying		***Two week drying***		
Top logs	77.3	Base logs	84.0	- 6.7
		Middle logs	80.4	- 3.1
		One week drying		
		Base logs	79.6	- 2.3

Two week dried top logs produced chips with 6.7 % and 3.1 % less accept chips than base and middle logs dried for the same time period. Two week dried top logs also produced chips with 2.3 % less accept chips than one week dried base logs. Significant differences in accept chip production in relation to respective log drying periods and log sections are shown in Table 42 and Figure 20.

Table 43: Significant LSM differences in accept chip production: Middle two week dried logs vs base two week dried logs.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
Two week drying		***Two week drying***		
Middle logs	80.4	Base logs	84.0	- 3.6

Two week dried middle logs produced chips with 3.6 % less accept chips than base logs dried for the same time period (Table 43 and Figure 20).

4.3.1.4. Pin chips

Treatment × Drying-period × Log class

A significant three way interaction was observed between the main effects of debarking treatment, drying period and log class, and the amount of pins produced during chip production (p=0.037)(Table 29 and Figure 21).

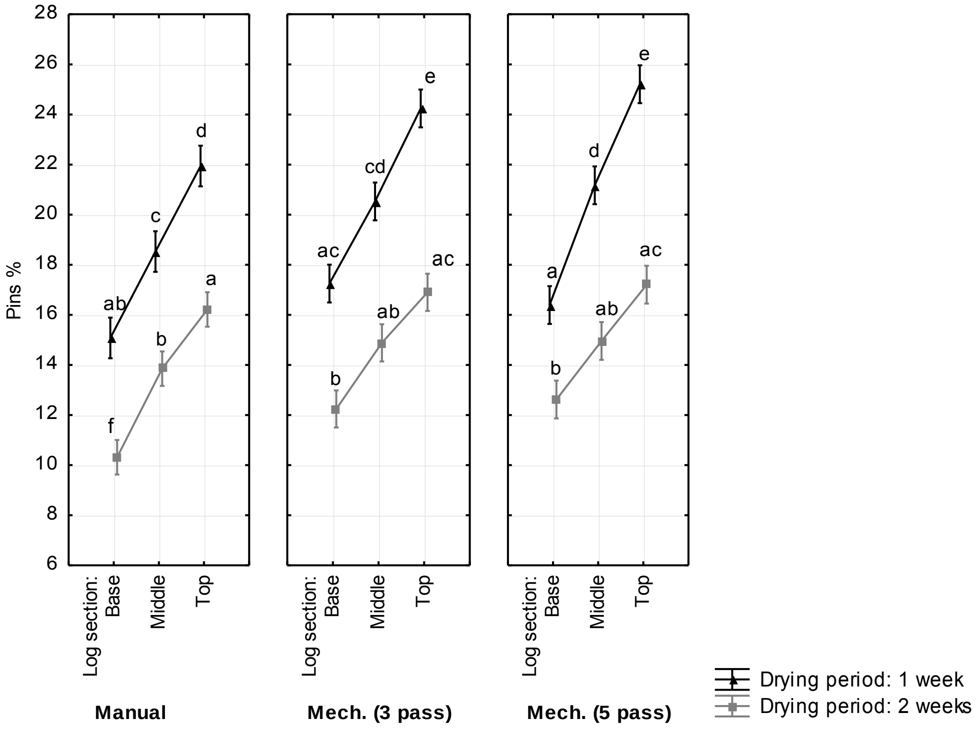


Figure 21: Influence of debarking treatment, log drying period and log sections on the production of pins (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, e, f, etc.).

Manually debarked base logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried manually debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 44).

Table 44: Significant LSM differences in pin sized chip production: Manually debarked base two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	%	Treatment	%	Diff.
Manually debarked		***Manually debarked***		
Base logs (two week drying)	10.3	Middle logs (two week drying)	13.9	- 3.6
		Top logs (two week drying)	16.2	- 5.9
		Mech. debarked (three pass)		
		Base logs (two week drying)	12.2	- 1.9
		Middle logs (two week drying)	14.9	- 4.6
		Top logs (two week drying)	16.9	- 6.6
		Mech. debarked (five pass)		
		Base logs (two week drying)	12.6	- 2.3
		Middle logs (two week drying)	15.0	- 4.7
		Top logs (two week drying)	17.2	- 6.9
		Manually debarked		
		Base logs (one week drying)	15.1	- 4.8
		Middle logs (one week drying)	18.5	- 8.2
		Top logs (one week drying)	21.9	- 11.6
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 6.9
		Middle logs (one week drying)	20.5	- 10.2
		Top logs (one week drying)	24.2	- 13.9
		Mech. debarked (five pass)		
		Base logs (one week drying)	16.4	- 6.1
		Middle logs (one week drying)	21.2	- 10.9
		Top logs (one week drying)	25.2	- 14.9

Two week dried manually debarked base logs produced chips with 3.6 % and 5.9 % less pins than manually debarked middle and top logs dried for the same time period and 4.8 %, 8.2 % and 11.6 % less pins than one week dried manually debarked base, middle and top logs respectively. Two week dried manually debarked base logs also produced chips with1.9 %, 4.6 % and 6.6 % less pins than two week dried three pass debarked base, middle and top logs and 6.9 %, 10.2 % and 13.9 %less pins than one week dried three pass debarked base, middle and top logs respectively. Furthermore two week dried manually debarked base logs also produced chips with 2.3 %, 4.7 % and 6.9 % less pins than two week dried five pass debarked base, middle and top logs respectively and 6.1 %, 10.9 % and 14.9 % less pins than one week dried five pass debarked base middle and top logs respectively.

Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 44 and Figure 21.

Manually debarked middle logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried manually debarked middle logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 45).

Table 45: Significant LSM differences in pin sized chip production: Manually debarked middle two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Manually debarked***		
Middle logs (two week drying)	13.9	Top logs (two week drying)	16.2	- 2.3
		Mech. debarked (three pass)		
		Top logs (two week drying)	16.9	- 3.0
		Mech. debarked (five pass)		
		Top logs (two week drying)	17.2	- 3.3
		Manually debarked		
		Middle logs (one week drying)	18.5	- 4.6
		Top logs (one week drying)	21.9	- 8.0
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 3.3
		Middle logs (one week drying)	20.5	- 6.6
		Top logs (one week drying)	24.2	- 10.3
		Mech. debarked (five pass)		
		Base logs (one week drying)	16.4	- 2.5
		Middle logs (one week drying)	21.2	- 7.3
		Top logs (one week drying)	25.2	- 11.3

Two week dried manually debarked middle logs produced chips with 2.3 % less pins than manually debarked top logs dried for the same time period and 4.6 % and 8.0 % less pins than one week dried manually debarked middle and top logs respectively. Two week dried manually debarked middle logs also produced chips with 3.0 % less pins than two week dried three pass debarked top logs and 3.3 %, 6.6 % and 10.3 % less pins than one week dried three pass debarked base, middle and top logs respectively. Furthermore two week dried manually debarked middle logs also produced chips with 3.3 % less pins than two week dried five pass debarked top logs and 2.5 %, 7.3 % and 11.3 % less pins than one week dried five pass debarked base, middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 45 and Figure 21.

Manually debarked top logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried manually debarked top logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 46).

Table 46: Significant LSM differences in pin sized chip production: Manually debarked top two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	%	Treatment	%	Diff.
Manually debarked		***Manually debarked***		
Top logs (two week drying)	16.2	Middle logs (one week drying)	18.5	- 2.3
		Top logs (one week drying)	21.9	- 5.7
		Mech. debarked (three pass)		
		Middle logs (one week drying)	20.5	- 4.3
		Top logs (one week drying)	24.2	- 8.0
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 5.0
		Top logs (one week drying)	25.2	- 9.0

Two week dried manually debarked top logs produced chips with 2.3 % and 5.7 % less pins than one week dried manually debarked middle and top logs respectively. Two week dried manually debarked top logs also produced chip with 4.3 % and 8.0 % less pins than one week dried three pass debarked middle and top logs respectively, and 5.0 % and 9.0 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 46 and Figure 21.

Manually debarked base logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried manually debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 47).

Table 47: Significant LSM differences in pin sized chip production: Manually debarked base logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Mech. debarked (five pass)***		
Base logs (one week drying)	15.1	Top logs (two week drying)	17.2	- 2.1
		Manually debarked		
		Middle logs (one week drying)	18.5	- 3.4
		Top logs (one week drying)	21.9	- 6.8
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 2.1
		Middle logs (one week drying)	20.5	- 5.4
		Top logs (one week drying)	24.2	- 9.1
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 6.1
		Top logs (one week drying)	25.2	- 10.1

One week dried manually debarked base logs produced chips with 3.4 % and 6.8 % less pins than manually debarked middle and top logs dried for the same time period and 2.1 %, 5.4 % and 9.1 % less pins than one week dried three pass debarked base middle and top logs respectively. One week dried manually debarked base logs also produced chips with 2.1 % less pins than two week dried five pass debarked top logs and 6.1 % and 10.1 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 47 and Figure 21.

Manually debarked middle logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried manually debarked middle logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 48).

Table 48: Significant LSM differences in pin sized chip production: Manually debarked middle logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Manually debarked***		
Middle logs (one week drying)	18.5	Top logs (one week drying)	21.9	- 3.4
		Mech. debarked (three pass)		
		Middle logs (one week drying)	20.5	- 2.0
		Top logs (one week drying)	24.2	- 5.7
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 2.7
		Top logs (one week drying)	25.2	- 6.7

One week dried manually debarked middle logs produced chips with 3.4 % less pins than manually debarked top logs dried for the same time period. One week dried manually debarked middle logs also produced chips with 2.0 % and 5.7 % less pins than one week dried three pass debarked middle and top logs respectively, and 2.7 % and 6.7 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 48 and Figure 21.

Manually debarked top logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried manually debarked top logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 49).

Table 49: Significant LSM differences in pin sized chip production: Manually debarked top logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Mech. debarked (three pass)***		
Top logs (one week drying)	21.9	Top logs (one week drying)	24.2	- 2.3
		Mech. debarked (five pass)		
		Top logs (one week drying)	25.2	- 3.3

One week dried manually debarked top logs produced chips with 2.3 % and 3.3 % less pins than one week dried three pass and five pass debarked top logs respectively (Table 49 and Figure 21).

Mechanical (three pass) debarked base logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried three pass debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 50).

Table 50: Significant LSM differences in pin sized chip production: Three pass debarked base two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Base logs (two week drying)	12.2	Middle logs (two week drying)	14.9	- 2.7
		Top logs (two week drying)	16.9	- 4.7
		Manually debarked		
		Top logs (two week drying)	16.2	- 4.0
		Mech. debarked (five pass)		
		Middle logs (two week drying)	15.0	- 2.8
		Top logs (two week drying)	17.2	- 5.0
		Manually debarked		
		Base logs (one week drying)	15.1	- 2.9
		Middle logs (one week drying)	18.5	- 6.3
		Top logs (one week drying)	21.9	- 9.7
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 5.0
		Middle logs (one week drying)	20.5	- 8.3
		Top logs (one week drying)	24.2	- 12.0
		Mech. debarked (five pass)		
		Base logs (one week drying)	16.4	- 4.2
		Middle logs (one week drying)	21.2	- 9.0
		Top logs (one week drying)	25.2	- 13.0

Two week dried three pass debarked base logs produced chips with 2.7 % and 4.7 % less pins than three pass debarked middle and top logs dried for the same time period and 5.0 %, 8.3 % and 12.0 % less pins than one week dried three pass debarked base, middle and top logs respectively. Two week dried three pass debarked base logs also produced chips with 4.0 % less pins than two week dried manually debarked top logs and 2.9 %, 6.3 % and 9.7 % less pins than one week dried manually debarked base, middle and top logs respectively, and 2.7 % and 4.7

% less pins than two week dried five pass debarked middle and top logs respectively, and 4.2 %, 9.0 % and 13.0 % less pins than one week dried five pass debarked base, middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 50 and Figure 21.

Mechanical (three pass) debarked middle logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried three pass debarked middle logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 51).

Table 51: Significant LSM differences in pin sized chip production: Three pass debarked middle two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	%	Treatment	%	Diff.
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Middle logs (two week drying)	14.9	Top logs (two week drying)	16.9	- 2.0
		Mech. debarked (five pass)		
		Top logs (two week drying)	17.2	- 2.3
		Manually debarked		
		Middle logs (one week drying)	18.5	- 3.6
		Top logs (one week drying)	21.9	- 7.0
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 2.3
		Middle logs (one week drying)	20.5	- 5.6
		Top logs (one week drying)	24.2	- 9.3
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 6.3
		Top logs (one week drying)	25.2	- 10.3

Two week dried three pass debarked middle logs produced chips with 2.0 % less pins than three pass debarked top logs dried for the same time period and 2.3 %, 5.6 % and 9.3 % less pins than one week dried three pass debarked base, middle and top logs respectively. Two week dried three pass debarked middle logs also produced chips with 3.6 % and 7.0 % less pins than one week dried manually debarked middle and top logs respectively, and 2.3 % less pins than two week dried five pass debarked top logs and 6.3 % and 10.3 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 51 and Figure 21.

Mechanical (three pass) debarked top logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried three pass debarked top logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 52).

Table 52: Significant LSM differences in pin sized chip production: Three pass debarked top two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		**Mech. debarked (three pass)**		
Top logs (two week drying)	16.9	Middle logs (one week drying)	20.5	- 3.6
		Top logs (one week drying)	24.2	- 7.3
		Manually debarked		
		Top logs (one week drying)	21.9	- 5.0
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 4.3
		Top logs (one week drying)	25.2	- 8.3

Two week dried three pass debarked top logs produced chips with 3.6 % and 7.3 % less pins than one week dried three pass debarked middle and top logs respectively. Two week dried three pass debarked top logs also produced chips with 5.0 % less pins than one week dried manually debarked top logs and 4.3 % and 8.3 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 52 and Figure 21.

Mechanical (three pass) debarked base logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried three pass debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 53).

Table 53: Significant LSM differences in pin sized chip production: Three pass debarked base logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Base logs (one week drying)	17.2	Middle logs (one week drying)	20.5	- 3.3
		Top logs (one week drying)	24.2	- 7.0
		Manually debarked		
		Top logs (one week drying)	21.9	- 4.7
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 4.0
		Top logs (one week drying)	25.2	- 8.0

One week dried three pass debarked base logs produced chips with 3.3 % and 7.0 % less pins than three pass debarked middle and top logs dried for the same time period. One week dried three pass debarked base logs also produced chips with 4.7 % less pins than one week dried manually debarked top logs and 4.0 % and 8.0 % less pins than one week dried five pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 53 and Figure 21.

Mechanical (three pass) debarked middle logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried three pass debarked middle and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 54).

Table 54: Significant LSM differences in pin sized chip production: Three pass debarked middle logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Middle logs (one week drying)	20.5	Top logs (one week drying)	24.2	- 3.7
		Mech. debarked (five pass)		
		Top logs (one week drying)	25.2	- 4.7

One week dried three pass debarked middle logs produced chips with 3.7 % less pins than three pass debarked top logs dried for the same time period. One week dried three pass debarked middle logs also produced chips with 4.7 % less pins than one week dried five pass debarked top logs. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 54 and Figure 21.

Mechanical (five pass) debarked base logs: two week drying period
Significant LSM differences were observed in chip pin content between chips produced from two week dried five pass debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 55).

Table 55: Significant LSM differences in pin sized chip production: Five pass debarked base two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Base logs (two week drying)	12.6	Middle logs (two week drying)	15.0	- 2.4
		Top logs (two week drying)	17.2	- 4.6
		Manually debarked		
		Top logs (two week drying)	16.2	- 3.6
		Mech. debarked (three pass)		
		Middle logs (two week drying)	14.9	- 2.3
		Top logs (two week drying)	16.9	- 4.3
		Manually debarked		
		Base logs (one week drying)	15.1	- 2.5
		Middle logs (one week drying)	18.5	- 5.9
		Top logs (one week drying)	21.9	- 9.3
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 4.6
		Middle logs (one week drying)	20.5	- 7.9
		Top logs (one week drying)	24.2	- 11.6
		Mech. debarked (five pass)		
		Base logs (one week drying)	16.4	- 3.8
		Middle logs (one week drying)	21.2	- 8.6
		Top logs (one week drying)	25.2	- 12.6

Two week dried five pass debarked base logs produced chips with 2.4 % and 4.6 % less pins than five pass debarked middle and top logs dried for the same time period respectively and 3.8 %, 8.6 % and 12.6 % less pins than one week dried five pass debarked base, middle and top logs respectively. Two week dried five pass debarked base logs also produced chips with 3.6 % less pins than two week dried manually debarked top logs and 2.5 %, 5.9 % and 9.3 % less pins than one week dried manually debarked base, middle and top logs respectively and 2.3 % and 4.3 % less pins than two week dried three pass debarked middle and top logs respectively, and 4.6 %, 7.9 % and 11.6 % less pins than one week dried three pass debarked base middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 55 and Figure 21.

Mechanical (five pass) debarked middle logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried five pass debarked middle logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 56).

Table 56: Significant LSM differences in pin sized chip production: Five pass debarked middle two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	%	Treatment	%	Diff.
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Middle logs (two week drying)	15.0	Top logs (two week drying)	17.2	- 2.2
		Manual debarked		
		Middle logs (one week drying)	18.5	- 3.5
		Top logs (one week drying)	21.9	- 6.9
		Mech. debarked (three pass)		
		Base logs (one week drying)	17.2	- 2.2
		Middle logs (one week drying)	20.5	- 5.5
		Top logs (one week drying)	24.2	- 9.2
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 6.2
		Top logs (one week drying)	25.2	- 10.2

Two week dried five pass debarked middle logs produced chips with 2.2 % less pins than five pass debarked top logs dried for the same time period and 6.2 % and 10.2 % less pins than one week dried five pass debarked middle and top logs respectively. Two week dried five pass debarked middle logs also produced chips with 3.5 % and 6.9 % less pins than one week dried manually debarked middle and top logs respectively, and 2.2 %, 5.5 % and 9.2 % less pins than one week dried three pass debarked base, middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 56 and Figure 21.

Mechanical (five pass) debarked top logs: two week drying period

Significant LSM differences were observed in chip pin content between chips produced from two week dried five pass debarked top logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 57).

Table 57: Significant LSM differences in pin sized chip production: Five pass debarked top two week dried logs vs respective debarking treatments, log drying periods and log sections.

Treatment	%	Treatment	%	Diff.
Mech. debarked (five pass)		***Manually debarked***		
Top logs (two week drying)	17.2	Top logs (one week drying)	21.9	- 4.7
		Mech. debarked (three pass)		
		Middle logs (one week drying)	20.5	- 3.3
		Top logs (one week drying)	24.2	- 7.0
		Mech. debarked (five pass)		
		Middle logs (one week drying)	21.2	- 4.0
		Top logs (one week drying)	25.2	- 8.0

Two week dried five pass debarked top logs produced chips with 4.0 % and 8.0 % less pins than one week dried five pass debarked middle and top logs respectively. Two week dried five pass debarked top logs also produced chips with 4.7 % less pins than one week dried manually debarked top logs and 3.3 % and 7.0 % less pins than one week dried three pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 57 and Figure 21.

Mechanical (five pass) debarked base logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried five pass debarked base logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 58).

Table 58: Significant LSM differences in pin sized chip production: Five pass debarked base logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Base logs (one week drying)	16.4	Middle logs (one week drying)	21.2	- 4.8
		Top logs (one week drying)	25.2	- 8.8
		Manually debarked		
		Middle logs (one week drying)	18.5	- 2.1
		Top logs (one week drying)	21.9	- 5.5
		Mech. debarked (three pass)		
		Middle logs (one week drying)	20.5	- 4.1
		Top logs (one week drying)	24.2	- 7.8

One week dried five pass debarked base logs produced chips with 4.8 % and 8.8 % less pins than five pass debarked middle and top logs dried for the same time period. One week dried five pass debarked base logs also produced chips with 2.1 % and 5.5 % less pins than one week dried manually debarked middle and top logs respectively, and 4.1 % and 7.8 % less pins than one week dried three pass debarked middle and top logs respectively. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 58 and Figure 21.

Mechanical (five pass) debarked middle logs: one week drying period

Significant LSM differences were observed in chip pin content between chips produced from one week dried five pass debarked middle logs and chips produced from logs subject to respective debarking treatments, log drying periods and log sections (Table 59).

Table 59: Significant LSM differences in pin sized chip production: Five pass debarked middle logs dried for one week vs respective debarking treatments, log drying periods and log sections.

Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Middle logs (one week drying)	21.2	Top logs (one week drying)	25.2	- 4.0
		Mech. debarked (three pass)		
		Top logs (one week drying)	24.2	- 3.0

One week dried five pass debarked middle logs produced chips with 4.0 % less pins than five pass debarked top logs dried for the same time period. One week dried five pass debarked middle logs also produced chips with 3.0 % less fines than one week dried three pass debarked top logs. Significant differences in pin chip production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 59 and Figure 21.

4.3.1.5. Fines

Treatment × Log class

Interactions between debarking treatment and log class had a very highly significant effect on the amount of fines produced (p<0.001)(Table 29 and Figure 22).

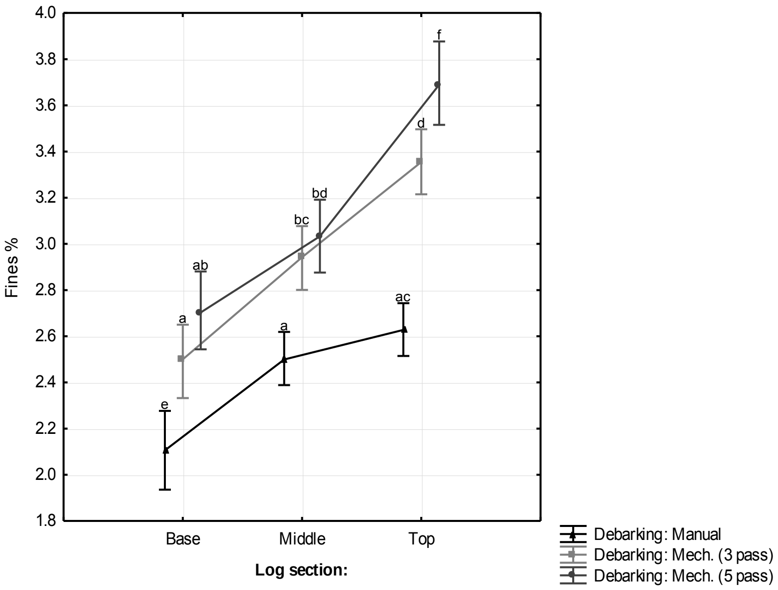


Figure 22: Influence of debarking treatments and log sections on the production of fines (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, e, f, etc.).

Manually debarked logs

Significant LSM differences were observed in chip fines content between chips produced from manually debarked logs and chips produced from logs subject to respective debarking treatments and log sections.

Table 60: Significant Bootstrap means differences in chip fines production: Manually debarked base logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Manually debarked***		
Base logs	2.1	Middle logs	2.5	- 0.4
		Top logs	2.6	- 0.5
		Mech. debarked (three pass)		
		Base logs	2.5	- 0.4
		Middle logs	2.9	- 0.8
		Top logs	3.4	- 1.3
		Mech. debarked (five pass)		
		Base logs	2.7	- 0.6
		Middle logs	3.0	- 0.9
		Top logs	3.7	- 1.6

Manually debarked base logs produced chips with 0.4 % and 0.5 % less fines than manually debarked middle and top logs respectively. Manually debarked base logs also produced chips with 0.4 %, 0.8 % and 1.3 % less fines than three pass debarked base, middle and top logs respectively, and 0.6 %, 0.9 % and 1.6 % less fines than five pass debarked base, middle and top logs respectively. Significant differences in fines production in relation to respective debarking treatments, log drying periods and log sections are shown in Table 60 and Figure 22.

Table 61: Significant Bootstrap means differences in chip fines production: Manually debarked middle logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Mech. debarked (three pass)***		
Middle logs	2.5	Middle logs	2.9	- 0.4
		Top logs	3.4	- 0.9
		Mech. debarked (five pass)		
		Middle logs	3.0	- 0.5
		Top logs	3.7	- 1.2

Manually debarked middle logs produced chips with 0.4% and 0.9 % less fines than three pass debarked middle and top logs respectively, and 0.5 % and 1.2 % less fines than five pass debarked middle and top logs respectively (Table 61 and Figure 22).

Table 62: Significant Bootstrap means differences in chip fines production: Manually debarked top logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Manually debarked		***Mech. debarked (three pass)***		
Top logs	2.6	Middle logs	2.9	- 0.3
		Top logs	3.4	- 0.8
		Mech. debarked (five pass)		
		Middle logs	3.0	- 0.4
		Top logs	3.7	- 1.1

Manually debarked top logs produced chips with 0.3 % and 0.8 % less fines than three pass debarked middle and top logs respectively, and 0.4 % and 1.1 % less fines than five pass debarked middle and top logs respectively (Table 62 and Figure 22).

Mechanical (three pass) debarked logs

Significant LSM differences were observed in chip fines content between chips produced from three pass debarked logs and chips produced from logs subject to respective debarking treatments and log sections.

Table 63: Significant Bootstrap means differences in chip fines production: Three pass debarked base logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Base logs	2.5	Middle logs	2.9	- 0.4
		Top logs	3.4	- 0.9
		Mech. debarked (five pass)		
		Middle logs	3.0	- 0.5
		Top logs	3.7	- 1.2

Three pass debarked base logs produced chips with 0.4 % and 0.9 % less fines than three pass debarked middle and top logs respectively, and 0.5 % and 1.2 % less fines than five pass debarked middle and top logs respectively (Table 63 and Figure 22).

Table 64: Significant Bootstrap means differences in chip fines production: Three pass debarked middle logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (three pass)***		
Middle logs	2.9	Top logs	3.4	- 0.5
		Mech. debarked (five pass)		
		Top logs	3.7	- 0.8

Three pass debarked middle logs produced chips with 0.5 % less fines than three pass debarked top logs and 0.8 % less fines than five pass debarked top logs (Table 64 and Figure 22).

Table 65: Significant Bootstrap means differences in chip fines production: Three pass debarked top logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)		***Mech. debarked (five pass)***		
Top logs	3.4	Top logs	3.7	- 0.3

Three pass debarked top logs produced chips with 0.3 % less fines than five pass debarked top logs (Table 65 and Figure 22).

Mechanical (five pass) debarked logs

Significant LSM differences were observed in chip fines content between chips produced from five pass debarked logs and chips produced from logs subject to respective debarking treatments and log sections.

Table 66: Significant Bootstrap means differences in chip fines production: Five pass debarked base logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Base logs	2.7	Top logs	3.7	- 1.0
		Mech. debarked (three pass)		
		Top logs	3.4	- 0.7

Five pass debarked base logs produced chips with 1.0 % less fines than five pass debarked top logs and 0.7 % less fines than three pass debarked top logs (Table 66 and Figure 22).

Table 67: Significant Bootstrap means differences in chip fines production: Five pass debarked middle logs vs respective debarking treatments and log sections.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (five pass)		***Mech. debarked (five pass)***		
Middle logs	3.0	Top logs	3.7	- 0.7
		Mech. debarked (three pass)		
		Top logs	3.4	- 0.4

Five pass debarked middle logs produced chips with 0.7 % less fines than five pass debarked top logs and 0.4 % less fines than three pass debarked top logs (Table 67 and Figure 22).

Drying period × Log class

Interactions between drying period and log class had a very highly significant effect on the amount of fines produced (p<0.001)(Table 29 and Figure 23).

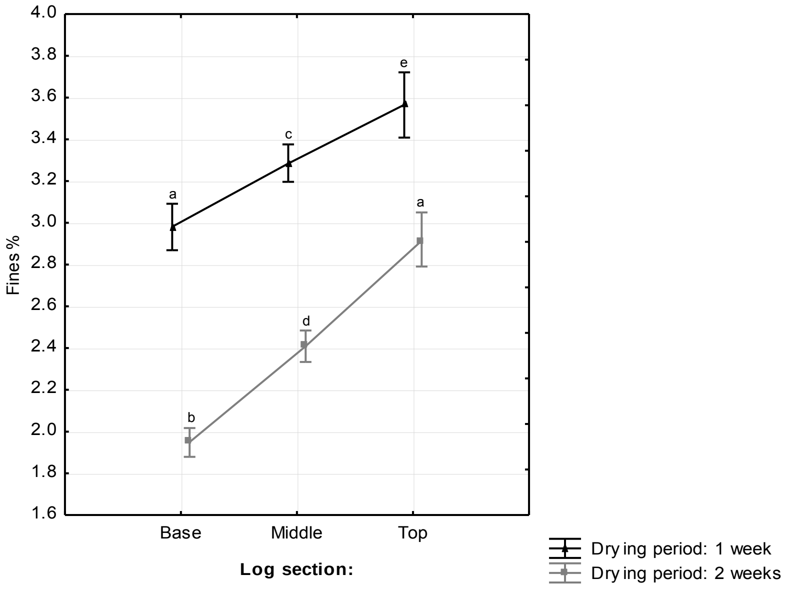


Figure 23: Influence of log drying periods and log sections on the production of fines (treatment means which do not significantly differ are indicated with the same letter, i.e. a, b, c, d, e, etc.).

Two week dried logs

Significant LSM differences were observed in chip fines content between chips produced from two week dried logs and chips produced from logs subject to respective log drying periods and log sections.

Table 68: Significant Bootstrap means differences in chip fines production: Base two week dried logs vs respective drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
Two week drying period		***Two week drying period***		
Base logs	1.9	Middle logs	2.4	- 0.5
		Top logs	2.9	- 1.0
		One week drying period		
		Base logs	3.0	- 1.1
		Middle logs	3.3	- 1.4
		Top logs	3.6	- 1.7

Two week dried base logs produced chips with 0.5 % and 1.0 % less fines than middle and top logs dried for the same drying period respectively and 1.1 %, 1.4 % and 1.7 % less fines than one week dried base, middle and top logs respectively (Table 68 and Figure 23).

Table 69: Significant Bootstrap means differences in chip fines production: Middle two week dried logs vs respective drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
Two week drying period		***Two week drying period***		
Middle logs	2.4	Top logs	2.9	- 0.5
		One week drying period		
		Base logs	3.0	- 0.6
		Middle logs	3.3	- 0.9
		Top logs	3.6	- 1.2

Two week dried middle logs produced chips with 0.5 % less fines than top logs dried for the same time period and 0.6 %, 0.9 % and 1.2 % less fines than one week dried base, middle and top logs respectively (Table 69 and Figure 23).

Table 70: Significant Bootstrap means differences in chip fines production: Top two week dried logs vs respective drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
Two week drying period		***One week drying period***		
Top logs	2.9	Middle logs	3.3	- 0.4
		Top logs	3.6	- 0.7

Two week dried top logs produced chips with 0.4 % and 0.7 % less fines than one week dried middle and top logs respectively (Table 70 and Figure 23).

One week dried logs

Significant LSM differences were observed in chip fines content between chips produced from one week dried logs and chips produced from logs subject to respective log drying periods and log sections.

Table 71: Significant Bootstrap means differences in chip fines production: Base logs dried for one week vs respective drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
One week drying period		***One week drying period***		
Base logs	3.0	Middle logs	3.3	- 0.3
		Top logs	3.6	- 0.6

One week dried base logs produced chips with 0.3 % and 0.6 % less fines than middle and top logs dried for the same time period respectively (Table 71 and Figure 23).

Table 72: Significant Bootstrap means differences in chip fines production: Middle logs dried for one week vs respective drying periods and log sections.

Log drying period	**%**	**Log drying period**	**%**	**Diff.**
One week drying period		***One week drying period***		
Middle logs	3.3	Top logs	3.6	- 0.3

One week dried middle logs produced chips with 0.3 % less fines than top logs dried for the same time period (Table 72 and Figure 23).

4.4. Feed roller induced fibre loss

4.4.1. Fibre loss due to mechanical debarking

Both the parametric ANOVA univariate t-test and the non-parametric Mann-Whitney U t-test indicated that mechanise debarking treatments differed significantly in regards to: wood volume loss per harvesting setting (p=0.001), extractable wood volume % loss per harvesting setting (p=0.006) and wood volume loss per planted ha (p=0.001) (Table 73, Figure 24, 25 and 26).

Table 73: ANOVA table for wood volume loss per ten trees, wood volume loss percentage per ten trees and wood volume loss per ha one way factorial experiment.

Variable		**Wood volume loss (m3) per 10 trees**					**Wood volume loss % per 10 trees**					**Wood volume loss per ha (m3)**				
	DF	SS	MS	F	p	Prob.	SS	MS	F	p	Prob.	SS	MS	F	p	Prob.
Intercept	1	0.01	0.01	212.60	0.000	***	17.47	17.47	124.20	0.000	***	179.22	179.22	212.60	0.000	***
Main effect																
Treatment	1	0.00	0.00	21.40	0.001	**	1.72	1.72	12.20	0.006	**	18.04	18.04	21.40	0.001	**
Error	10	0.00	0.00				1.41	0.14				8.43	0.84			
Total	11	0.00					3.12					26.47				

4.4.1.1. *Fibre loss per harvester setting (10 trees)*

Highly significant LSM differences (p=0.001) were observed in relation to wood fibre loss per ten trees, when comparing trees subject to three pass mechanical debarking and five pass mechanical debarking respectively.

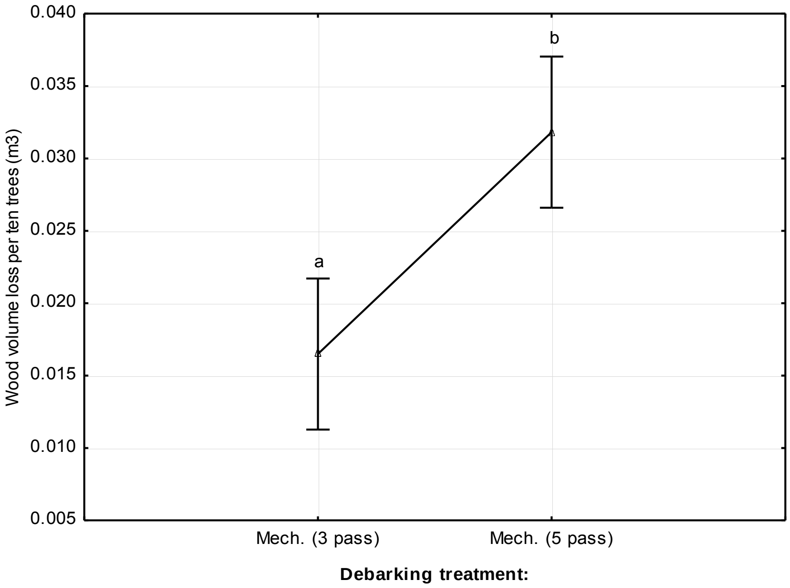


Figure 24: Influence of mechanical debarking treatments on wood fibre lost per harvester setting.

Table 74: Significant Bootstrap means differences in fibre losses associated with mechanical debarking (m^3 ten trees^{-1}): Three pass mechanically debarked logs vs five pass mechanically debarked logs.

Treatment	**(m^3)**	**Treatment**	**(m^3)**	**Diff.**
Mech. debarked (three pass)	0.016	Mech. debarked (five pass)	0.032	- 0.016

Three pass mechanically debarked trees had 0.016 m^3 less wood fibre loss, than five pass mechanically debarking trees per harvester setting (Table 74 and Figure 24).

4.4.1.2. *Fibre loss % (per 10 trees)*

Highly significant LSM differences (p=0.006) were observed in relation to the percentage fibre loss of the total extractable wood volume per ten trees, when comparing trees subject to three pass mechanical debarking and five pass mechanical debarking respectively.

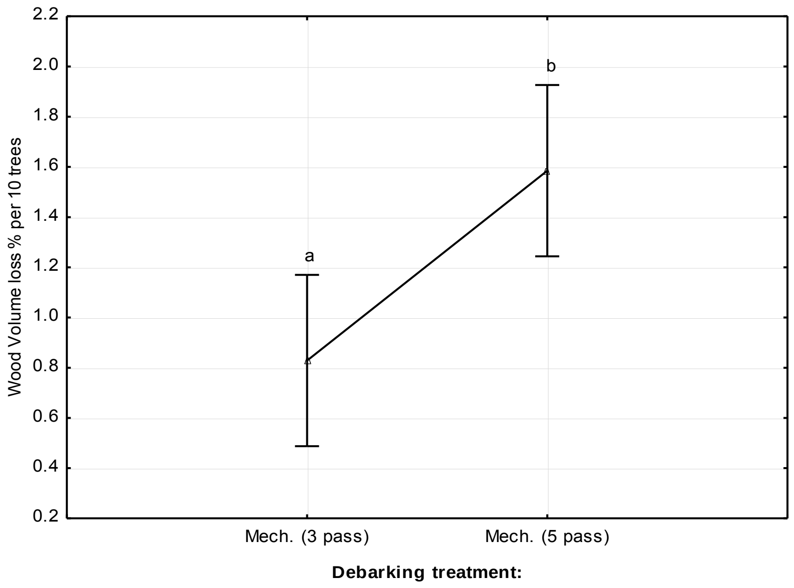


Figure 25: Influence of mechanical debarking treatments on the percentage of wood fibre lost per harvester setting.

Table 75: Significant Bootstrap means differences in fibre losses associated with mechanical debarking (m^3 ten trees^{-1}): Three pass mechanically debarked logs vs five pass mechanically debarked logs.

Treatment	**%**	**Treatment**	**%**	**Diff.**
Mech. debarked (three pass)	0.8	Mech. debarked (Five pass)	1.6	- 0.8

Three pass mechanically debarked trees had 0.8 % less total merchantable wood volume losses, than five pass mechanically debarked trees (Table 75 and Figure 25).

4.4.1.3. Fibre loss per ha

Highly significant LSM differences (p=0.001) were observed in relation to wood fibre loss per planted ha when comparing trees subject to three pass mechanical debarking and five pass mechanical debarking respectively.

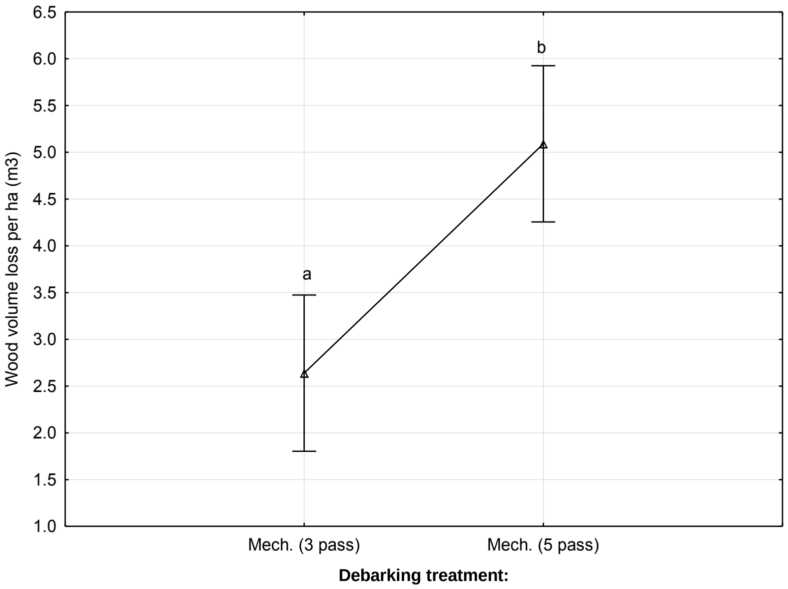


Figure 26: Influence of mechanical debarking treatments on wood fibre lost per ha.

Table 76: Significant Bootstrap means differences in fibre losses associated with mechanical debarking (m^3 ha^{-1}): Three pass mechanically debarked logs vs five pass mechanically debarked logs.

Treatment	**m^3**	**Treatment**	**m^3**	**Diff.**
Mech. debarked (three pass)	2.6	Mech. debarked (five pass)	5.1	- 2.5

Three pass mechanically debarked trees had 2.5 m^3 ha^{-1} less fibre loss, than fibre loss related to five pass mechanically debarked trees (Table 76 and Figure 26).

4.5. Economic evaluation

4.5.1. Value of recoverable pulp

Pulp yields are strongly related to chip size and uniformity. Therefore recoverable pulp value per BDt of chips varied according to both debarking treatments and log drying periods, as these variables influence chip size and uniformity (Table 77).

Table 77: ANOVA table for chip recoverable pulp value two way factorial experiment.

Source of variation	Df	Value of recoverable pulp (R t^{-1})				
		SS	MS	F	P	Prob.
Intercept	1	7280970732.7	7280970732.7	1072017	0.000	***
Main Effect						
Treatment	2	382998.0	191499.0	28	0.000	***
Drying period	1	2584599.7	2584599.7	381	0.000	***
2 Factor interaction						
Treatment*Drying period	2	12607.0	6303.5	1	0.40	NS
Error	543	3687969.4	6791.8			
Total	548	6803927.6				

4.5.1.1. Debarking treatment

Debarking treatment had a very highly significant effect on the value of chips, due to chip pulp yields (p<0.001)(Table 77 and Figure 27).

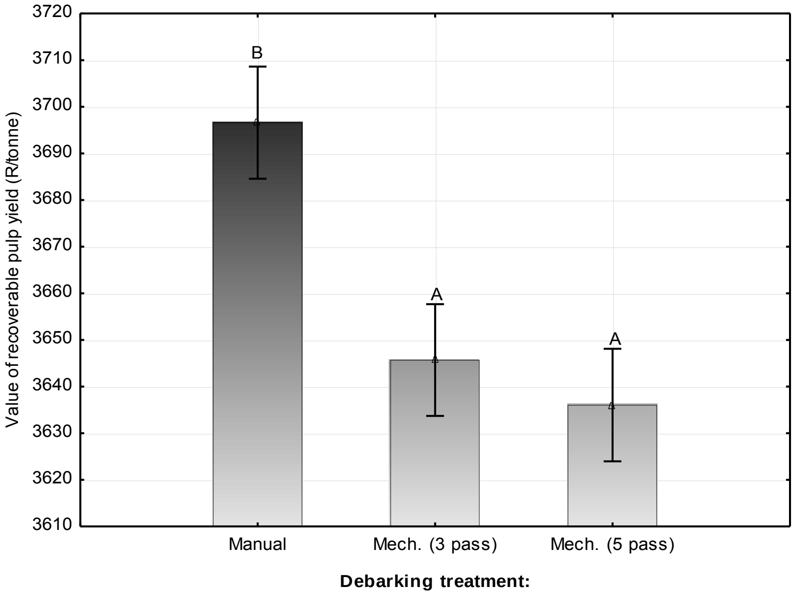


Figure 27: Influence of debarking treatments on the value of recoverable pulp per BDt (treatment means which do not significantly differ are indicated with the same letter, i.e. A, B, etc.).

Both mechanical debarking treatments produced chips, with significantly lower pulp yield and therefore a lower value per BDt of chips.

Table 78: Significant LSM differences in chip value in relation to extractable pulp yields: Three pass debarked logs vs manually debarked logs.

Treatment	Value (R t^{-1})	Treatment	Value (R t^{-1})	Diff.
Mech. debarked (three pass)	R 3 645.69	Manually debarked	R 3 696.59	- R 50.90

Three pass debarked logs produced chips with pulp yields valued at R 50.90 BDt^{-1} less than chips produced from manually debarked logs (Table 78 and Figure 27).

Table 79: Significant LSM differences in chip value in relation to extractable pulp yields: Five pass debarked logs vs manually debarked logs.

Treatment	**Value (R t^{-1})**	**Treatment**	**Value (R t^{-1})**	**Diff.**
Mech. debarked (five pass)	R 3 636.05	Manually debarked	R 3 696.59	- R 60.54

Five pass debarked logs produced chips with pulp yields valued at R 60.54 BDt^{-1} less than chips produced from manually debarked logs (Table 79 and Figure 27).

4.5.1.2. Log drying period

Log drying period had a very highly significant effect on the value of chips, due to chip pulp yields (p<0.001)(Table 77 and Figure 28).

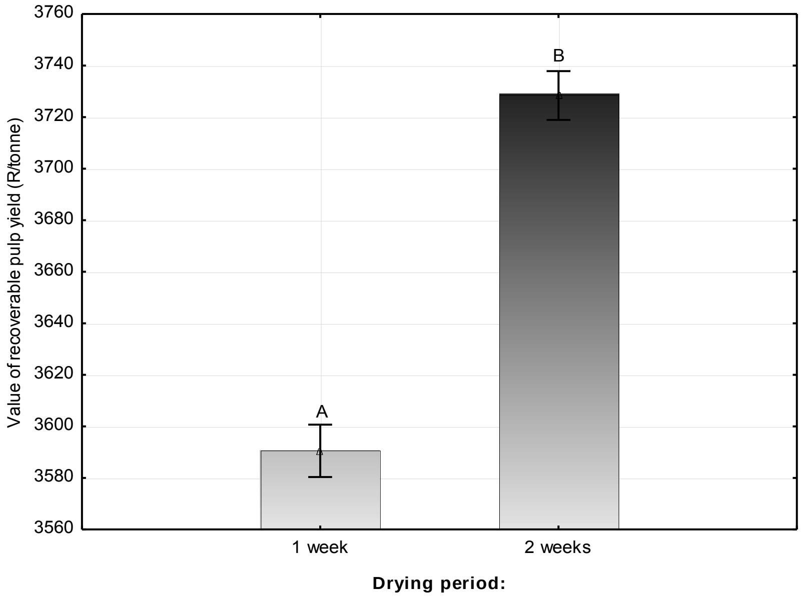


Figure 28: Influence of log drying period on the value of recoverable pulp per BDt (treatment means which do not significantly differ are indicated with the same letter, i.e. A, B, etc.).

Table 80: Significant LSM differences in chip value in relation to extractable pulp yields: Logs dried for one week vs two week dried logs.

Log drying period	**Value (R t^{-1})**	**Log drying period**	**Value (R t^{-1})**	**Diff.**
One week drying period	R 3 590.49	Two week drying period	R 3 728.39	- R 137.90

One week dried logs produced chips with pulp yields valued at

R 137.90 BDt^{-1} less than chips produced from two week dried logs (Table 80 and Figure 28).

4.5.2. Value of fibre lost

Main effect debarking treatment had a very highly significant effect on the value fibre lost during mechanical debarking per harvester setting of ten trees and per ha ($p<0.001$)(Table 81 and Figure 29 and 30).

Table 81: ANOVA table for value of fibre lost per ten trees and per planted ha two way factorial experiment.

Source of variation	Df	**Value of fibre lost (R 10 trees^{-1})**					**Value of fibre lost (R ha^{-1})**				
		SS	MS	F	P	Prob.	SS	MS	F	P	Prob.
Intercept	1	483.8	483.8	417.0	0.000	***	12385410	12385410	417.0	0.000	***
Main Effect											
Treatment	1	66.3	66.3	57.1	0.000	***	1696904	1696904	57.1	0.000	***
Drying period	1	2.7	2.7	2.4	0.141	NS	69930	69930	2.4	0.141	NS
2 Factor interaction											
Treatment*Drying period	1	0.5	0.5	0.4	0.540	NS	11526	11526	0.4	0.540	NS
Error	20	23.2	1.2				593991	29700			
Total	23	92.7					2372350				

4.5.2.1. Value of fibre lost per harvester setting (10 trees)

Significant LSM differences were observed in the value of fibre lost per debarked ten trees, when comparing trees subject to three and five pass mechanical debarking respectively.

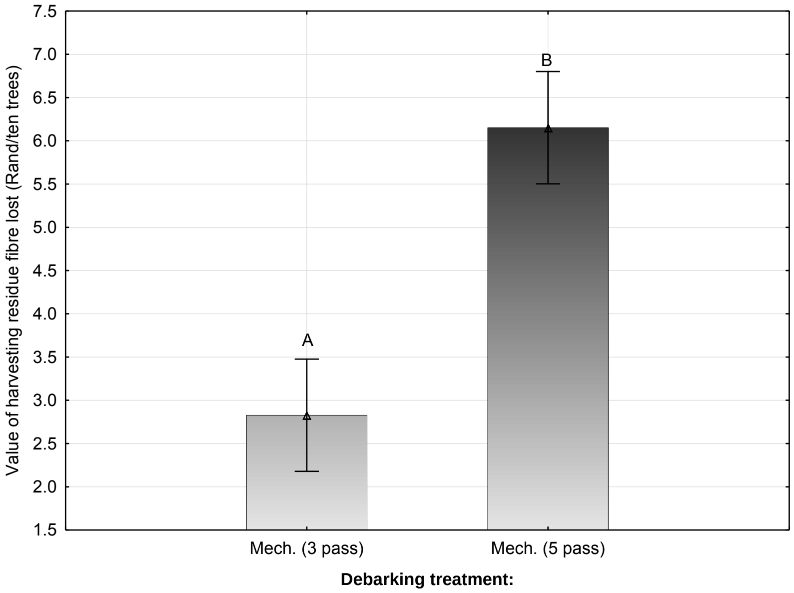


Figure 29: Influence of mechanical debarking treatments on the value of fibre lost due to log surface fracturing per harvester setting (treatment means which do not significantly differ are indicated with the same letter, i.e. A, B, etc.).

Table 82: Significant LSM differences in fibre value lost due to mechanical debarking per ten trees.

Treatment	**Value (R 10 trees^{-1})**	**Treatment**	**Value (R 10 trees^{-1})**	**Diff.**
Mech. debarking (three pass)	R 2.83	Mech. debarking (five pass)	R 6.15	- R 3.32

Trees subject to three pass mechanical debarking had fibre losses valued at R 3.32 ten trees^{-1} less than five pass mechanical debarked trees (Table 82 and Figure 29).

4.5.2.2. Value of fibre lost per ha

Significant LSM differences were observed in the value of fibre lost per ha (1600 trees), when comparing trees subject to three and five pass mechanical debarking respectively.

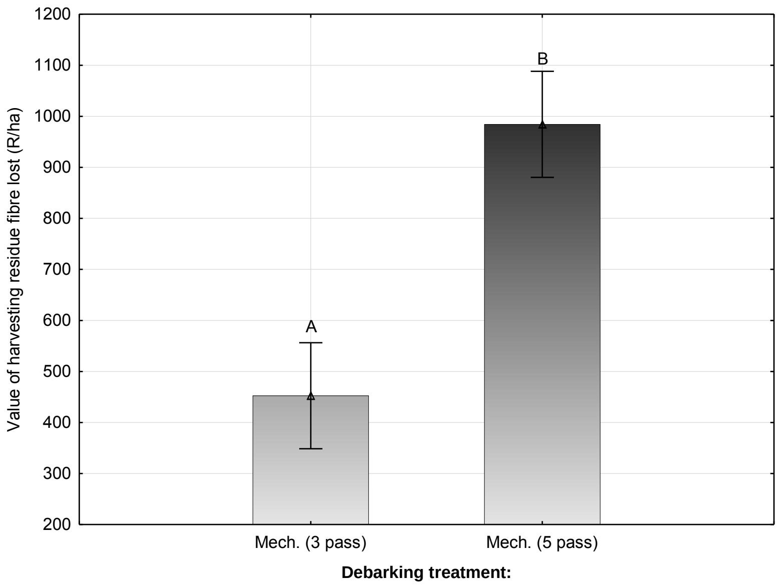


Figure 30: Influence of mechanical debarking treatments on the value of wood fibre lost due to log surface fracturing per planted ha (treatment means which do not significantly differ are indicated with the same letter, i.e. A, B, etc.).

Table 83: Significant LSM differences in fibre value lost due to mechanical debarking per ha.

Treatment	**Value (R ha^{-1})**	**Treatment**	**Value (R ha^{-1})**	**Diff.**
Mech. debarking (three pass)	R 452.47	Mech. debarking (five pass)	R 984.28	- R 531.81

Trees subject to three pass mechanical debarking also had fibre losses valued at R 531.81 ha^{-1}less than five pass mechanical debarked logs (Table 83 and Figure 30).

5. Discussion

5.1. Physical log properties

5.1.1. Moisture content

Interactions between debarking treatments and log sections had a significant effect on chip MC; however, no significant difference in chip MC was observed within individual log sections when comparing MC of chips produced from the different debarking treatments. Chip MC varied according to log sections used for chip production. Log drying rates increased with decreasing logs size, hence the lowest chip MC was recorded for chips produced from the smaller top logs (Connel, 2003; Defo and Brunette, 2007). Chip MC varied between 35.9 % and 38.6 % for chips produced from top logs, between 41.9 % and 43.0 % for chips produced from middle logs and between 46.2 % and 46.7 % for chips produced from base logs. The lowest chip MC for log sections was found in manually debarked logs followed by five pass and three pass debarked logs. Because manually debarked logs were not stacked immediately after harvesting, this may initially have led to higher log drying rates in these logs, due to their exposure to the elements (Persson *et al.*, 2002; Gjerdrum and Salin, 2009). However, the impact of this variable on individual log moisture loss was not sufficient to cause a significant statistical difference in chip MC for chips produced from individual log sections across the debarking treatments.

Log drying period had a significant effect on chip MC for the different log sections. Differences in chip MC produced from the logs section classes were greater during the second week of drying. For two week dried logs, the MC of chips produced from top logs were 6.7 % lower than that of middle logs (31.5 % vs 38.2 %) and chips produced from middle logs were 5.78 % lower than base logs (38.2 % vs 44.0 %). However chips produced from one week dried top logs were 3.2 % lower in MC than chips produced from middle logs (44.4 % vs 47.6 %) and chips produced from middle logs were 1.7 % lower in MC than chips produced from base logs (47.6 % vs 49.3 %). The relatively low rate of moisture loss during the first week of drying was most likely due to the logs being protected by a tarpaulin during the transport from the harvesting site to the chipping facility 1 800 km to the south-west of the country (Persson *et al.*, 2002; Gjerdrum and Salin, 2009).

Differences in chip MC also gradually increased with decreasing log size when compared to chips produced from the different log sections subjected to one week and two week drying periods. Two week dried base logs produced chips

5.3 % lower in MC than one week dried base logs (44.0 % vs 49.3 %), two week dried middle logs produced chips 9.4 % lower in MC than one week dried middle logs (38.2 % vs 47.6 %) and two week dried top logs produced chips12.9 % lower in MC than one week dried top logs (31.5 % vs 44.4 %). These findings are supported by studies by Hartsough *et al*. (2000) and Defo and Brunette, (2007).

5.1.2. Wood density

It was found that wood density increased with tree height, a statement supported by Jorge *et al.* (2000), Megown *et al.* (2000), Shashikala & Rao (2009) and Githiomi & Kariuki (2010). Chips produced from base logs were 18.0 kg m^{-3} lower in basic wood density than chips produced from middle logs (446.3 kg m^{-3} vs 464.3 kg m^{-3}) and chips produced from middle logs were 15.3 kg m^{-3} lower in basic wood density than chips produced from top logs (464.3 kg m^{-3} vs 479.6 kg m^{-3}).

5.2. Wood chip purity

5.2.1. Knot content

Knot content is a function of branch frequency and size (Malan, 2003). For eucalypts branch frequency decreases and diameter increases respectively with tree height; therefore, knot content will increase proportionally with tree height (Kearney *et al.* 2007). It is thus not surprising that the top logs produced chips with significantly higher knot content values than those produced from base and middle logs. Base logs produced chips 1.4 % lower in knot content than middle logs (1.6 % vs 3.0 %) and 2.1 % lower in knot content than top logs (1.6 % vs 3.7 %). Middle logs produced chips 0.7 % lower in knot content than top logs (3.0 % vs 3.7 %).

5.2.2. Bark content

Harvesting of the experimental plots was initiated in September during the wet spring growth season. During this period sap flow is usually high facilitating debarking due to low BWBS (Öman, 2000; Dunlop and MacLennan, 2002; Dye *et al.,* 2004; Baroth, 2005; Bjurulf, 2006; Eggers, 2010). During dryer winter months sap flow is low and debarking more difficult due to bark adhesion to the log surface (Dunlop and MacLennan, 2002; Eggers, 2010). When harvesting trees during winter, more bark may remain on the log surface after debarking and chips with higher bark content can potentially be expected.

In this study no significant difference in bark content was found when comparing manual and five pass debarked logs. However manual and five pass debarked logs produced chips significantly lower in bark content than three pass debarked logs. Manually debarked logs produced chips 0.054 % lower in bark content than the three pass process (0.008 % vs 0.062 %) and five pass logs produced chips 0.044 % lower in bark content than the three pass process (0.018 % vs 0.062 %). The results indicate that the less aggressive three pass process produced chips with higher bark content values. Nonetheless chips produced from all three debarking treatments still had significantly lower bark content values than generally specified by pulp mill specifications which typically range between 0.8 % and 1.0 %. This suggests that eucalypt pulpwood logs in South Africa are potentially subjected to unnecessarily aggressive and excessive mechanical debarking treatments.

Middle and top logs produced chips significantly lower in bark content than those produced from the larger base logs. Middle logs produced chips 0.040 % lower in bark content than base logs (0.016 % vs 0.056 %) and top logs produced chips 0.039 % lower in bark content than base logs (0.017 % vs 0.056 %). No significant difference in chip bark content was observed for chips produced from middle and top logs. Smaller sized middle and top logs had smaller log surface areas than the larger base logs, while bark thickness also decreases with tree height (Shashikala and Rao, 2009). Previous studies suggest that bark thickness influences debarking efficiency (Laganiére and Bédard, 2009; Retief and Stanger, 2009, Nuutinen *et al.*, 2010). Thinner bark on the smaller logs would explain lower chip bark contents for chips produced from these logs. Still, it is important to note that even though three consecutive 5.5 m logs were removed from each tree the shorter logs which can potentially extend into the tree crown were not prepared and hence were not subjected to this study. Logs extending into the tree crown are often more difficult to debark, due to high branch frequencies and potentially more irregular stem shape (Bassler, 1987; Bjurulf, 2006). Therefore chips produced from these logs would be expected to have higher bark content values.

5.3. Chip size and uniformity

5.3.1. Chip size distribution

The methodology developed for this study to investigate the influence of debarking treatments, log drying periods and log size on chip quality is unique. The method applied to separate chip fractions produced during chipping was sound in relation to the study objectives. However an additional screen separating small sized accepts from prime sized accepts during screening would have been beneficial to better understand the trends observed regarding chip size distributions and the factors affecting them. Unfortunately the necessary equipment was not available.

5.3.1.1. Over-size chips

The main effects and the interactions between the main effects had no significant influence on the volume of over-size chips produced. Previous studies have shown that chips produced from horizontal feed disc chippers have significantly less over-size chips than chips produced from drop feed disc chippers (Twaddle and Watson, 1992(a); Twaddle and Watson, 1992(d)). It has been found that logs fed into drop feed chippers have highly variable log orientations during chipping (Isokangas, 2010). Logs from the thin ends of trees are also often forced into chipping knives causing fracturing and even breakages due to uncontrolled log feeding speeds (Isokangas, 2010). This factor can often lead to greater over-size chip production (Isokangas, 2010).

5.3.1.2. Over-thick chips

The interactions between the main effects, debarking treatment and log drying period had a significant effect on the amount of over-thick chips produced. One week dried logs produced chips with significantly less over-thick chips than two week dried logs. This trend was observed across all debarking treatments. One week dried manually debarked logs produced chips with 0.9 % less over-thick chips than two week dried manually debarked logs (1.6 % vs 2.5 %). One week dried three pass debarked logs produced chips with 0.8 % less over-thick chips than two week dried three pass debarked logs (1.6 % vs 2.4 %) and one week dried five pass debarked logs produced chips with 1.3 % less over-thick chips than two week dried five pass debarked logs (1.4 % vs 2.7 %). There was no significant difference in the amount of over-thick chips produced across all the debarking treatments within each drying period. Watson and Stevenson (2007) found that the amount of over-sized chips produced during chipping increased with decreasing log MC, which supports the results presented.

Interactions between debarking treatments and log sections had a significant effect on over-thick chip production during chipping. No significant difference in over-thick chip production was recorded for individual log sections irrespective of the harvesting treatment applied; however, a significant difference in over-thick chip production was observed for chips produced from mechanically debarked log sections. Three pass debarked base logs produced chips with 1.2 % less over-thick chips than three pass debarked top logs (1.5 % vs 2.7 %) and three pass debarked middle logs produced chips with 1.0 % less over-thick chips than three pass debarked top logs (1.7 % vs 2.7 %). However three pass debarked logs showed a dramatic increase in the amount of over-thick chips produced when comparing chips produced from three pass debarked middle and top logs. It was observed that three pass debarking caused relatively less log surface damage on larger sized base and middle logs while severe feed roller induced log surface damage was observed on the smaller top logs. As such three pass debarked base and middle logs produced chips with significantly less over-thick chips than three pass debarked top logs, due to lower degrees of surfaced and subsurface wood fracturing.

Five pass debarked base logs produced chips with 0.9 % less over-thick chips than top logs (1.6 % vs 2.5 %). Five pass debarked logs gradually produced more over-thick chips as log size decreased. After five feed roller passes across the log surface, surface and subsurface wood fracturing seemed more severe on all log sections, leading to more gradual increases in over-thick chip production with decreasing log size.

It was observed that log surface damage was more severe on smaller sized logs, due to a proportional increase in log surface area to wood volume. Smaller sized logs also have smaller feed roller to log surface contact areas, which lead to greater log surface damage as feed roller induced mechanical forces cannot be evenly distributed across the log surface as is the case for larger middle and base logs (Brunberg, 2006; Nuutinen *et al.*, 2010; Sveningsson, 2011).

5.3.1.3. Accept chips

The volume of accept chips produced during chip production is a function of the volume of undesirable chip size fractions produced. As the volume of under-sized and over-sized chip fractions produced increases, the proportion of accept chips correspondingly decreases. Therefore it is no surprise that five pass debarked logs with greater feed roller induced log surface damage produced chips with 2.7 % less accept chips than manually debarked logs with no log surface damage (76.7% vs 79.4 %) and 0.6 % less accept chips than three pass debarked logs with lower degrees of log surface damage (76.7 % vs 77.3 %). The less aggressive three pass debarked logs also produced chips with 2.1 % less accept chips than manually debarked logs (77.3 % vs 79.4 %). Bassler (1987) and Araki (2002) found that log surface damage had a negative effect on the amount of accept chips produced during chipping.

The interactions between drying periods and log sections had a significant effect on the volume of accept chips produced. One week dried logs produced chips with significantly less accept chips than two week dried logs. This trend was also observed within each log section class. One week dried top logs produced chips with 6.8 % less accept chips than two week dried top logs (70.5 % vs 77.3 %). One week dried middle logs produced chips with 5.3 % less accept chips than two week dried middle logs (75.1 % vs 80.4 %) and one week dried base logs produced chips with4.4 % less accept chips than two week dried base logs (79.6 % vs 84.0 %).

Individual log section also had a significant effect on the amount of accept chips produced during chip production. With decreasing log size, the volume of accept chips produced decreased linearly. The trend was also observed for chips produced from logs dried for both one week and two week drying periods. Comparing log sections dried for one week, it was found that top logs produced chips with 4.6 % less accept chips than middle logs (70.5 % vs 75.1 %) and middle logs produced chips with 4.5 % less accept chips than base logs (75.1 % vs 79.6 %).

Comparing log sections dried for two weeks it was found that top logs produced chips with 3.1 % less accept chips than middle logs (77.3 % vs 80.4 %) and middle logs produced chips with 3.6 % less accept chips than base logs (80.4 % vs 84.0 %). The effect of wood MC on chip size and uniformity has been investigated internationally and it was shown by Pulkki (1991), Uhmeier and Persson (1997), Watson and Stevenson (2007), Färlin (2008), Hellström (2010) and Niedźwiecki (2011) that chips produced from logs with low or high MC produced greater amounts of non-optimum chips during chipping. Surface wood dried quicker than sub-surface wood (Defo and Brunette, 2007). With log surface to volume ratios increasing with decreasing log size, smaller logs have larger portions of surface wood with greater drying rates leading to larger portions of excessively dry wood and lower proportions of accept chips produced (Bassler, 1987; Pulkki, 1991; Uhmeier and Persson, 1997; Defo and Brunette, 2007; Färlin, 2008; Hellström, 2008). After the one week drying period the surface wood is dryer than the sub surface wood which then negatively impacts accept chip production (Araki, 2002; Defo and Brunette, 2007; Watson and Stevenson, 2007; Niedźwiecki, 2011).

5.3.1.4. Pins

Interactions between the debarking treatment, drying periods and log sections had a significant effect on the amount of pins produced during chip production.

Logs dried for one week

The manually debarked base logs produced chips with 3.4 % less pins than manually debarked middle logs (15.1 % vs 18.5 %) and manually debarked middle logs produced chips with 3.4 % less pins than manually debarked top logs (18.5 % vs 21.9 %). Manually debarked logs produced the least pins when comparing chip pin content of chips produced from all the other debarking treatments after one week of drying. Manually debarked logs had no log surface damage, which would explain their relatively low pin contents (Araki, 2002). Smaller sized logs have higher surface to wood volume ratios and therefore greater proportions of dryer surface wood when related to sub-surface wood. Larger portions of dryer surface wood could potentially contribute to the significant increase in pin production during chipping of smaller sized middle and top logs (Araki, 2002; Defo and Brunette, 2007).

Three pass debarked base logs produced chips with 3.3 % less pins than three pass debarked middle logs (17.2 % vs 20.5 %) and three pass debarked middle logs produced chips with 3.7 % less pins than three pass debarked top logs (20.5 % vs 24.2 %). Three pass debarked logs with lower degrees of feed roller induced log surface damage produced chips with significantly higher pin content than manually debarked logs with no log surface damage. There was also no significant difference in chip pin content when comparing three pass and five pass debarked logs. Logs subject to three pass debarking had moderate feed roller induced log surface damage. Higher degrees of log surface damage were recorded on smaller sized logs due to a smaller feed roller to log surface contact area (Nuutinen *et al*., 2010; Sveningsson, 2011; Brunberg, 2006). It could be assumed that surface wood would have a more rapid moisture loss rate, due to surface and subsurface wood fracturing by feed roller knives (Nuutinen *et al.,* 2010).

The five pass debarked base logs produced chips with 4.8 % less pins than five pass debarked middle logs (16.4 % vs 21.2 %) and the five pass debarked middle logs produced chips with 4.0 % less pins than five pass debarked top logs (21.2 % vs 25.2 %). There was no significant difference in chip pin content when comparing chips produced from five and three pass debarked logs for all log sections.

However logs subject to five pass debarking with greater feed roller induced log surface damage produced chips with significantly more pins than manually debarked logs after a one week drying period. Chip pin content increased with decreasing log size. Increases in pin production associated with decreasing log size were observed for chips produced from five pass debarked logs. As previously mentioned smaller sized logs have smaller feed roller to log surface contact areas, therefore leading to a higher concentration of hydraulic forces applied to log surfaces (Nuutinen et al. 2010; Brunberg 2006; Sveningsson 2011). In addition smaller sized logs have greater proportions of drier surface wood, due to larger proportions of surface wood with greater drying rates (Defo and Brunette 2007). It could be argued that surface wood with feed roller induced damage has greater drying rates, as more severe surface and subsurface wood fracturing leads to greater wood exposure (Nuutinen et al. 2010). Larger portions of dryer surface wood had a negative impact on chip size and uniformity during chip production, and lead to greater quantities of pins being produced during chipping as reported by Bassler (1987), Pulkki (1991), Uhmeier and Persson (1997), Araki (2002), Defo and Brunette (2007), Färlin (2008) and Hellström (2008).

Two week dried logs

Manually debarked base logs produced chips with 3.6 % less pins than manually debarked middle logs (10.3 % vs 13.9 %) and manually debarked middle logs produced chips with 2.3 % less pins than manually debarked top logs (13.9 % vs 16.2 %). Pin chip content again was a function of log size. Smaller sized logs produced significantly more pins than larger sized logs across all debarking treatments. Smaller sized logs had higher surface to wood volume ratios and therefore greater proportion of dryer surface wood leading to greater quantities of pin chip produced during chipping (Araki, 2002; Defo and Brunette, 2007; Nuutinen *et al.*, 2010). Two week dried manually debarked base logs also produced chips with 1.9 % less pins than three pass debarked base logs (10.3 % vs 12.2 %) and 2.3 % less pins than five pass debarked base logs (10.3 % vs 12.6 %). There was however no significant difference in the amount of pins produced, when comparing chips produced from manually debarked middle and top logs across respective debarking treatments.

Three pass debarked base logs produced chips with 2.7 % less pins than three pass debarked middle logs (12.2 % vs 14.9 %) and three pass debarked middle logs produced chips with 2.0 % less pins than three pass debarked top logs (14.9 % vs 16.9 %). However there was no significant difference in pin chip content when comparing chips produced from three pass and five pass debarked logs.

Five pass debarked base logs produced chips with 2.4 % less pins than five pass debarked middle logs (12.6 % vs 15.0 %) and five pass debarked middle logs produced chips with 2.2 % less pins than five pass debarked top logs (15.0 % vs 17.2 %). Chips produced from five pass mechanical debarked logs, did not have significantly greater pin chip content values, when compared to chips produced from three pass debarked logs with a lower degrees of log surface damage. Pin production during chipping was more strongly related to wood MC, than to log surface damage. After a two week drying period log MC is expected to be more uniform. The larger portion of the subsurface wood was dryer and reached more favourable MC for chip production. Surface wood is still dryer and thus contributes to pin production during chipping; therefore, greater pin contents were observed for chips produced from smaller sized logs as confirmed by Bassler (1987) and Araki (2002).

Two week vs one week log drying periods

Two week dried logs produced chips with significantly lower pin contents than one week dried logs. This was observed across all debarking treatments.

Two week dried manually debarked base logs produced chip with 4.8 % less pins than one week dried manually debarked base logs (10.3 % vs 15.1 %). Two week dried manually debarked middle logs also produced chips with 4.6 % less pins than one week dried manually debarked middle logs (13.9 % vs 18.5 %) and two week dried manually debarked top logs produced chips with 5.7 % less pins than one week dried manually debarked top logs respectively (16.2 % vs 21.9 %).

Two week dried three pass debarked base logs produced chips with 5.0 % less pins than one week dried three pass debarked base logs (12.2 % vs 17.2 %). Two week dried three pass debarked middle logs also produced chips with 5.6 % less pins than one week dried three pass debarked base logs (14.9 % vs 20.5 %) and two week dried three pass debarked top logs produced chips with 7.3 % less pins than one week dried three pass debarked top logs respectively (16.9 % vs 24.2 %).

Two week dried five pass debarked base logs produced chips with 3.8 % less pins than one week dried five pass debarked base logs (12.6 % vs 16.4 %). Two week dried five pass debarked middle logs also produced chips with 6.2 % less pins than one week dried five pass debarked logs (15.0 % vs 21.2 %) and two week dried five pass debarked top logs produced chips with 8.0 % less pins than one week dried five pass debarked top logs (17.2 % vs 25.2 %).

It can be concluded that log surface damage had a greater effect on the amount of pins produced from logs after the one week drying period when compared to the amount of pins produced from two week dried logs. Log surface damage had an indirect and negative effect on chip pin content values in the form of wood moisture loss. Log surface damage causes surface wood to lose moisture more rapidly, and therefore surface wood will have MC below a potential optimum for chip production (Nuutinen *et al.,* 2010). When wood is too dry or too wet, more pins are produced during chip production (Araki, 2002; Watson and Stevenson, 2007; Niedźwiecki, 2011). Therefore one week dried mechanically debarked logs produced more pins, not only due to the excessively wet sub surface wood, but also due to excessively dry surface wood.

Manually debarked logs produced chips with significantly less pins than mechanically debarked logs when comparing chips produced from all log sections after a one week log drying period. The same trend was observed for manually debarked base logs after a two week log drying period with manually debarked base logs producing chips with 1.9 % less pins than three pass debarked base logs (10.3 % vs 12.2 %) and manually debarked base logs producing chips with 2.3 % less pins than five pass debarked base logs respectively (10.3 % vs 12.6 %). No significant difference in chip pin content was observed when comparing chips produced from middle and top logs across respective debarking treatments after a two week log drying period.

5.3.1.5. Fines

The interactions between the debarking treatments and log sections had a significant effect on fines produced. The fines content increased with decreasing log size across the debarking treatments and log drying periods.

Manually debarked base logs produced chips with 0.4 % less fines than manually debarked middle logs (2.1 % vs 2.5 %) and manually debarked base logs also produced chips with 0.5 % less fines than manually debarked top logs (2.1 % vs 2.6 %). No significant differences in chip fines content was observed from manually debarked middle and top logs. Log surface to volume ratios increased exponentially as log size decreased; therefore, smaller logs have greater proportions of exposed surface wood with low MC. Larger proportions of drier surface wood potentially led to greater quantities of chip fines during chip production (Araki, 2002; Watson and Stevenson, 2007; Niedźwiecki, 2011).

The three pass debarked base logs produced chips with 0.4 % less fines than three pass debarked middle logs (2.5 % vs 2.9 %) and three pass debarked middle logs produced chips with 0.5 % less fines than the three pass debarked top logs respectively (2.9 % vs 3.4 %). Three pass debarked logs had a linear increase in chip fines content with decreasing log size due to moderate feed roller induced fracturing of surface and subsurface wood. Feed roller induced log surface damage was more severe on smaller logs and therefore it is possible that chip fines content would increase with decreasing log size (Brunberg, 2006; Nuutinen *et al.,* 2010; Sveningsson, 2011). Greater fines production was not only attributed to drier surface wood, but also due to feed roller induced surface damage as mentioned in other studies (Bassler, 1987; Araki, 2002).

The five pass debarked base logs produced chips with 1.0 % less fines than the five pass debarked top logs (2.7 % vs 3.7 %) and five pass debarked middle logs produced chips with 0.7 % less fines than five pass debarked top logs (3.0 % vs 3.7 %). Five pass debarked logs had an exponential increase in chip fines content with decreasing log size. Feed roller induced log surface damage due to five passes across the log surface lead to more rapid rates of surface wood moisture loss, and surface and subsurface wood fracturing (Nuutinen *et al.,* 2010). It was observed that these factors influenced chip fines production.

Manually debarked logs with no log surface damage produced chips with significantly less fines than the three pass and five pass debarked logs. Manually debarked base logs produced chips with 0.4 % less fines than three pass debarked base logs (2.1 % vs 2.5 %) and 0.6 % less fines from five pass debarked base logs respectively (2.1 % vs 2.7 %). Manually debarked middle logs produced chips with 0.4 % less fines than three pass debarked middle logs (2.5 % vs 2.9 %) and 0.5 % less fines than five pass debarked middle logs respectively (2.5 % vs 3.0 %). Manually debarked top logs produced chips with 0.8 % less fines than three pass debarked top logs (2.6 % vs 3.4 %) and 1.1 % less fines than five pass debarked top logs respectively (2.6 % vs 3.7 %). There was no significant difference in fines contents when comparing chips produced from base and middle logs subject to both three pass and five pass debarking treatments respectively. However the three pass debarked top logs produced 0.3 % less fines than five pass debarked top logs (3.4 % vs 3.7 %). It can be concluded that log surface damage and log size had a significant effect on the amount of fines produced during chip production, an argument supported by results from previous studies by Bassler (1987) and Araki (2002).

Interactions between respective log drying periods and log sections had a significant effect on chip fines produced during chipping.

One week dried base logs produced chips with 0.3 % less fines than one week dried middle logs (3.0 % vs 3.3 %) and one week dried middle logs produced chips with 0.3 % less fines than one week dried top logs (3.3 % vs 3.6 %).

Two week dried base logs produced chips with 0.5 % less fines than two week dried middle logs (1.9 % vs 2.4 %) and two week dried middle logs produced chips with 0.5 % less fines than two week dried top logs (2.4 % vs 2.9 %).
Two week dried logs produced chips with significantly less fines than one week dried logs, across all log sections. Chip fines content also increased with decreasing log size for chips produced from logs dried for respective drying periods. Comparing fines content across the drying periods for individual log sections the fines content differences increased with increasing log size. Two week dried base logs produced chip with 1.1 % less fines than one week dried base logs (1.9 % vs 3.0 %), two week dried middle logs produced chips with 0.9 % less fines than one week dried middle logs (2.4 % vs 3.3 %) and two week dried top logs produced chips with 0.7 % less fines than one week dried top logs (2.9 % vs 3.6 %). A higher rate of moisture loss for smaller sized logs, may explain why smaller sized logs have smaller differences in the amount of fines produced, as smaller logs may be closer

to optimum log MC for limiting fines production during chipping. It can be concluded that log MC has a significant effect on fines production (Bassler, 1987; Araki, 2002; Watson and Stevenson, 2007; Niedźwiecki, 2011).

5.4. Feed roller induced fibre losses

5.4.1. Fibre loss due to mechanical debarking

Processing head feed rollers inflict damage to the surface of the log during debarking and debranching (Connel, 2003; Brunberg, 2006; Nuutinen *et al.,* 2010; Gerasimov and Seliverstov, 2010; Sveningsson, 2011). The more frequently the feed rollers pass over a section of a log the greater the log surface damage and fibre losses will be. During the process of the feed rollers passing over the log surface wood is dislodged from the log surface and left at the stump site (Connel, 2003; Gerasimov and Seliverstov, 2010). When comparing these fibre losses the three pass debarked trees had 0.016 m^3 10 $trees^{-1}$ less fibre loss than the five pass debarked trees (0.016 m^3 10 $trees^{-1}$ vs 0.032 m^3 10 $trees^{-1}$). Expressing these values as a percentage of the total volume of recoverable wood fibre, the three pass system had 0.8 % less total fibre loss than the five pass system (0.8 % vs 1.6 %). On a per ha basis, the three pass system had 2.5 m^3 ha^{-1} less total fibre loss (1600 trees) as compared to the five pass system (2.6 m^3 ha^{-1} vs 5.1 m^3 ha^{-1}). Manually debarked logs had no log surface fracturing and therefore no fibre losses during debarking.

5.5. Economic evaluation

5.5.1. Recoverable pulp yield

Debarking treatments and log drying periods had a significant effect on the size and uniformity of chips produced and therefore impacted on eventual pulp recovery (Bassler, 1987; Uhmeier and Persson, 1997; Araki, 2002; True, 2006; Watson and Stevenson, 2007; Niedźwiecki, 2011).

5.5.1.1. Debarking treatment

Mechanical debarked logs produced chips with more undesired chip size fractions, which according to True (2006) will have a negative effect on pulp recovery. Both five and three pass debarked logs produced chips with significantly lower pulp value recovery when compared to chips produced from manually debarked logs. Five pass debarked logs produced chips with pulp yield revenue losses valued at R 60.54 BDt^{-1} as compared to chips produced from manually debarked logs (R 3 636.05 BDt^{-1} vs R 3 696.59 BDt^{-1}) and three pass debarked logs produced chips with pulp yield revenue losses valued at R 50.90 BDt^{-1} as compared to chips produced from manually debarked logs (R 3 645.69 BDt^{-1} vs R 3 696.59 BDt^{-1}). No significant differences in pulp value recovery were observed when comparing chips produced from three pass and five pass debarked logs respectively. Relating these figures to a kraft mill processing 1 million BDt^{-1} of round wood annually, R 60.54 million could potentially be lost due to five pass mechanical debarking and R 50.90 million due to three pass mechanical debarking.

5.5.1.2. Log drying period

One week dried logs produced chips with greater quantities of undesired chip fractions and according to True (2006) will impact eventual pulp yield. One week dried logs produced chips with pulp yield revenue losses valued at R 137.90 BDt^{-1} as compared to chips produced from two week dried logs (R 3 590.49 BDt^{-1} vs R 3 728.39 BDt^{-1}). Therefore log drying period has an impact on chip pulp yields and chip pulp value recovery. Relating these figures to a kraft mill processing 1 million BDt^{-1} of roundwood annually, R 137.90 million could potentially be lost due to a one week log drying period prior to chipping.

5.5.2. Value of fibre lost due to mechanical debarking

Mechanical debarking caused fibre loss and was quantified in monetary terms per harvester setting of ten trees and then scaled up to a ha^{-1} basis (Connel, 2003; Gerasimov and Seliverstov, 2010). Three pass debarked trees had fibre losses valued at R 3.32 10 trees^{-1} less than when compared to five pass debarked trees (R 2.83 10 trees^{-1} vs R 6.15 10 trees^{-1}). On a ha^{-1} value three pass debarking fibre losses was R 531.81 ha^{-1} less than that of five pass mechanical debarked trees (R 452.47 ha^{-1} vs R 984.28 ha^{-1}).

6. Conclusion

The South African pulpwood industry has made the strategic decision to fully mechanise harvesting of eucalypt roundwood logs for pulp and paper manufacturing, due to health and safety risks associated with motor-manual and manual harvesting operations, and labour shortages. A study to determine the impact of feed roller induced log surface damage on wood chip quality and fibre loss, when processing eucalypt round wood logs with a single grip harvester was conducted. The study included three different debarking treatments, including two mechanical debarking treatments (three and five processor head passes across the log surface). The wood chips produced from mechanical debarked logs were compared against chips produced from manual debarked logs with no surface damage. In addition the effect of log size and log drying periods after felling before the chipping process was quantified. Trees included in the study were harvested during the relatively wet spring months in the Kwambonambi area in Northern KwaZulu-Natal of South Africa. The logs samples were chipped at a chipping facility located in the Western-Cape province of South Africa. The resultant chip sample processing was done at Stellenbosch University.

It was found that debarking treatment and log sections had a significant effect on chip purity. Both manually and five pass debarked logs produced chips with significantly lower bark content. Chips from manually debarked logs had 0.054 % and 0.044 % less bark content than from the three pass (0.008 % vs 0.062 %) and five pass debarked logs respectively (0.018 % vs 0.062 %). However chip bark content values were still significantly lower than general mill specification across all of the investigated debarking treatments.

Results show that debarking treatment, log drying period and log size had a significant impact on chip size, and therefore chip pulp yields.

Interactions between; debarking treatments and log drying periods and debarking treatments and log sections showed significant influence on the amount of over-thick chips produced. Between debarking treatment and log drying period, two week dried logs produced chips with greater amounts over-thick chips than one week dried logs. The trend was observed across all the debarking treatments. For debarking treatment and log sections, log size only had a significant impact on over-thick chip production for mechanical debarking treatments. Over-thick chip production increased with decreasing log size for mechanically debarked logs. The three pass system for base logs produced 1.2 % less over-thick chip than from top logs (1.5 % vs 2.7 %) and three pass debarked middle logs produced chips with 1.0 % less over-thick chips than top logs (1.7 % vs 2.7 %). Five pass debarked base logs produced chips with 0.9 % less over-thick chips than top logs (1.6 % vs 2.5 %).

Debarking treatment and its interactions between log drying periods and log sections had a significant effect on the amount of accept chips produced during chipping. The amount of accept chips produced during chipping decreased with increasing log surface damage. Logs subject to five passes produced 2.7 % and 0.6 % less accept chips than manually debarked (76.7 % vs 79.4 %) and three pass debarked logs respectively (76.7 % vs 77.3 %). Two week dried logs also produced chips with significantly more accept chips, than one week dried logs. The trend was observed across all log sections. The amount of accept chips produced also decreased with decreasing log size for all debarking treatments and for both drying periods.

The interaction between debarking treatments, log drying periods and log sections had a significant effect on the amount of pins produced during chipping. Pin content was greater for chips produced from mechanically debarked logs as compared to manually debarked logs. However the influence of the debarking treatments on pin production for individual log sections was more severe after a one week log drying period than for two week dried logs. One week dried logs produced significantly more pins than with the two week dried logs. Chip pin content also increased with decreasing log size. Two week dried manually debarked base logs produced 4.8 % less pins than one week dried manually debarked base logs (10.3 % vs 15.1 %). On the other hand two week dried manually debarked middle logs produced 4.6 % less pins than one week dried middle logs (13.9 % vs 18.5 %) and two week dried manually debarked top logs produced chips with 5.7 % less pins than one week dried top logs (16.2 % vs 21.9 %). Two week dried base logs subject to the three pass system produced 5.0 % less pins than one week dried base logs (12.2 % vs 17.2 %). Two week dried middle logs subject to the three pass system produced 5.6 % less pins than one week dried middle logs (14.9 % vs 20.5 %) and two week dried top logs subject to the three pass system produced 7.3 % less pins than one week dried top logs (16.9 % vs 24.2 %). Two week dried base logs subject to the five pass system produced 3.8 % less pins than one week dried base logs (12.6 % vs 16.4 %). Two week dried middle logs subject to the five pass system produced 6.2 % less pins than one week dried middle logs (15.0 % vs 21.2 %) and two week dried top logs subject to the five pass system produced 8.0 % less pins than one week dried top logs (17.2 % vs 25.2 %).

The interactions between debarking treatments and log sections and drying periods and log sections had a significant effect on chip fines production. For debarking treatments and log sections, manually debarked logs produced chips with significantly less fines than from both three pass and five pass debarked logs across all log sections. Fines production also increased with decreasing log size, which was directly related to the log surface damage. As log size decreased manual debarked logs produced more fines. Three pass debarked logs had a more linear increase in fines content as log size decreased, but a more exponential increase with the five pass system. For drying periods and log sections, two week dried logs produced less fines when compared to one week dried logs. Two week dried base logs produced 1.1 % less fines than one week dried base logs (1.9 % vs 3.0 %). Two week dried middle logs produced 0.9 % less fines than one week dried middle logs (2.4 % vs 3.3 %) and two week dried top logs produced 0.7 % less fines than one week dried top logs (2.9 % vs 3.6 %).

The debarking treatments and drying periods had an influence on chip size and therefore potentially eventual pulp yield. Mechanical debarked logs produced more undesired chip size fractions, due to surface fracturing during debarking and because of irregular drying rates between the surface and subsurface layers of the logs. Chips produced from logs subject to five passes had R 60.54 BDt^{-1} lower pulp value recovered than chips produced from manually debarked logs (R 3 636.05 BDt^{-1} vs R 3 696.59 BDt^{-1}). Chips produced from logs subject to three passes had R 50.90 BDt^{-1} lower pulp value recovery than chips produced from manually debarked logs (R 3 645.69 BDt^{-1} vs R 3 696.59 BDt^{-1}). Chips produced from one week dried logs also produced more undesired chip size fractions across all debarking treatments. Chips produced from one week dried logs had R 137.90 BDt^{-1} lower pulp value recovery, than two week dried logs (R 3 590.49 BDt^{-1} vs R 3 728.39 BDt^{-1}). Therefore log drying period had the greatest impact on chip size and potential pulp value recovery.

Feed roller induced surface damage caused substantial fibre losses during debarking. The three and five pass systems accounted for 0.8 % and 1.6 % loss of the total extractable wood volume respectively. When scaled up to a per ha basis, the three pass system produced 2.5 m^3 ha^{-1} less fibre losses than the five pass system (2.6 m^3 ha^{-1} vs 5.1 m^3 ha^{-1}). In financial terms fibre losses of trees subject to the three pass system experienced fibre losses of R 3.32 ten trees^{-1} less than five passed logs (R 2.83 (10 trees)$^{-1}$ vs R 6.15 (10 trees)$^{-1}$). When viewed on a per ha basis the three pass system contributed to R 531.81 ha^{-1} less fibre losses than five passed logs (R 452.47 ha^{-1}vs R 984.28 ha^{-1}).

7. Recommendations

Forestry companies should aim to improve the quality of round wood used for pulp and paper manufacturing in relation to:

- Debarking practices
- Log MC
- Tree size

Less aggressive mechanical debarking with limited feed roller induced log surface damage, will greatly improve chip size and uniformity and their pulp recovery rates. Fibre loss attributed to mechanical induced log surface fracturing will also be limited, and therefore improve wood fibre procurement. Mechanical debarking intensity will have a direct influence on chip purity in regards to chip bark content. Therefore mechanical debarking intensity needs to be adjusted according to the season, tree species, tree size and debarking equipment used to ensure chips are produced with bark contents within the mill specifications.

Log MC greatly influences chip size and uniformity during chip production. Infield log drying periods need to be adjusted according to climatic conditions, tree species and tree size. Log assortments extracted from individual trees during harvesting vary in size, and therefore will have a wide range of drying rates. Therefore log drying periods need to cater for a variety of log assortments, to ensure that log MC are as close as possible to the optimal MC for chip production.

Tree size has a significant effect on chip quality. With decreasing log size, the amounts of undesired chip fractions produced during chipping increased. Plantation compartments scheduled for annual harvesting operations should be revised to eliminate the harvesting of under-sized trees. Forestry companies should consider adjusting plantation felling ages to ensure larger tree sizes at the time of felling. Closer investigation is needed in regards to the debarking breakpoint or as to which point in the trees diameter it will still economically viable to debark trees, from a chip quality and pulp value recovery point of view.

8. Future work

A qualitative roundwood model needs to be developed to quantify chip quality and fibre loss with regards to:

- Mechanical debarking systems
- Log drying periods
- Debarking seasonality
- Tree species
- Tree sizes

The impact of roundwood quality on the cost efficiency of pulping operations will have an indirect effect on costs related to transport logistics, roundwood handling and pulp processing, which needs further investigation.

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