The effect of irregular stand structures on growth, wood quality and its mitigation in operational harvest planning of *Pinus patula* stands

By

Simon A. Ackerman

Thesis presented in partial fulfilment of the requirements for the degree Master of Science in Forestry at the faculty of AgriScience, Stellenbosch University

Supervisor: Prof. Dr. Thomas Seifert

Co-Supervisor: Dr. Stefan Seifert

December 2013

Declaration

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December 2013

Abstract

The practice of combining row and selective thinning in commercial pine plantation silviculture carries the risk of unwanted irregularities in tree distribution within the stand. This situation is aggravated with poor tree selection during marking. The potential consequences of poor tree selection are gaps created along row removals, which are necessary for access to harvesting operations. These gaps lead to spatially asymmetric growing space among adjacent trees.

The effect of irregular stand structures on tree morphology and growth are investigated in this study, and are based on two stands of *Pinus patula,* (Schiede ex Schlechtendal *et* Cham.) in Langeni plantation, South Africa. This study focuses on two aspects. Firstly, a comparison between trees grown in all-sided and one-sided spatial competition situations in order to assess if there are differences in growth and selected quality parameters. Secondly, the mitigation of irregular structures using a simulation based study on changing the planting geometry in order to investigate the effect on harvesting in terms of stand impact, simulated harvesting productivity and harvesting system costs.

Results showed that trees grown in an irregular competitive status have significantly larger crown diameters, crown lengths, longer and thicker branches, disproportionately one sided crown growth and a reduction in space-use efficiency. Simulations indicated that changing planting geometry from the current 2.7m x 2.7m to 2.3m x 3.1m and 2.4m x 3m would result in up to a 20% reduction of machine trail length and fewer rows being removed for machine access. The simulation of harvesting thinnings showed that various planting geometry alternatives increased harvesting productivity by 10% to 20% and reduced overall thinning harvesting cost by up to 11%.

This study successfully investigated the factors that potentially negatively affect saw timber quality and volume production of the stand at final felling. It also illustrated the applicability of simulation methods for testing harvesting scenarios and developing economically viable alternatives.

Opsomming

Die praktiese kombinasie van ryuitdunning en seleksiedunning in kommersiële denneplantasies dra die risiko van ongewensde onreelmatighede in die verspreiding van bome in die opstand. Hierdie situasie word vererger deur swak boomseleksie tydens die merk van dunnings. Die potensiële gevolge van swak boomseleksie is die ontstaan van onreelmatige gapings tussen boomkrone, veral langs die rydunnings, wat nodig is vir toegang tydens die ontginning van die hout. Dit lei daartoe dat die bome langs die dunningsrye asimmetriese ruimtes het om in te groei.

Die effek van onreelmatige opstandstrukture op boom-morfologie en -groei word in hierdie studie ondersoek in twee *Pinus patula,* (Schiede ex Schlechtendal *et* Cham.) *vakke* te Langeni plantasie, Suid-afrika. In die studie word daar gefokus op twee aspekte. Eerstens word bome wat onder toestande van eweredige ruimetlike kompetisie groei vergelyk met die wat onder toestande van eensydige ruimtelike kompetisie groei om sodoende vas te stel of daar verskille is in die groeipatroon aan die hand van geselekteerde gehalteparameters. Tweedens word daar gefokus op die verbetering van onreelmatige opstandstrukture deur gebruik te maak van ’n simulasie-gebasseerde studie om veranderinge in die aanplantingsgeometrie te ondersoek met die doel om die effek van plantspasieering op ontginningsimpakte, gesimuleerde ontginningsproduktiwiteit en -sisteem koste te bepaal.

Die resultate het getoon dat bome wat onder toestande van onreelmatige spasieering en kompetisie groei krone met groter deursnee asook langer lengtes ontwikkel, langer en dikker takke het, disproporsionele, eensydige kroongroei en ’n reduksie in ruimte-gebruik toon, wat die groeidoeltreffendheid nadelig beinvloed. Simulasies met betrekking tot die verandering in boomaanplantgeometrie vanaf die huidige 2.7m x 2.7m na 2.3m x 3.1m en 2.4m x 3m het gedui op ’n reduksie van 20% in die masjienpadafstand en na minder rye wat uitgehaal moes word om die toegang van masjiene moontlik te maak. Die simulasie van die ontginning van dunnings het getoon dat verskillende aanplantgeometriealternatiewe die ontginningsproduktiwiteit met 10% tot 20% verbeter het, en die algehele dunningsoeskoste met tot 11% verminder het.

In hierdie studie is die faktore, wat die gehalte van saaghoutkwaliteit en volume tydens die finale oes van die plantasie potensieel negatief mag beinvloed, suksesvol ondersoek. Dit illustreer ook die geskiktheid van simulasietoepassings vir die toets van ontginningsalternatiewe en die ontwikkelling van meer ekonomies voordelige praktyke .

Acknowledgements

Thanks are due to my supervisor, Prof. Dr. Thomas Seifert, for his guidance and support throughout this study. My appreciation to my co-supervisor Dr. Stefan Seifert for sharing knowledge and encouragement.

Merensky Timber Limited’s Singisi Forests management staff; Johan van Heerden, Bernard Bakker and George Theart are gratefully acknowledged for identifying the project and for their assistance. Johan de Graaf and the late Louis van Zyl need special mention for their support of the project, financially and from a research management point of view.

Special thanks to my family, especially my father, for encouragement and support.

Thank you to Cynthia Lu, Daniel Müsgens and Nicky Wiles for their assistance.

This work is based upon research supported by the National Research Foundation. Any opinion, findings and conclusions or recommendations expressed in this material are those of the author(s) and the NRF does not accept any liability in regard thereto

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1 Introduction

Commercial forestry plantation management makes use of set prescriptions for silvicultural activities at defined times during a specific rotation period. In industrial saw timber production plantations these activities are aimed at stimulating the growth of trees to produce knot free timber of sufficient diameter and height. Thinning prescriptions developed in South Africa are mainly based on results obtained from Correlated Curve Trend (CCT) spacing trials. This is where the quantitative correlation between stand density and individual tree volume growth for some South African commercial tree species was first established (von Gadow & Bredenkamp, 1992).

Historically, marking trees for thinning remained largely the responsibility of skilled forest workers. The marked trees were then felled motor-manually and extracted to roadside by draught animals and/or light agricultural tractors. Mechanisation of timber harvesting (both felling and extraction) has led to the proliferation of geometric row thinning to allow access to a stand for this equipment. Typically, every seventh row in a 2.7m x 2.7m planting (or other) arrangement was removed at first thinning to serve as a machine trail while in inter-rows a selective thinning was applied (Bredenkamp, 1984).

These row removals are currently more often than not marked out by less skilled workers, while the areas between machine trails are selectively marked by trained workers. If the marking of these two entirely different thinning systems is not well aligned, i.e., that the selective thinning is carried out first without marking the rows, irregular stand structures where gaps occur along the thinned rows, may be the consequence.

The basis of this study was to divide the investigation into two aspects. Firstly, an empirical investigation of the effects of irregular stand structure on tree characteristics to quantify these effects on tree growth and some selected wood quality variables. Secondly to perform a timber harvesting (felling and extraction) simulation taking into account both the growing conditions of the stand and the subsequent harvesting operation, where row (for access) and selective thinning were simulated with the aim of maintaining regular stand structure. The outcome of these two approaches was used to determine the effect of different planting geometries on mechanised harvesting productivity and costs.

Firstly, the study analysed sample trees obtained from two stands of different ages in the Eastern Cape of South Africa. Specific focus was on the quantitative description of crown dimension, crown extension, space-use efficiency and the effects on tree branchiness to assess the potential impact on timber quality.

Furthermore, the Operations Research technique of simulation, now widely used in forest operations research worldwide (Asikainen, 1995, 2001 & 2010), was used to test different planting geometries on thinning harvesting productivity and cost. This technique offers powerful systems evaluation potential as alternatives can be tested virtually without actual implementation of the said systems in the field.

A fraction of the available knowledge on pine originates from experiments on *P. patula*, a predominant sawlog producing species in South Africa. This species makes up 45% of South Africa's sawlog resource (Crickmay, 2004). However, the importance of *P. patula*, is not only limited to South Africa as the species occurs in Central and South America, across Southern Africa, as well as in India and Australia. Thus, the focus of this study on *P. patula's* tree characteristics subject to various thinning and spacing conditions and some Operations Research simulations in this regard were seen as warranted.

Objectives

The main objectives of this thesis are stated in the following hypotheses (formulated as alternative hypotheses) and research questions:

The effects of irregular stand structure on tree characteristics.

A_1: DBH, crown radius and crown height differ between trees in regular and in irregular competitive status.

A_2: Crown plasticity and crown eccentricity differ between trees in regular and in irregular competitive status.

A_3: Branch length and branch diameter differ between trees in regular and in irregular competitive status.

A_4: The space-use efficiency differs between trees in regular and in irregular competitive status.

To quantify the effects of alternative planting geometries to the conventional 2.7m x 2.7m for mechanised harvesting; the following research questions were posed.

Will a change in planting geometry:

- reduce machine trail length per hectare but still maintain suitable access to harvesting machines?
- maintain compartment tree spacing regularity when simulated thinnings are done?
- improve harvesting productivity?
- reduce harvesting system costs?

By testing these hypotheses and answering the questions above, the study serves as a link for and combines the fields of silviculture, growth and yield management and timber harvesting and illustrates how the different segments of the forestry supply chain interact and potentially complement each other.

2 Literature review

2.1 Characteristics of *Pinus patula*

As one of the most widely grown species in Southern Africa (DAFF, 2001), *Pinus patula* is best suited to summer rainfall areas, more specifically, the mist belt of the escarpment from the Eastern Cape to Northern Mpumalanga (Poynton, 1977). This species grows especially vigorously in the former Transkei area where soils and soil moisture are optimum (Poynton, 1977). *P. patula* grows best on well drained, deep moist soils with adequate nutrition present. Shallower soils may lead to moisture deficiency and dieback resulting from drought (Poynton, 1977). Generally the species is only established at altitudes higher than 750m above sea level and is not particularly susceptible to frost or light snow falls; however, younger trees tend to be prone to dieback from extremes of these factors (Poynton, 1977; Morris & Pallet, 2000). It is well known that *P. patula* can be prone to drought and attack from insects, fungi and diseases, most notably *Fusarium* (pitch canker) and the Pine Tree Emperor Moth (Poynton, 1977; Morris & Pallet, 2000).

Stem form is usually good when growing under ideal conditions, although the species does have a tendency to develop nodal swellings (Poynton, 1977). These swellings are usually absent in younger trees but appear later in the rotation (Poynton, 1977). Nodal swellings do lead to a downgrading of the timber in terms of its strength characteristics (Wright, 1994).

In summary, *Pinus patula* is an important resource for both pulp and saw timber in South Africa (Crickmay, 2004). Although susceptible to disease and climatic extremes, tree breeding and optimised species- site matching has the potential to mitigate these effects.

2.2 Crown and DBH relationships

Crowns are the production centre of the tree with their shape reliant and reactive to its spatial growing situation. Visually crown length and radius show the extent and growing capacity of trees, while the DBH is the measure of the physical size and volume potential of the stem. It is common knowledge to state that DBH and crown area increase when more growing space is available. This fact forms the foundation of the information discussed.

Tree crowns are adaptive by nature and the tree is able to position different parts, like leaves and branches to increase competitive advantage for the individual tree - with the goal to intercept light resources (Umeki, 1995b and Nepal & Somers, 1996). As variable as crown shapes can be, crowns have a predetermined average shape that is based on the species and their habitat (Nepal & Somers, 1996).

Crown radius as a variable has never been widely measured in forest management, even though it is important in determining how the tree reacts to stand competition and composition (Gill et al. 2000). This is particularly true in South African plantation inventory, where timber volume cruising mainly focuses on DBH and height measurements, as well as a few other stand characteristics such as stand density, weeds, disease and damaged trees.

There is a positive and strong relationship between crown diameter and stem diameter of trees, especially at younger ages, as highlighted in studies by Deetlefs (1954) and Hemery et al. (2005). This is also true for trees growing in the open and free of competition, making the determination of tree characteristics possible through the crown and DBH relationships (Ottorini, 1991; Hasenauer, 1997). The impact of local competition on crown development and growth has been shown for conifers (Deleuze et al. 1996; Seifert, 1999) and for broad leaved species (Longuetaud et al. 2008). The effects of spatially asymmetric competition on crown symmetry and branchiness of conifers, particularly, has been a subject of research in publications by Rouvinen & Kuuluvainen (1997) Seifert (2003) and Seifert and Pretzsch (2004).

Crown area (based on crown radius) is closely associated with the canopy cover of an area of forest and this is very often used in the estimation of growing stock and health, in various forms of remote sensed information (Biging & Gill, 1997; Gill et al. 2000; Alam & Strandgard, 2012). Although, identifying the actual crown area of individual trees can prove to be difficult. As a definition the projected length of the longest branch can be seen as the maximum crown radius (Gill et al. 2000). However, trying to determine where crowns of individual trees intercept or end is extremely difficult (Alam & Strandgard, 2012). Accurate methods of measurement and models to determine clear crown definition of individual trees in the canopy need to be developed to overcome this limitation.

The ratio between crown and stem diameter can be applied to tree spacing associated with thinning regimes and desired stocking levels (Biging & Gill, 1997; Hemery et al. 2005). Trees growing in situations of little inter-tree competition generally have larger crowns and higher stem taper, mostly in the stem area within the crown (Deetlefs, 1954). ‘Butt swell’ or an abnormal thickening of the base of the stem is also influenced by increased crown size (Deetlefs, 1954). This adds evidence that the symmetry of growth in between the crown and stem and its competitive relationship to other trees are important. When trees grow in highly competitive situations, crowns need to effectively intercept light. Local shading of each of the trees branches can be the main cause of crown asymmetry, as the trees react to each other on a local level (Umeki, 1995b).

There is evidence, from natural forests with multi-level canopies, that crowns react to local competition between trees for available resources. In plantation forestry, the genetic variation between the growing stock or micro-site variability can lead to dominant trees exhibiting the same reaction on those that are growing less effectively. Artificially relieving competition, as in the process of thinning, removes these less dominant underperforming trees allowing the remaining ones to capitalise on the available space. However, the degree to which the crown extends into space around it requires further investigation. The use of crowns as indicators of stand health, the reaction to thinning, as well as volume potential should be explored further in commercial forest management.

2.3 Tree reaction to thinning operations

As alluded to in the previous section, stem form and other growth features of trees are inherent to the particular species. However, some of these features can be modified and adjusted through silvicultural activities (Larson, 1963). The purpose of thinnings in a particular area or plantation has been to improve the final harvestable crop for a desired product (Pretzsch, 2009). In plantation forestry, growth responses to intensive management are largely seen in crown diameter and length (Weiskittel et al. 2007). Therefore, releasing competition in the stand can lead to greater crown growth and potential increased production of tree volume.

In natural density dependent thinning, the tree crown compensates by moving away from the stem centre. This change in symmetry is made possible because of the plasticity of crowns (Getzin & Wiegand, 2007). For this reason tree branches will grow towards gaps in the canopy or areas of less competition, thus unbalancing the tree (Getzin & Wiegand, 2007). Thinning therefore appears to have an effect on tree growth characteristics and the crown distribution of the stand, as well differences in tree size (Longuetaud et al. 2008, Crecente-Campo et al. 2009).

The effects of thinnings on DBH, tree height and basal area are apparent, in particular when thinnings are done incorrectly causing irregular spacing. Cancino (2005) reported that trees with one-sided competition (especially edge trees) grow faster and larger than those under even competition and also have larger crowns to capitalise on the greater availability of light for interception. Pretzsch (1995) Pacala and Deutschman (1995) and Rötzer et al. (2012) found that tree distribution within a stand is an important factor for tree growth and this has been proven empirically, as well as in simulation studies. An increase in space, in particular after thinning, results in an increase in branch diameter and tree diameter (Johansson, 1992). However, Johansson (1992) also stated that there is an increase in timber quality with a decrease in spacing, reduction of the branch diameter in particular. Similar results where obtained by Seifert (2003), Nickel et al. (2008) and Seifert et al (2009).

Thinning as a silvicutural treatment, increases the number of branches in the remaining trees, usually in the lower half of the crown, but the number of branches per whorl is independent of this (Seifert 2003, Weiskittel et al. 2007). However, the same authors found that the branch diameter was not readily influenced by thinning, but the length usually increased in the lower half of the crown until competition suppressed the crown in the tree species studied. In general, an increase in branch length usually results in an increase in branch diameter. In order to limit the effect of this, regular spacing should be maintained so that the length and size of the branches are not increased thus potentially affecting wood quality.

Furthermore, branch diameter is closely related to tree diameter. However, in Norway spruce the relative branch diameter, expressed as maximum branch diameter per DBH, did not increase dramatically with the increase in tree growing space (Johansson, 1992). Seifert (2003) was able to show a clear genetically determined component influencing the relative branch diameter in this species. Bier (1986), Samson (1993), Lemieux and Beaudoin (1999) and Bowyer et al. (2007) found that branch size is a good predictor of knot size, which is known to influence the bending strength of timber. This is relevant for saw timber quality since Lemieux and Beaudoin (1999), Todoroki et al. (2001) and Ivković et al. (2007) also found that branchiness substantially influenced timber grade recovery in sawing. This links with the fact that crowns are highly reactive to their environmental situation, and can affect wood quality in their response to silvicultural treatment and environmental conditions (Roeh & Maguire, 1997).

An additional reaction to irregular thinning is compression wood. This phenomenon is common in pines, and is usually found as reaction tissue on the undersides of branches or on the leaning side of tree stems. This is greatly increased and accentuated in relatively short rotations as used in South Africa (Kromhout & Bosman, 1982). The occurrence of compression wood varies from one compartment/growing situation to another. The occurrence of compression wood is also closely linked to taper (van der Sijde et al. 1985). It can be seen as the reaction of the tree to external stresses that lead to stem eccentricity, as well as the tree's mechanism to bring itself back into spatial equilibrium (Duncker & Spiecker, 2008). Furthermore it is easily recognised on cross sections cut from the stem as dark bands of thicker cell walls, usually visible on one side of the cross section of the stem (van der Sijde et al. 1985). Trees that are neighbours to larger trees growing in areas of less competition are possibly subject to lean, induced by the competition of the aforementioned larger trees. This in turn can cause eccentricity and the associated reaction wood in the stems (Cancino, 2005).

The question then arises: If thinning is done incorrectly and leads to gaps in the canopy and irregular stand structure, will trees grow differently than those in regular competition? The studies highlighted have shown that irregular stand structure does adversely affected tree growth and characteristics.

2.4 Thinning operations

2.4.1 Timing

The timing of thinnings in South Africa is based on research from CCT experiments done and described by von Gadow & Bredenkamp (1992). These trials yielded growth data from a variety of stand stocking intensities. For the thinned plots, the aim of these experiments was to grow trees to a point where competition sets in, relieve this competition by removing trees and allowing the remaining trees to make use of extra space allocated to them.

A variety of spacing prescriptions were developed from these experiments and remain in use as industry standards for different products and rotation lengths as illustrated in Kotze & du Toit (2012). These authors recommend that the relative density (RD) of stands is a useful tool to test the efficacy of thinning. This can then be used to predict when a thinning should take place to keep the stand's RD at an optimum level. This method can also be applied to determine target mean basal areas for products required from the stand thus optimising the rotation length. This can be especially useful when optimising tree size for mechanised harvesting. However, timing of thinnings and target stems per hectare

(SPHA) vary greatly according to the management decisions of the particular company or land owner.

The correct timing of thinnings in industrial forestry operations is imperative. Early and regular thinning stimulates diameter growth, and this combined with artificial pruning, limits the associated knotty core (Kromhout & Bosman, 1982). Forestry saw timber rotations in South Africa are classed as short (20-35 years) and it is therefore important to accurately manage thinning and pruning regimes to produce timber with certain specifications (Kromhout & Bosman, 1982). Bredenkamp et al. (1983) investigated the possibility of changing current thinning practices from conventional 2.7m x 2.7m planting geometry to wider dimensions with earlier and fewer thinning operations aimed at reducing the rotation age of pine saw timber stands. The potential result would be reduced costs throughout the rotation and be favourable in reducing the effects of compound interest over long periods of time (Bredenkamp et al. 1983). It was thought that this would also allow plantation management to be more flexible by making use of market conditions and to potentially ease the effects of forest fires, pests and diseases (Bredenkamp et al. 1983).

However, it is important to balance low stocking levels at planting required for large dimension saw timber production and the potential loss in stand production potential throughout the rotation (Strub & Bredenkamp, 1985). Sites with high potential can be planted at a high initial stocking and then receive a heavy/intense thinning and still be able to recover and utilise the increase in growing space (Strub & Bredenkamp, 1985). Stand health and stability can, however, be negatively influenced through this practice (Strub & Bredenkamp, 1985). Well-scheduled and efficient marking for thinning allows both the stability and overall utilisation of the stand to be optimised, as well as intermediate products to be harvest while maintaining the final product goal.

The economic viability of first thinnings has always been questionable. The advent of mechanisation has necessitated the possible modification of planting geometry and thinning practices in order to make these operations more viable (Bredenkamp, 1984). One of these modifications was the use of row thinnings where an entire row or rows are removed at predetermined intervals. However, there needs to be a balance between the improved efficiency of row thinning by mechanised techniques and the possible loss through eliminating a part of the selective thinning process (Bredenkamp, 1984). The arguments for row thinning have been that it is quicker to implement and facilitates easier extraction of timber than time consuming selective thinning. Depending on the distance between the rows removed, selective thinning would still need to be done in-between the removed rows to achieve the silvicultural goals of thinning. Bredenkamp (1984) stated that row thinning, although efficient, should be scheduled before inter-tree competition occurs. If thinnings are delayed trees can become susceptible to wind and snow damage due to the stability factor of the stand being compromised (Bredenkamp, 1984). Furthermore, Bredenkamp (1984) found that delayed row thinnings cause trees adjacent to the thinned row to lean excessively.

There has been a move towards row thinnings, especially, because of the use of machines for harvesting. As benefit, Bredenkamp (1984) also noted that Australian *P. radiata* stands experienced a growth stimulation after a third row thinning and there was minimal loss of volume production, the same was found to be the case in *Pinus taeda*. Bredenkamp (1984) stated that no negative stem form changes, due to row thinning, were obvious in his experimental work, however, this was not researched further in terms of a quantitative assessment of wood quality.

Belbo (2010) highlighted the fact that thinning of small diameter timber, similar to some first thinnings in South Africa, are not always economically viable. The small piece sizes negatively affect the productivity of the system and this often makes these thinning operations less desirable, requiring additional planning and machine resource allocation (Belbo, 2010). Smaller diameter products, such as pulp, are easily acquired from early thinning operations (Donald, 1956). These operations are, however, highly dependent on the market price of such products to make them economically feasible (Donald, 1956). By acquiring pulp as an early product from saw-timber rotations allows for some form of diversification and early revenue for lengthy regimes. Although, longer rotations require a greater number of thinning operations or more intense initial ones (Kromhout & Bosman, 1982).

The timing of thinnings for specific target product becomes important and in some cases the traditional three thinnings haves been replaced by two thinnings (Bakker 2010). Larger sized timber dimensions are not needed as the product specifications of this sawn timber are currently not desired by the market (Bakker, 2010). Company growth and yield analysis found that the third thinning (to about 250 SPHA) does not allow the tree enough time to react to the release of competition and produces sufficient volume by clearfelling to be economically viable (Bakker, 2010).

For a given site, potential stand volume and top height cannot be increased through thinning practices, due to inherent stand potential limitations (Donald, 1956). Empirical research done on *Pinus pinaster* showed that total volume production was relatively the same at rotation age, however, the volume distribution of the individual trees differed under changes in thinning intensity (Donald, 1956).

The work done on the timing of thinnings, the resulting product mix and the potential market influences have been well documented and researched. It is, however, obvious that influences on wood quality (knots and mechanical stresses) are far less known and thus would require further quantification.

2.4.2 Space-use efficiency

Space-use efficiency is the ability of a tree to capitalise on growing space for volume increment (Webster & Lorimer, 2003; Pretzsch & Schütze, 2005). In thinned and unthinned stands investigations into the ability of crown growing area to transform into volume have shown that some tree species are more efficient users of space than others (Pretzsch & Schütze, 2005). Pretzsch and Schütze (2005) also found that there is a trade-off between space use effciency and space exploitation, where some species are especially good at using space as they are pioneers and take advantage of stand disturbance.

Generally, it has been found that trees with smaller, narrow crowns (small to medium) i.e. trees that are either under competitive stress or in areas where the spacing is regular, are more efficient volume producers per crown area than trees with large and wider crowns (Hamilton, 1969). This was confirmed by the study done by Webster and Lorimer (2003) who found that space-use efficiency of trees decreased as the crown area disproportionately increased due to increased space. However, this does not mean that the trees under less competition are smaller and have less volume. Space-use efficiency and the ability to translate available crown area to volume make trees under regular competition better potential volume producers.

Not only does the species influence space-use efficiency but also the degree to which the tree crown has potential area to grow. To relate this to industrial plantations: If excessive irregular growing space, created by inconsistent thinning, is kept to a minimum it will be beneficial for plantation volume growth. Maintaining growing space that is relatively the same for all trees in the stand will therefore maintain even space-use efficiency and a uniform final crop at rotation age.

2.4.3 Degree of irregularity in plantation stands

Various methods have been developed to measure the clustering or aggregation in ecological systems. This is particularly interesting when determining the uniformity in forests in order to determine where increased tree competition can suppress growth.

Three methods of determining this are very prominent in the literature. Ripley's K function (Ripley, 1977), the aggregation index (R) by Clark and Evans (1954) and relative variance (Clapham, 1936). Ripleys K function relates the distance between objects in a population as a function of a truly uniform spatial pattern (Ripley, 1977). This according to Pretzsch (1997) is highly complex and requires very detailed compartment data and measurements.

The aggregation index (R) relates the mean distance between objects and neighbours (irrespective of direction to the neighbour) to an expected mean of a uniform (Poisson distributed) population (Clark & Evans, 1954). The closer the calculated value tends to 0 the more irregular (clustered) the pattern of spacing is, while the closer to 1 the more regular the spacing becomes (Clark & Evans, 1954).

Relative variance, as proposed by Clapham (1936) determines the relative frequency of a particular plant or object appearing in an area as random and can be found in all parts of the target area. This is calculated through relating the observed frequency of species in a sample area and relating this to the expected occurrence of that species in the sample plots (Clapham, 1936). If the observed frequency is higher than the expected occurrence, the species are scattered less evenly, should the observed frequency be lower than expected the opposite would be true (Clapham, 1936).

By evaluating the different methods of determining the degree of irregularity in forests, the aggregation index (R) provides the most effective and simplest method. This method, as compared to others (Pretzsch, 1997), uses spatial information, which is easy to acquire. The aggregation index can be used to determine the degree of mismatch between regular tree growth (at planting and before thinning) and after thinning to determine if sound stand structure has been maintained effectively. Its simplicity is also evident as the index (R) describes the stand with one value (Pommerening, 2002).

Using indicators to determine whether trees are occupying a stand efficiently does not appear to have been applied in South African plantation forestry. The application of competition indices has shown benefit in studies mentioned, although these studies were on natural managed forests. One can hypothesise that using them to test thinning operations in industrial plantations on resulting stand structure would be effective.

2.5 Simulation and harvesting productivity

2.5.1 Simulation of harvesting operations

Simulation has become a significant part of forest operations research in forestry. These simulations can be applied to an individual machine or operation, as well as to a full system (Asikainen, 1995) and have increased in popularity. A simulator models real life situations virtually (Väätäinen et al. 2006) and is able to provide a snapshot of real systems, thus providing an indication of how they could possibly perform in a real world situation.

Deviation from the real-life situation is, always part of any simulation and can be expected to affect its outcome (Baumgras et al. 1993). Even though this may be a limitation, Wang and Greene (1999) conclude that the use of simulation is a low cost and effective method of testing forestry operations and tree growth responses. This was confirmed in a study by Hogg et al. (2010). Simulations make use of user input information, from real situations, and makes the output of these simulations acceptable as viable and representative results (Wang & Greene 1999). It has been shown that simulations allow the testing of a wide variety of systems on different sites quickly and with a high degree of accuracy (Baumgras et al. 1993; Wang & Greene, 1999).

Simulations in timber harvesting operations are generally used to test systems and improve them (Wang & Greene, 1999), as well as to identify the effects of wood and machine utilisation on productivity and costs (Baumgras et al. 1993). These harvesting simulations must also mimic the movements of machines as close to reality as possible (Eliasson and Lageson, 1999) in order to deliver the best results from the investigation.

The great benefit of testing actual systems and modelled systems by means of simulation was confirmed by Hogg et al. (2010). It was found that a simulation is truly effective in identifying difficulties in primary wood supply, where operational problems and bottlenecks can occur (Talbot et al. 2003, Hogg et al. 2010).

Although the discussion presented is predominantly related to simulation in timber harvesting, it is not necessarily limited to this. A major part of the research method adopted in this thesis involved the use of stand growth and thinning simulations. Various methods have been developed, based on computer programmes, to simulate the progression of a forest through its rotation (e.g. Pretzsch et al. 2002a and b; Kotze, 2003). These growth simulators allow the user to adjust the management regime for a stand and the programme will produce an output detailing varied stand and product information and their development over time. Details of simulation methods adopted by these are presented in Pretzsch (2009), where growth and yield information can be simulated for environmental conditions and a specific product.

As discussed, simulation provides a powerful technique of testing and applying harvesting systems and management regimes to virtual environments without the costly need to implement them in ‘real life’. Combined application of thinning models in growth simulators and harvesting simulation has the potential to produce results that would be representative of real systems (Hogg et al. 2010) and can be used to tweak current and potential systems to determine the effects of these in terms of possible cost, productivity and final product.

2.5.2 Harvesting productivity in row thinning

Row thinnings for access have become part of forest operations. However, the spacing between the rows to be removed to allow for machine access appears to be based solely on the perceived capabilities of the machines that make up the harvesting system. The question remains, how does the spacing of the removed rows influence harvesting productivity?

This productivity is influenced by the distance between the machine and the furthest reachable tree (boom reach), the number of trees to be harvested and the volume of these trees. Olsen (2012) recommended that the limit of the harvester boom reach should determine the distance between machine trails. This opinion was confirmed by results of Eliasson & Lageson (1999) in a study on thinning and trail spacing in Scandinavia when comparing the distance between machine trails and harvester capabilities. The machine trails removed during thinning are generally in uneven numbers; third, fifth, seventh or ninth, as this enables and even number of tree rows to be covered by the harvesting boom on either side of the machine.

Investigations into the differences in productivity between row removals (combined with selective thinning) and silvicultural selective thinning throughout the stand have been done. The following results proved the former’s applicability. Shepherd and Forrest

(1973) found that a third row thinning in Australian *P. radiata* was reported to yield small losses of production due to other trees managing to compensate their growth rate with little influence to final harvestable volume. Hall (1970) found no significant differences in volume production loss between third row thinning and selective thinning in *P. radiata* in a pulp wood working circle in New Zealand. This result was confirmed by Bredenkamp (1984) on *Pinus taeda* grown on a sawlog production working circle in South Africa. However, Cremer and Meredith (1976), as well as Jacobs (1970) report contradictory results with a substantial volume loss for pine species. Therefore, one can see that there are various views on the volume production effects between row and selective thinning.

Row thinning for access increases the speed of the thinning process. However, there needs to be a balance between the improved efficiency of row thinning by mechanised techniques and the possible loss through replacing the more growth efficient selective thinning in favour of row thinning (Bredenkamp, 1984).

In South Africa, it was found that seventh row thinning for access did lead to volume losses over the full rotation; however, the effects on form and taper were limited to trees neighbouring the removed rows (Bredenkamp, 1984). If a higher intensity row thinning was done (third row) this effect would have been greater and throughout the stand (Bredenkamp, 1984). Row thinnings are, however, for this reason, only truly effective in very uniform growing stands (Bredenkamp, 1984). This limits losses due to ineffective selective marking and allows the proliferation of mechanised thinning, which is becoming more popular (Bredenkamp, 1984).

Australian studies, on the other hand, found that increasing the distance between the thinned rows requires the harvester to work faster to complete its progression on the machine trail (Strandgard, 2009), in order to maintain a certain/required productivity per productive machine hour. However, the productivity in a study on *Eucalyptus nitens* did not differ significantly between 3rd and 5th row thinning (Strandgard, 2009). The main productivity issue was found to be dead timber (removing or moving around it) and reversing the machine to deal with timber not processed (Strandgard, 2009). This factor was more of a stand management (silviculture) issue than that of harvesting.

It is well known that piece size and number of stems per hectare are important factors affecting productivity in timber harvesting (Eliasson & Lageson, 1999). Various methods have been tested to try to alleviate this, one of them being multi-stem harvesting. In terms of productivity a Swedish study tested the use of multi-stem harvesting, and showed a significant improvement in productivity of the first thinning (Bergkvist, 2003). However, the end user, usually pulp mills, need to readily accept timber which may contain branches and needles (Bergkvist, 2003) if harvested that way. This system may work effectively in *Pinus spp.* Plantations but debarking of *Eucalyptus spp.* in a multi stem configuration may not be as feasible

Harvesting time consumption not only depends on the previously mentioned characteristics of the stand but also on the skill of the operator (Eliasson et al. 1999; Nurminen et al. 2006). The difference between selective harvesting (thinning) and clear cuts is mainly the time consumption of moving the boom in and out from the machine trail to the cutting site (Eliasson et al. 1999). This is highly dependent on stand density, and should improve in second thinning, with the increase in volume per tree for each boom movement (Eliasson et al. 1999). With the increase of mechanised harvesting operations and the spill over of this to thinning, the use of row removal for access to the compartment has become part of operational planning. Although the effects on tree growth are seen as contradictory, the increase in harvesting productivity is evident. In order to make a row thinning truly effective in terms of the future stand growth and structure, selective thinning needs to be done in conjunction with it. This does add time to the operation especially when trees are small. Unfortunately small trees are mostly unavoidable, especially in first thinnings.

2.6 Changing planting geometries

It appears that convention and ease of marking for planting has led to square geometry being adopted in commercial plantation forestry establishment.

Investigations into the effect of planting geometries by Daniels and Schutz (1975) on *P. patula* found that, in spacing trials, rectangular spacing did not affect tree characteristics. Salminen and Varmola (1993) found similar results in a Nordic study where there was slight ovality and the difference between cross sectional diameters did not differ significantly. Salminen & Varmola (1993) also found that when planting in rectangular manner, branch diameters were larger on the side of the longest length but only significantly when these distances were excessively large. This finding is in line with the results published by Sharma et al. (2002) and simulation studies by Seifert (2003). Sharma et al. (2002) showed that mortality, diameter and height were not influenced but crown growth increased at larger spacing. However, this was not proportion to the spacing differences. In South Africa studies on *Eucalyptus spp*. found that the degree of crown eccentricity was not found to be affected by growing space, in this study wind was the main cause (Bredenkamp, 1982).

When critically looking at why these industry standards have been adopted, one can see no reason why not to propose a change in planting geometry. Salminen & Varmola (1993) found that when considering mechanised harvesting, rectangular patterns ease the implementation of these systems, this can be done.

According to current knowledge tree growth and form are not substantially influenced by changing the planting geometry, but the benefits are evident in the implementation of mechanised harvesting. An investigation into the combination of planting geometry and harvesting productivity is therefore warranted.

2.7 Conclusion

The majority of the literature reviewed originates from countries abroad and a substantial proportion of the results were obtained for species not grown in South Africa. In particular the finer detailed investigations into crown growth and reactions to varied levels of stand occupation have not been investigated locally. This is perhaps due to South African forestry being plantation based and it has never been considered as important to quantify the reactive relationship between trees of the same species in a planted compartment. Whereas in natural managed forests, elsewhere, multi-species relationships require specific growing conditions for each species as these react differently to changes in silvicultural management.

Through the investigations presented in this thesis, the benefits of investigating these factors and quantifying the loss from stand underutilisation and changes in growth, due to irregular stand structure, will be shown.

Information found on simulation and the potential benefits of changing planting geometries to ease mechanised harvesting support the objectives of this study. Using tools to plan and test harvesting systems need to be implemented in order to improve the use of highly technical and costly machines effectively.

3 Materials and methods

3.1 Study site

The study site is located in the Merensky Timber Limiteds Singisi Forests Products' Langeni plantation on the eastern foothills of the Southern Drakensburg range of South Africa. The area falls in the Matiwane region situated approximately 50 km west of Mthatha (Figure 1). The region comprises a planted area of approximately 17 000 ha, the majority of which is planted to a variety of *Pinus spp*. with *P. patula* being predominant.

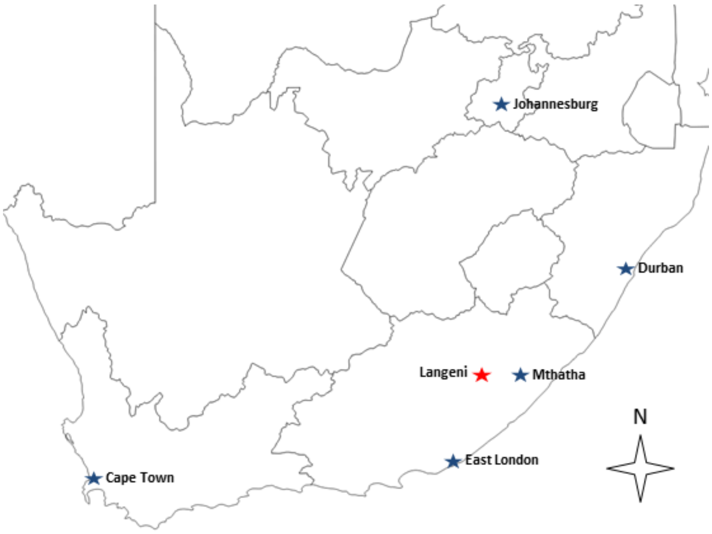


Figure 1: Map showing location of study site and major cities (source: d-maps.com).

Two 1.0 ha sample plots of different ages and levels of thinning where chosen from within compartments H18b and J37. Each compartment had been enumerated and all individual trees mapped with coordinates as part of a student internship in late 2009 (Persch, 2010). The two compartments had received typical seventh row (for access) and selective thinning of the inter rows.

The two sample plots H18b (31°453, 28°548) and J37 (31°419, 28°573) were located in compartments planted with *P. patula* on a sawlog working circle at approximately 935 m above mean sea level. The plots were approximately 10 km apart and situated on level terrain (slope ≤ 11%), according to classification by Erasmus (1994), limiting the effect of slope on tree form. Both compartments were established at 2.7m x 2.7m (1371 stems ha^{-1}). At sampling time compartment H18b was 17 years old and had received a first thinning (to 650 trees·ha^{-1}), while J37 (23 years old) was thinned to 400 trees·ha^{-1} as part of a second thinning (Table 1).

Table 1: Study area compartment data.

Compartment data	H18b	J37
Age	17	23
Species	*P. patula*	*P. patula*
Initial Spacing	2.7m x 2.7m 1371 stems·ha^{-1}	2.7m x 2.7m 1371 stems·ha^{-1}
Thinning received	First thinning	Second thinning
Trees per sample plot (1ha)	618 (at approx. 8 years)	318 (at approx. 14 years)

3.2 Climate, natural vegetation and soils

Long term rainfall and temperature recorded at the Langeni Plantation office revealed a mean monthly and annual rainfall of 102mm and 1233mm respectively (Bakker, 2010). Mean monthly temperature was 19.4°C, with maximum and minimum temperatures of 38°C and 0°C respectively (Bakker, 2010). These climatic figures were confirmed to be in range with those proposed by Schulze (2007). The area falls within a semi-arid climatic zone, characterised by summer rainfall and dry winters. The area is prone to north-westerly berg winds during the later winter months leading to the potential spread of wild fires (Morris & Pallet 2000). Snow and frost is common. The target species studied, *P. patula,* is, however, not very susceptible to snow damage and growth retardation due to frost (Morris & Pallet 2000).

The natural vegetation of the area is predominantly grasslands and afro-montane forest on mountain sides and associated valleys and ravines. Soils are predominantly Kranskop, Inanda and Sweetwater. Soil depths range between 80 cm and 151 cm and are regarded as well suited to most commercial forestry species (Bakker, 2010).

3.3 Irregular stand structure and tree form

As an observation, irregular stand structure or large gaps in the canopy have been prominent in mechanised-harvesting thinned compartments in the Langeni Plantation. This in particular where seventh row thinnings were done. In order to quantify these effects, measurement and analysis of trees in the sample stands were done.

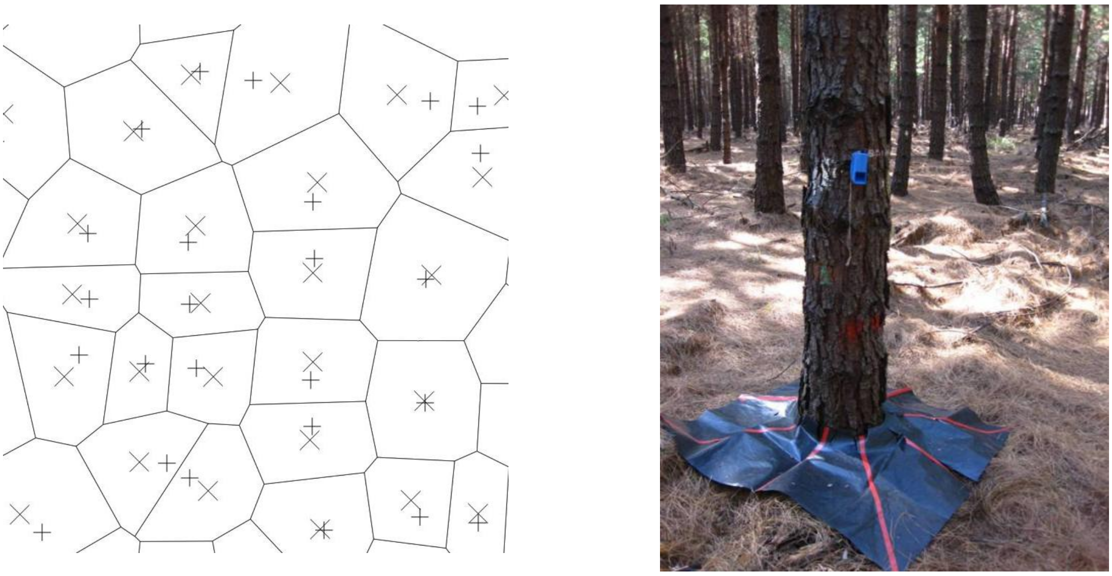
3.3.1 Data collection

For each tree in each study plot, x- and y- co-ordinates, DBH and tree height were recorded. Following this, a two-phase sampling method was applied to each plot. Individual trees were classified as either in an irregular or regular competitive status according to the following method:

1. Tree maps were imported into the Quantum GIS system (QGIS) (Quantum GIS Development Team, 2010) on an x- and y-coordinate grid.
2. Voronoi polygons relating distances between trees and their neighbours were calculated (Figure 2a). The use of Voronoi polygons allows the relationship between tree neighbours to be quantified in a more subjective manner than other methods used (Nelson et al., 2004*)* by determining a growing area around the trees in relation to the neighbours.
3. The offset of the actual tree position from the Voronoi centre of gravity was calculated.
4. The distances of the tree position from the Voronoi centre were ranked from smallest to largest (regular to irregular spacing). The distances were divided into three range classes (small, medium and large) and trees were then randomly selected from the two respective extremes.
5. The trees were then plotted on the map ensuring that their position did not fall on the edge of the measured sample plots. Lastly, the selection of each of the sample trees was verified in-field. Their suitability according to their visual spatial arrangement and crown shape related to their competitive status and in proximity to the thinned seventh row. Damaged and forked trees were excluded.

From the total number of trees a sub-set of 120 trees was selected, 30 regular and 30 irregularly spaced trees from each of the two plots.

DBH, tree height and crown height, defined as the lowest green branch, were recorded for each of the sample trees. Crown extension was measured in eight cardinal directions in order to gather data on crown projections (Figure 2b). A hand-held crown mirror was used to measure the crown radius. The method is known to provide simple and relatively quick means of measuring crown radii, although it is prone to a risk of inherent bias due to inconsistencies in measurements between different users on the same tree (Gill et al. 2000). For this reason the same individual conducted all these measurements.



(a)

(b)

Figure 2: (a) Voronoi polygons indicating tree position (+) and Voronoi centre (x), (b) Sample tree marked to be measured for crown projections.

A further sub-sample of 15 trees per plot was selected for destructive sampling. The sample was divided into seven regular and eight irregularly spaced trees. The trees were chosen at random on the research plot map and then traced in-field. These trees were felled, and the most prominent/visible cardinal direction (North or South) marked along the stem so as to avoid confusion in orientating stem sections and disks to be cut out later.

A first disk was removed at 1.3m (DBH) to be used later for tree ring analysis. Branches on each of the felled trees were measured for diameter and projection length along with the particular quadrant (cardinal direction) the branch was projecting away from the stem (Figure 3). The diameter and projection lengths were used for further analysis.

Figure 3: Branch length and diameter measuring quadrants.

3.3.2 Data analysis

Dominant diameter D_{dom} was calculated based on the 20% largest diameter trees on the whole research plot (Bredenkamp, 1993). Dominant height (H_{dom}) is the regression height of the tree with the dominant diameter. This calculation prescription was proposed as a standard for the South African Forestry Industry by Bredenkamp (1993).

A further set of indicators for growth and crown form were calculated to compare the trees in terms of crown plasticity, crown eccentricity and space-use efficiency.

3.3.2.1 Crown plasticity

Crown plasticity is a measure of the variation of crown growth in different cardinal compass directions from the centre of the stem (Umeki, 1995a). This measure describes the extent to which the crown is projected into a particular cardinal direction. The coefficient of variation (CV) was used to measure this index. CV is a proportional scale and is independent of the actual crown size.

The larger the CV the higher the crown plasticity and thus its ability to occupy free space not occupied by other trees crowns. The CV is calculated according to Equation 1.

$$CV = \left(\frac{s}{\bar{x}}\right) \cdot 100 \qquad \textbf{(1)}$$

where

CV = *coefficient of variation*

s = *standard deviation of crown radii*

$\bar{x}$ = *quadratic mean of the crown radii*

3.3.2.2 Crown eccentricity

Crown eccentricity is a measure of the displacement of the crown centre from the centre of the stem (Umeki, 1995b). Eccentricity measures the crown’s competitive ability to make use of and occupy space available around the stem (Longuetaud et al. 2008) and was calculated according to Equations 2 to 6.

The first step is a transformation of polar coordinates of the crown radii into Cartesian coordinates for X and Y in Equation 2 and Equation 3 (Pretzsch, 1992).

$$x = r \cdot \cos\theta \qquad \textbf{(2)}$$

$$y = r \cdot \sin\theta \qquad \textbf{(3)}$$

where:

r = distance of the crown extension

θ = angle in radians (N = 0, NE = 0.25 π, E = 0.5π …)

Secondly, the mean X and Y distances from the centre of the tree are determined (Equation 4 and Equation 5)

$$\bar{x} = \sum\left(\frac{x_i \cdot r_i}{\sum r_i}\right) \qquad \textbf{(4)}$$

$$\bar{y} = \sum\left(\frac{y_i \cdot r_i}{\sum r_i}\right) \qquad \textbf{(5)}$$

Finally, the radius of the distance from the centre of the stem, indicating the degree of eccentricity, is calculated (Equation 6).

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \qquad \textbf{(6)}$$

3.3.2.3 Space-use efficiency

Space-use efficiency is a measure to determine how much stem wood is produced with a certain available crown or leaf area/volume. Trees that are more productive are able to grow more biomass, or in merchantable terms stem wood per unit crown. In the present study a simple ratio of the basal area increment over the last five years and mean crown area was used to determine space-use efficiency of the trees (Equation 7). The mean crown area for each tree was calculated using the quadratic mean radius of the crown projections.

Tree ring analyses of the disks taken at breast height were used to calculate under bark basal area. Basal area was determined over an interval of the last five years in order to achieve a snap shot of a portion of the trees' life and to minimise the effects of, in particular, dramatic climatic events over the lifetime of the tree.

$$SE = \frac{BAi}{mCA} \tag{7}$$

Where,

SE = *Space-use efficiency*

BAi = *Basal area increment*

mCA = *Mean crown area*

3.4 Harvesting thinnings from optimised stand structure

Once the tree reaction to internal competitive stresses was established, as outlined previously, the potential for simulating harvesting operations on an optimised stand structure was evaluated. The procedure followed is summarised as a flow chart in Figure 4.

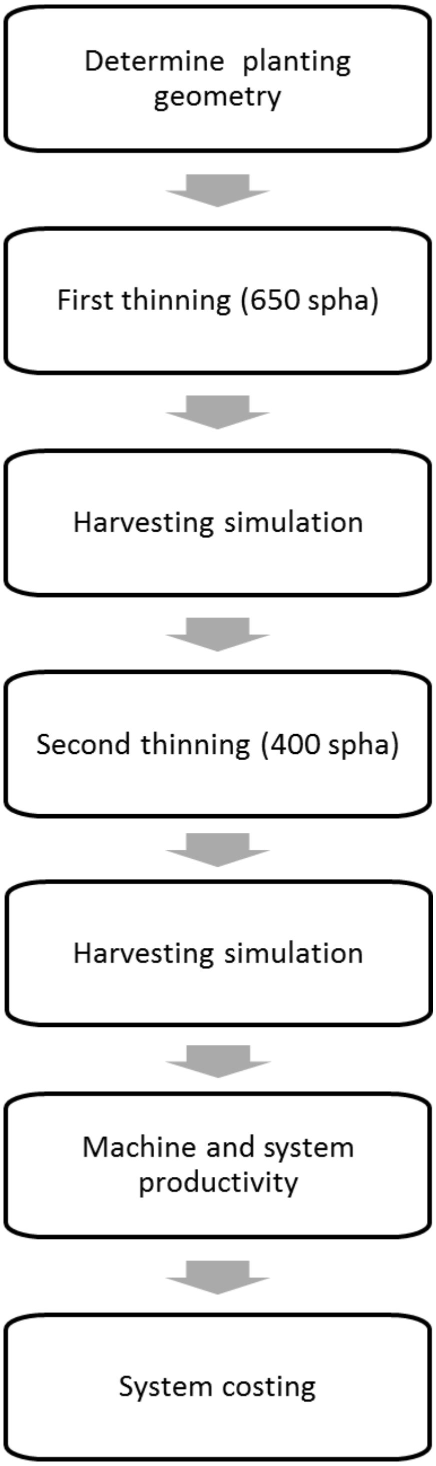


Figure 4: Flow chart of the procedure followed for the thinning and harvesting of compartments to maintain stand regularity.

Adjustments to the spatial arrangement of the compartments were done through computer simulations and were based on silvicultural prescriptions for saw-timber production in Table 2. Various alternative initial planting geometries returning the same final SPHA as prescribed were tested in the simulation. The simulated planting geometries took into account potential harvesting equipment (harvester and forwarder), physical characteristics and limitations and would then receive a simulated first and second thinning harvest operation.

Table 2: Standard Merensky establishment and thinning prescriptions.

Action	Desired density
Spacing (initial)	2.7m x 2.7m
Stems per hectare (SPHA)	1371 SPHA
First thinning (age 8)	650 SPHA
Second thinning (age 13)	400 SPHA

3.4.1 Determining tree characteristics to develop computer simulated stands

The first step in the process to determine new planting geometries involved using pre-thinning enumeration tree data for compartments at thinning ages eight and 13 years to determine tree characteristics for each thinning age. The data set contained information for compartments of similar Site Index (SI_{20}) to the two compartments sampled (H18b and J37). Site index is defined as the dominant height of the stand at a particular reference age. In this case the dominant height was 20m at reference age 20. The data included a wide range of pre-thinning and working plan enumeration aged compartments.

Compartment data were combined and then subdivided into age range subsets of between seven and nine years and from 12 to 14 years to ensure sufficient range of data for each thinning age. The ranges of data also allowed a representative sample of the DBH and height data to be used to compensate for variable site factors that would influence tree growth. A summary of this information (Table 3) shows the quadratic means and standard deviations for DBH and height measurements for this data.

Table 3: Pre-thinning enumeration data provided by Merensky on SI_{20} 20 stands at Langeni

	First thinning		Second thinning	
Mean DBH	16.14cm	σ 4.08cm	21.94cm	σ 5.29cm
Mean height	11.82m	σ 2.67m	16.30m	σ 2.54m

DBH and height values were applied to a grid of tree positions in order have an applicable growing stock for the different thinning ages. A random assignment of tree dimensions to the grid position does not sufficiently mimic the reaction of trees to growing space and neither to genetic variations. The reason is that stand structure is not a random process. Competition between trees leads to a distinct spatial pattern and stand structures, where larger trees suppress smaller neighbours. This means that two neighbouring trees do not have the same probability to be equally large. These spatial structures, resulting from competitive processes, must be taken into account.

The problem was complicated by the fact that Southern African forest management practices do not make use of individual tree growth models to simulate the growth of forests or plantations. An alternative and available single tree growth model simulator, SILVA (Pretzsch et al. 2002b), was used for this purpose. The simulator was applied to create DBH's and heights for single trees in the simulated compartments. SILVA is a European single tree, distance dependent growth simulator developed by the Chair of Forest Growth and Yield Science of the Technische Universität München (Pretzsch et al. 2002b). It has the ability to simulate individual tree and stand growth over an entire rotation, taking into account multi-species succession and growth competition of uneven aged stands (as is typical in Europe). SILVA has not as yet been calibrated to include tree species grown in South Africa.

Although growth characteristics in SILVA did not match *P. patula* perfectly, the tree architecture and growth pattern of *Picea abies (L.) Karst.* (Norway spruce), were assumed to relatively closely match those of *P. patula,* except for the growth rate over time. To reproduce size differentiations between trees as a result of competition processes SILVA was applied with the model for Norway spruce. As the general height and diameter growth patterns were assumed to be acceptable, the time axis of the model was compressed. This allowed for a plausible size distribution of trees in their spatial arrangement to be reproduced and stands grown on a 2.7m x 2.7m matrix were generated in the simulator.

SILVA generated an output at five-year intervals of tree and stand growth. For each of these periods a tree at a specific x- and y-co-ordinate position and with a specific DBH and height, related to the tree age at that point in time, was calculated by SILVA. Table 4 shows DBH and height values for periods six and eight (highlighted) used as representative tree data for thinnings in *P. patula* at ages eight and 13.

Table 4: Summary of the SILVA yield table for growth periods four to eight with modelled quadratic mean DBH and height.

	Mean DBH (cm)	Mean Height (m)
Period four	7.42	6.51
Period five	9.78	8.34
Period six	13.17	10.49
Period seven	15.84	12.48
Period eight	18.07	14.34

The individual tree data from SILVA (DBHs and heights) for each of these periods was used to generate stands for thinning simulation.

Tree number, x- and y-position, DBH and height information were extracted from the SILVA output. The simulation included natural mortality as experienced by a natural stand of Norway spruce. To simulate natural mortality from further competitive or environmental stresses on the sample stand, trees with a DBH of less than seven centimetre would be marked as dead (natural mortality) and have the value for DBH and height appearing as zero for a specific tree number. An example of a tree list for 2.7m x 2.7m spacing is shown in Table 5.

Table 5: Sample input of tree data as generated by SILVA for stand simulations for a 2.7m x 2.7m planting geometry.

treeNo	DBH	ht	x	y
1	10.2	9.3	0	0
2	16.6	11.7	0	2.7
3	11	9.2	0	5.4
4	13.9	10.5	0	8.1
5	0	0	0	10.8
6	11.9	9.4	0	13.5
…	…	…	…	…

SILVA was not used for tree growth simulation from first to second thinning. Trees' diameters and heights were manually increased in proportion to the mean DBH and height for Table 3 and Table 4 at the reference ages of each of these thinnings.

Natural mortality between first and second thinning was not taken into account as there was no sound method that could be used for determining this for these compartments. Although, as a standard in South African growth and yield modelling natural mortality is not taken into account in heavily thinned stands (Kotze et al. 2012), as evident between first and second thinning. This approach was applied to all the various alternative planting geometries investigated.

3.4.2 Determining optimal tree spacing and planting geometry

The second step involved matching machine size limitations to planting geometries and adjusting these to various alternatives, while still maintaining the conventional tree spacing (2.7m x 2.7m - 1370 trees·ha^{-1}). Traditionally machine trails for this geometry and others have been placed along the seventh row at right angles to the rows of trees (Figure 5). The removal of a seventh row applied for mechanised harvesting, at this espacement results in a machine trail 4.5m wide with a distance of 18.9m between machine trails and an average required reach distance from either side of 9.45m for the harvester boom.

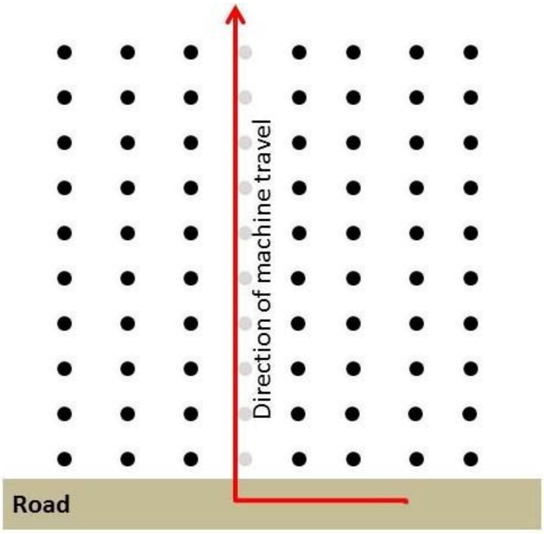


Figure 5: Conventional 2.7m x 2.7m tree spacing and removal of seventh row for machine travel as indicated by the arrow

By adjusting the distances of trees within and between the rows the planting geometries in Table 6 were proposed. Distance between machine trials, width of the machine trails and length of machine trail per hectare were used as deciding factors for selecting the spacing geometry to be used for the rest of the investigations.

Table 6: Breakdown of the various planting spacings tested. Each of the uneven spacings was repeated to include both the short and long tree spacing.

Spacing x – y	Rows to be removed
2.7m x 2.7m	7th and 8th
2.5m x 2.9m	7th, 8th and 9th
2.4m x 3.1m	7th, 8th and 9th
2.3m x 3m	7th, 8th and 9th

As discussed in Chapter 2, the effect of planting geometry on tree growth is considered negligible between rectangular and square spacing in *P. patula* (Daniels & Schutz 1975) and in more recent studies by Salminen and Varmola (1993) and Sharma et al. (2002).

The application of rectangular planting geometries was considered feasible for further investigation.

3.4.2.1 *Machine limitations used to determine minimum planting spacing*

A Tigercat harvester-forwarder CTL system was chosen for this study (Table 7) since these machines were already in operation on the plantation where the study took place. Table 7 provides the selected harvester and forwarder detail in terms of type, boom reach, machine width and payload (where applicable). A trail width of one meter wider than the machine was considered a feasible criterium for the different planting geometries to prevent damage to stems and to limit tree root disturbances.

Table 7: Machine limitations based on boom reach and machine track width for Tigercat harvesters and forwarders (Tigercat 2011).

Machine	Machine Type	Boom reach (max)	Boom reach (telescopic)	Machine Width	Payload
Tigercat H822c	Tracked harvester	8.91m	11.07m	3.43m	
Tigercat 1075B	Forwarder	7.83m	N/A	3.30m (bunk)	14000kg

To illustrate the reach of the machine boom and typical harvesting arcs for seventh and ninth row thinning are shown in Figure 6.

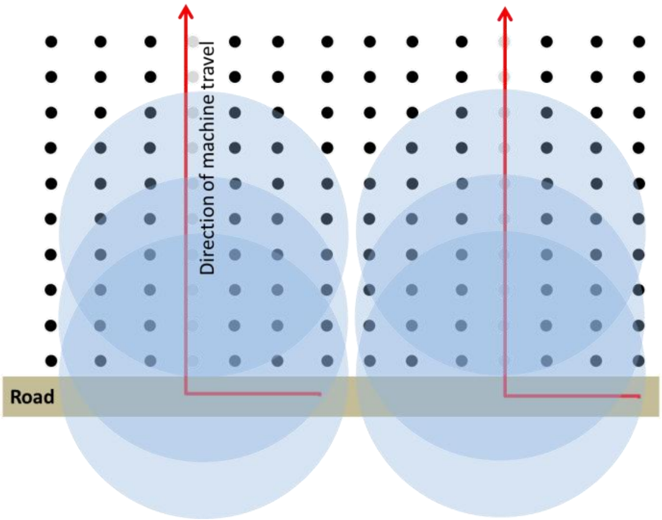


Figure 6: Typical seventh row thinning and boom reach from the machine trail.

3.4.2.2 *Planting geometries used in thinning and harvesting simulations*

Using the machine limitations (Table 7) an evaluation system was developed to test the feasibility of various planting geometries as shown in Table 6. The aim of the evaluation was to increase the distance between machine trails as much as possible (> 7th), reduce the machine trail distance per hectare and ensure the distance between machine trail was equal or less to 20m so that the harvester boom could reach trees from the machine trail (10m to the middle of the inter-row). Matching these criteria would limit stand impact and maximise the harvester boom reach.

Even row trail spacing was excluded from the simulations due to the centre point between two machine trails possibly falling exactly on the same tree row. This would lead to sub-optimal harvesting as the machine would essentially have to harvest four rows from one machine trail and only three from the other, thus not utilising absolute boom reach on one side. The harvesting reach for the overlap of the eighth row is illustrated in Figure 7.

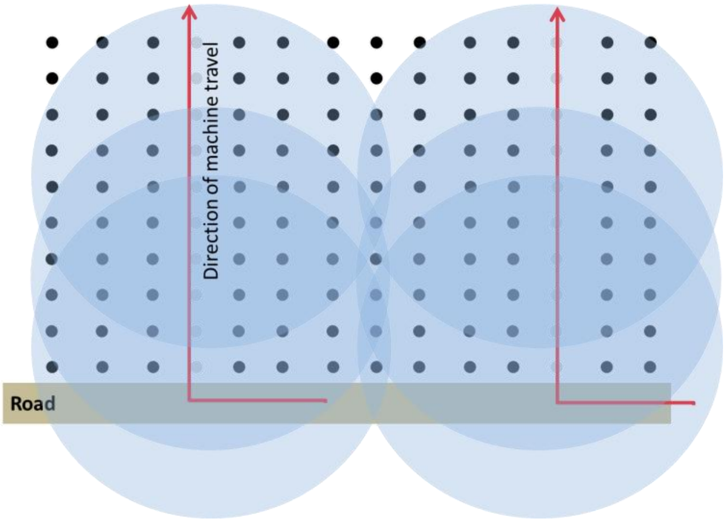


Figure 7: Eighth row thinning showing row overlap of the boom reach of a harvester, all even tree row thinning exhibit this pattern.

3.4.3 Compartment simulations

Following the process of matching machine specifications to various planting geometries spatial tree lists containing x-and y-coordinates, DBH and height information were created in Excel (Table 5). This was done for each of the planting geometries determined to be applicable. As a standard the x-value always indicates the planting spacing used where a row of trees are removed for a machine trail. These were used as input into a specially designed programme for thinning and harvesting simulation which was coded in the statistical language R (R Core Team, 2012). Each of the compartments received a thinning from below for each thinning operation. Trees that were marked as thinned were harvested separately through a harvesting simulator.

3.4.3.1 Thinning

The first step in the process was to simulate a thinning from below. This was based on a straight forward rule based algorithm without any stochastic components, as this would create another source of variance. Thinning from below deals with the removal of the trees that are smaller in relation to the neighbours in the same growing area, thus relieving competition (Murray & von Gadow, 1991; Kassier, 1993; Pukkala & Miina, 1998; Pretzsch, 2009). Input for the programme was the targeted final stem number per hectare as related to the size of the plantation area to be thinned (N_{target}) for each thinning. The programme would evaluate neighbouring trees in relation to a particular tree to determine the growing area and the growth status of the centre tree. Within the programme a defined local search radius for tree neighbours around a target tree from the N_{target} was calculated by estimating the average growing area per tree (Equation 8).

$$A_{grow}=\frac{10000}{N_{target}}m^2 \qquad \textbf{(8)}$$

The local search radius for neighbouring trees was determined as 2.5 times the radius of a circle with the same area as A_{grow} determined by Equation 9.

$$r_{grow}=\sqrt{\frac{A_{grow}}{\pi}} \qquad \textbf{(9)}$$

Each of the tree neighbours within the search radius were used to calculate the local stem density, a DBH rank of the target (centre) tree to its neighbours, the proportion of the trees thinned to the target tree and a flag to mark if the distance to the nearest neighbour was less than r_{grow}. The local density was divided by the maximum density found in the stand. In order to make the values rateable they were linearly transformed to be in a range between 0 and 1. This operation was done sequentially for all the trees in the stand.

Lastly, the values calculated were summed up to determine a potential for a tree to be removed in the thinning process. The summed values were then ranked, and the ones with the highest potential to remain to the target stems per hectare were marked FALSE (un-thinned) and the rest were marked TRUE (thinned) as flags in the output.

To limit the effect of compartment edges on thinning a subset of one hectare was taken as substitution from the middle of the compartment. A measure of aggregation (R) (Clark and Evans, 1954) was used to determine the uniformity of the spacing in the stand after thinning. The Clark and Evans (R) provided a test to evaluate the efficacy of the thinning algorithm. The particular data preparation and outputs for first and second thinnings are described below.

First thinning

Before the first thinning simulation, the row-thinned rows (7th or 9th) were removed from the dataset. The subset created by the thinning programme was combined with the original full tree data set with row-thinned trees reintroduced into the data set after thinning for further analysis of thinned and remaining trees. Because the row-thinned trees were removed, they were also marked TRUE (thinned). The resulting dataset would then be used for the harvesting simulations.

Second thinning

After the first thinning the trees marked as thinned and the row thinned trees were removed from the compartment data set. This new data set then provided the input for the second thinning simulation. As previously, the target stems per hectare, extrapolated to the size of the full area was calculated. This output provided input for the second thinning harvesting simulation.

3.4.3.2 Harvesting

The harvesting simulation programme simulated the spatial reach of a harvester while it moved along a skid trail. Based on x-and y-coordinates of trees and the flag for thinned or un-thinned trees, tree harvesting was simulated. Each individual skid trail's location (defined by start and end) was used as an input. Figure 8 illustrates the location of the machine trail to be harvested and the location of all the trees marked by the thinning simulator, to be removed by the harvesting simulator.

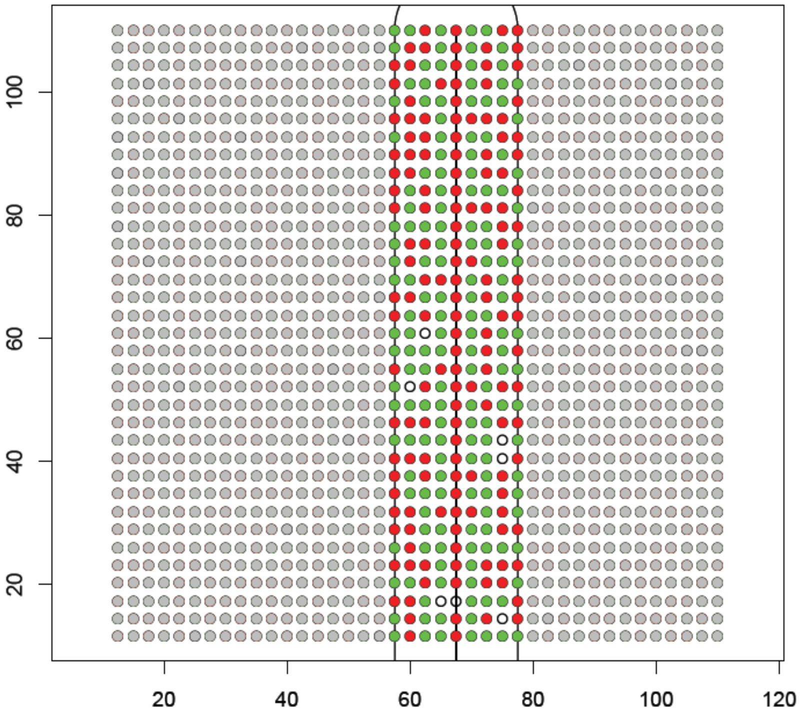


Figure 8: Machine trail before harvesting, red circles indicate trees to be removed (marked by the thinning simulator), green circles indicate trees to remain and empty circles are dead trees (natural mortality).

The output identified all the trees around the machine trail that could be reached by a 10m boom, and flagged them as accessible. If trees were attributed as accessible and marked to be thinned these would be flagged as harvested for a particular harvesting stop (Table 8). These stops were determined and calculated using a harvesting simulator, discussed later.

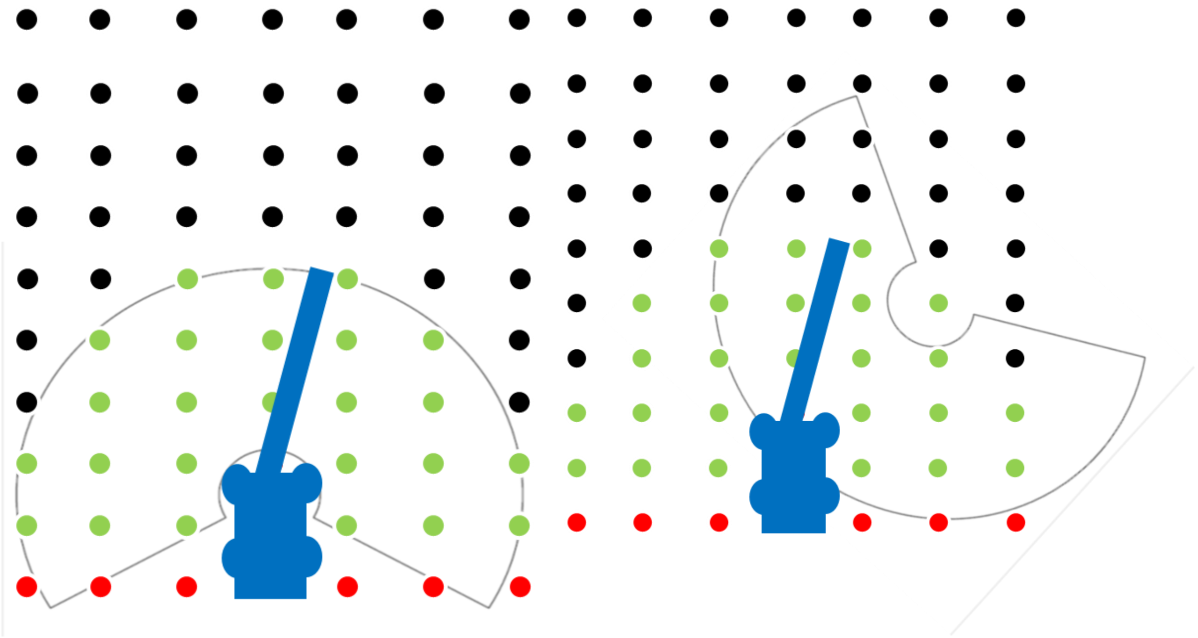
Table 8: Harvesting thinning output for 2.7m x 2.7m 1st thinning showing thinned and accessible trees and at which stop they were harvested.

row	Nr	d	h	X	Y	removed	thinned	accessible
1	235	14.5	10.8	13.5	10.8	0	FALSE	TRUE
1	236	11.8	9.6	13.5	13.5	1	TRUE	TRUE
1	237	13.7	10.3	13.5	16.2	1	TRUE	TRUE
1	238	12.7	10.3	13.5	18.9	1	TRUE	TRUE
1	239	8.6	7.9	13.5	21.6	2	FALSE	TRUE
1	240	10.8	9.2	13.5	24.3	2	TRUE	TRUE
1	241	12.3	9.9	13.5	27	2	TRUE	TRUE
…	…	…	…	…	…	…	…	…

The simulator was used to estimate the influence of spatial stand structure, skid rows and stem number reduction on harvesting costs, and was designed and implemented using R (R Core Team, 2012). This simulator is able to estimate the minimal number of position changes (harvesting position) of the harvester along a predetermined machine trail, and the number of trees harvested at each position.

The simulation was based on pure geometry using only the tree positions and the line on which the harvester moved on the machine trail. The assumption was made that the harvester would be most efficient if backward travel was not done. From a start position the harvester moves forward on the machine trail to the first optimal point at which most trees can be harvested. From this stop (first) point, once all the harvestable trees have been harvested, the next optimal point is selected and the harvester moves forward to that point.

The reach of the boom and the tree coordinates were used to identify the optimal point from which most trees could be harvested, (Figure 9a and b). All trees in the polygon of Figure 9a can be reached by the harvester head from the current position of the harvester, the boom swath area. In order to maintain simplicity, boom reach with obstacles in the way was not tested. It was assumed that the harvester could reach each tree unobstructed, which, in reality might not be the case.



(a)

(b)

Figure 9: a) harvester boom swath area and b) tree reach polygon

The next step was to define the area from which a specific tree could be reached by the harvester, namely the tree reach polygon (Figure 9b). The tree reach polygon can be derived by calculating all possible harvester positions from which the harvester boom can reach the tree. In a geometric sense this is the inversion of the boom swath area Figure 9a. By intersecting the tree reach polygon with the machine trail, a new harvester stop line segment was created (Figure 10). If the harvester was on this line segment, the boom could reach the tree.

The procedure follows a sequence in order to find the optimal position to harvest most trees from a position, without moving backwards. Selection of the nearest trees to harvest and the line selection for each stop are shown in Figure 10. The intersection of the tree reach polygon (Figure 9b) with the machine trail line defines the line of the segment where trees will be harvested for that stop. All tree polygons (Figure 10) which intersect the starting line segment are added to the list of harvested trees. When no more trees intersect the segment the maximum number of trees that can be harvested from that line segment has been found and the endpoint of this segment is used as the new harvester position.

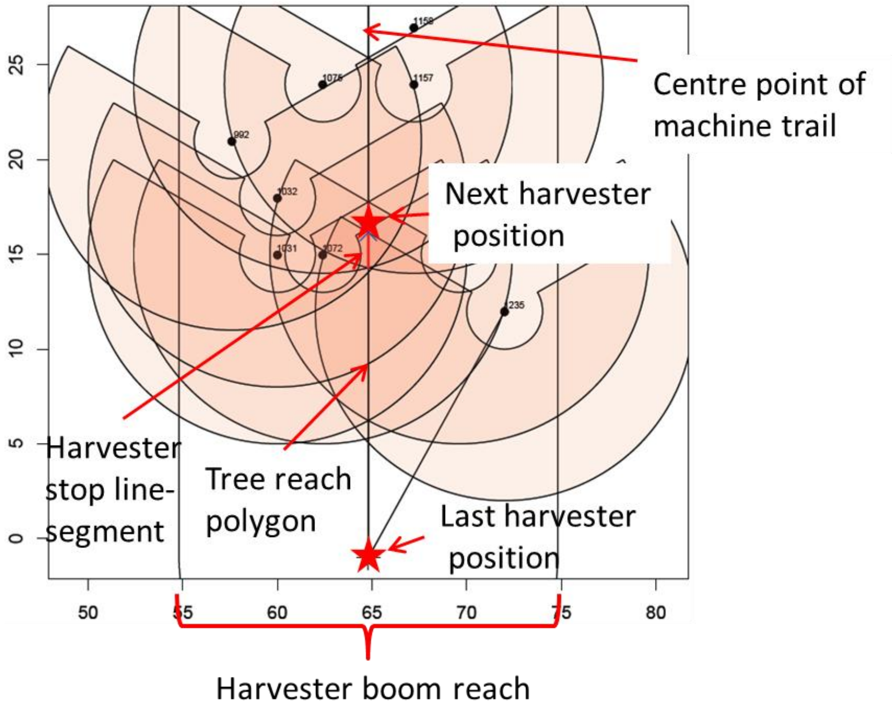


Figure 10: Nearest tree to harvesting stop and tree selection polygons inverted and translated to the tree position

These steps are repeated until harvester has reached the end of this machine trail. This process allows each harvested tree to be assigned to a specific harvester stop position. The total number of harvesting stops and the distance between stops were recorded. The accumulated distance along the machine trail was also calculated.

A tree volume, based on the DBH and height values, was calculated for each harvested tree using the Schumacher-Hall function (Equation 10) with parameters for *P. patula* (Bredenkamp, 2012).

$$lnV = b_0 + b_1 ln(dbh + f) + b_2 lnH \quad \textbf{(10)}$$

Where:

$b_0 = -13.469$

$b_1 = 2.440$

$b_2 = 1.325$

$f = 8$

The volume per harvesting stop was totalled for each row with the distance between harvesting stops and accumulated distance travelled along the machine trail (Table 9).

Table 9: Example pivot table for row one of first thinning 2.7m x 2.7m 7th row-thinning

Row	Stop	Volume per stop	Accumulated machine trail travel	Distance between stops
1	1	0.36	2.7	2.7
1	2	0.41	10.8	8.1
1	3	0.32	18.9	8.1
1	4	0.28	29.7	10.8
1	5	0.34	37.8	8.1
1	6	0.34	45.9	8.1
1	7	0.35	54	8.1
1	8	0.34	62.1	8.1
1	9	0.44	70.2	8.1
1	10	0.41	78.3	8.1
1	11	0.27	86.4	8.1
1	12	0.40	94.5	8.1
1	13	0.02	102.6	8.1
Totals:		**12.09**	**102.6**	

3.4.4 Harvester and forwarder productivity

The output from the virtual harvesting was used to identify volumes harvested at each harvesting stop. In order to determine the productivity of the harvesting system, the time taken to harvest and forward the timber needed to be determined. Time consumption was determined using existing time study functions with the harvesting and forwarding time consumption broken up into time elements. A collection of elements form a machine cycle. Each cycle is one complete work process with a predefined start and end point.

Time study elements used to determine harvester and forwarder cycles and cycle times are listed in Table 10. The centiminute (cmin) time unit was used in the time study.

Table 10: Time study elements for cycles to be used from time study functions to determine harvesting productivity in simulated compartments

Harvester	Forwarder
1. Move to harvesting position ($m \cdot cmin^{-1}$)	1. Travel empty ($m \cdot cmin^{-1}$)
2. Harvesting ($cmin \cdot m^{-3}$)	2. Loading ($cmin \cdot m^{-3}$)
a. Moving boom to cut	3. Travel partially loaded ($m \cdot cmin^{-1}$)
b. Felling	4. Travel loaded ($m \cdot cmin^{-1}$)
c. Processing	5. Unloading ($cmin \cdot m^{-3}$)
d. Boom in	
e. Cleaning	

The harvesting element included the sub elements (a – e) in Table 10. Total time for this element was calculated based on the duration of the sub-elements.

Due to actual time studies not being within the scope of the project, element times and machine speeds were used from previously published studies. Nordic countries have been operating cut-to-length (CTL) operations for more than 15 years (Nurminen et al. 2006). For this reason time study data from reputable literature was used on research done in this region, typically from Sweden and central Finland, and compiled by Eliasson et al. (1999) and Nurminen et al. (2006) respectively.

3.4.4.1 Time elements for harvesting and forwarding

According to results from Eliasson et al. (1999) and; Nurminen et al. (2006) the following calculations (Table 11) were used to determine the time elements listed in Table 10.

Table 11: Time element calculations used to determine time consumption in simulated operations

	Element		Time calculation
Harvester	1. Driving		33 m·cmin^{-1} (Eliasson et al. 1999)
	2. Harvesting	a. Moving boom to cut	0.1 cmin·tree^{-1} (Nurminen et al. 2006)
		b. Felling	$t = 0.093 + 0.101x$ *t = time (cmi·tree*$^{-1}$*)* *x = volume of the tree* (Nurminen et al. 2006)
		c. Processing	$t = 0.0359 + 1.1368x$ *t = time (cmi·tree*$^{-1}$*)* *x = tree volume* (Nurminen et al. 2006)
		d. Boom in	0.049 cmin·tree^{-1} (Nurminen et al. 2006)
		e. Clearing debris	0.017 cmin·tree^{-1} (Nurminen et al. 2006)
Forwarder	1. Travel empty		56 m·cmin^{-1} (Nurminen et al. 2006)
	2. Load	First thinning	$t = 2.022 + \frac{0.211}{x}$ *t = time (cmin·tree*$^{-1}$*)* *x = volume of the tree* (Nurminen et al. 2006)
		Second thinning	$t = 2.777 + \frac{0.211}{x}$ *t = time (cmin·tree*$^{-1}$*)* *x = volume of the tree* (Nurminen et al. 2006)
	3. Travel partially loaded		26.7 m·cmin^{-1} (Nurminen et al. 2006)
	3. Travel loaded		43.9 m·cmin^{-1} (Nurminen et al. 2006)
	4. Unloading		*0.569 cmin·m^{-3} (Nurminen et al. 2006) *Based on mixed sawtimber loads

3.4.4.2 Harvester and forwarder work method

Based on the output from the harvesting simulations a harvested volume for each harvesting stop was allocated for each machine trail that would have been harvested. The forwarder would then load timber from each of these harvesting stops. The simulated work method for each machine is described as follows.

Harvester

A harvester cycle started at the base of the first machine trail and moved to the first harvesting stop as determined by the harvesting simulation. All the trees for that particular harvesting stop were assumed to be harvested and processed (element 2 in the harvesting cycle, Table 10). Once the harvesting was complete the next cycle would start with the machine moving north to the next harvesting stop (Figure 11). At the end (highest x- and y- coordinate) of the machine trail, the machine would move to the base of the next machine and the simulation would start again.

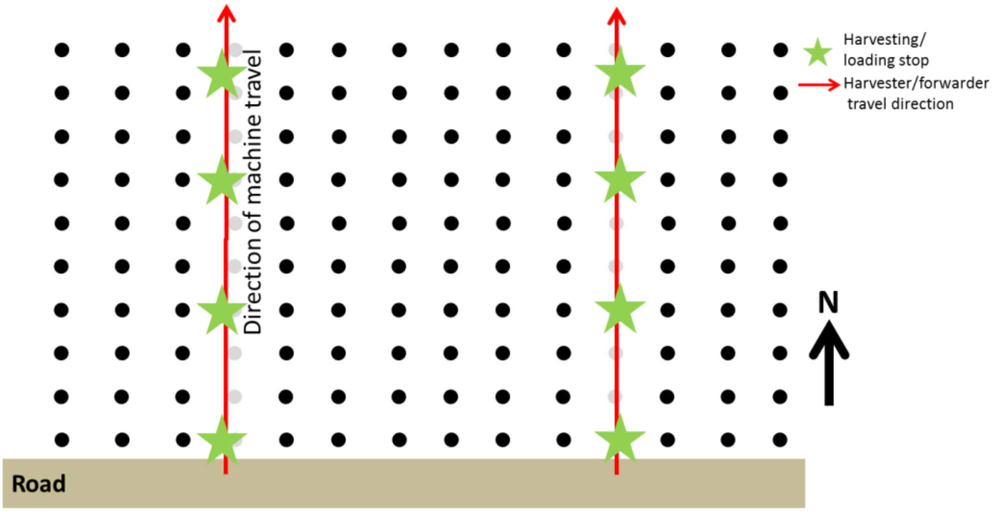


Figure 11: Simulation steps for harvester and forwarder for harvesting and loading time allocation

Forwarder

As with the harvester (Figure 11), the forwarder would move into the compartment from the start of machine trail one. It would then travel empty along the trail to the first timber stack, load, and travel partially loaded to the next stack and continue loading. This would be repeated until the forwarder was fully loaded to its capacity of 20000 kg or 18.86 m^3 (Table 7) for a Tigercat 1075B. This figure is based on a direct conversion of weight to volume of 1.06 determined by Bredenkamp (2012) for pines.

Once the forwarder reaches the end of the machine trail, it is moved to the next one. At the point where the forwarder is full, it stops loading and travels full down the machine trail (South) to the nearest road where timber is unloaded. The machine then travels unloaded back to the last unfinished stack or a new stack to continue the process.

3.4.4.3 Time units and productivity

The resultant total time for the volume harvest for each of the scenarios was determined. No delays were taken into account, as these delays are generally linked to specific compartment conditions. This information was used to determine the time taken to harvest a cubic meter of timber for each scenario and it was then compared to the standard spacing (2.7m x 2.7m). Based on this information machine costs were determined for each scenario.

3.4.4.4 System costing

Machine costs for each of the compartments were calculated based on replacement costs of the harvesting and forwarding machinery and the fuel consumption during harvesting operation. Details of the assumptions and costs used as a standard for each of the machines is summarised in Table 12.

Prices were based on retail prices from the Tigercat dealer in South Africa, landed at Durban harbour. Operator, licensing, insurance and other miscellaneous costs were not taken into account, as they would be too variable for the purposes of this study. Fuel prices were based on commercial retail prices. Fuel consumption for each of the machines was based on the dealer recommendations. Machine, attachment and component working lives and costs are those acquired and used by plantation management at Langeni.

Table 12: Costs and costing assumptions for machines and attachments used in system costings (Olsen, 2012; van Heerden, 2013).

Item	H822C Harvester	1075B Forwarder
Fixed cost inputs		
Machine cost	R4’056’754.00	R4’728’538.00
Harvesting attachment	R1’319’985.00	No attachment
Machine life	18000 hrs	18000 hrs
Harvesting attachment life	18000 hrs	NA
Salvage cost machine %	10	10
Salvage cost attachment %	0	NA
Interest rate %	9	9
Insurance, registration, set-up and garaging costs	R0.00	R0.00
Variable cost inputs		
Fuel costs	R11.60 (Feb, 2013)	R11.60 (Feb, 2013)
Fuel consumption	28 ℓ/hr	12 ℓ/hr
Oil cost of fuel cost	20%	10%
Maintenance cost machine %	100	100
Maintenance cost attachment %	100	NA
Number of tracks/tyres	2	8
Cost per track/tyre	R155’000.00	R42’000.00
Life of track/tyres	9000 hrs	8000 hrs
Cutter bar life	61.2 PMH	NA
Cutter bar cost	R1500.00	NA
Chain life	38.25 PMH	NA
Chain cost	R500.00	NA
Sprocket life	612 PMH	NA
Sprocket cost	R1100.00	NA
Operator inputs		
Operators per shit	1	1
No operator costs were taken into account		
Productivity inputs		
Working days per year	240	240
Shifts per day	2	2
Hours per shift	9	9
Productivity per hour	Based in time study information	Based in time study information
Machine utlisation	85%	85%

Information on costs, as well as productivity figures would be used in conjunction with an industry costing model to determine final cost per cubic meter for each of the different simulations.

3.5 Statistical analysis

Analysis of variance (ANOVA) was used to determine whether there were significant differences between the test criteria in the particular compartments or planting geometries. ANOVA, assumes, however, that the variance of the compared groups is homogenous (homoscedastic). A Levene-test for variance homogeneity was applied to test this assumption. In most cases the assumption was satisfied and ANOVA could be used. In others heteroscedasticity prohibited traditional t-tests and ANOVA. For these situations a non-parametric Welch's t-test, was used instead, which is more robust against homoscedasticity violations (Lyman Ott, 1990).

Subsequently, to determine further differences between planting geometries a Bonferroni multiple hypothesis test or a Tamhane T2 test were used, depending on homoscedastic or heteroscedasticity of variance respectively (Lyman Ott, 1990).

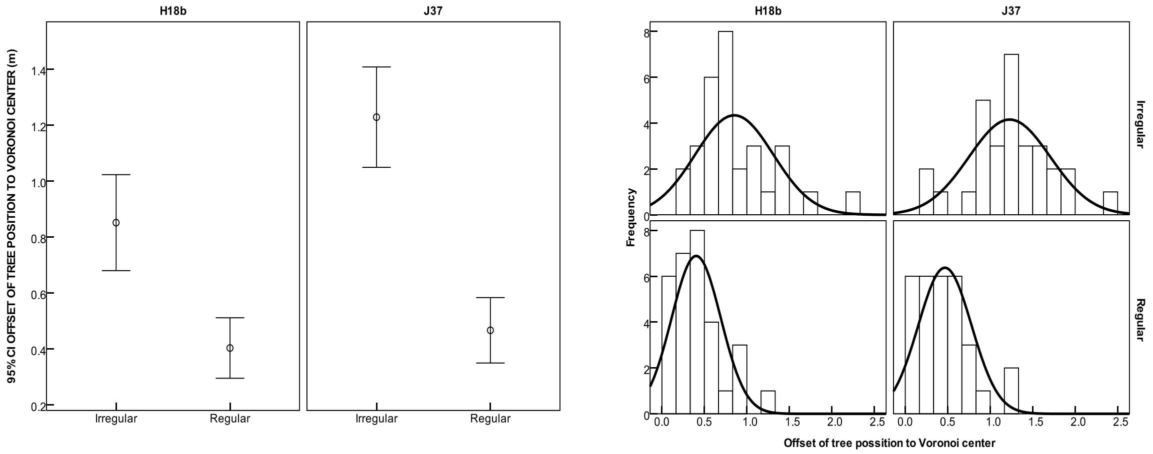
4 Results

This Chapter will follow the same flow as that of Chapter 3 and deal with the results of the internal stand competition reactions to irregular competition, followed by the results of the harvesting for thinning simulations.

4.1 Irregular stand structure and tree form

4.1.1 Determining regular and irregular competition trees

The evaluation of tree selection according to irregular and regular competitive status based on growing space symmetry according to the Voronoi polygons is shown in Figure 12 (a and b).



(a) (b)

Figure 12: Distance of the stem base from the calculated Voronoi centre of each tree for trees selected in irregular and regular competition with (a) error bar plots ($p < 0.05$). (b) Frequency histograms with a normal curve displaying the means of the two selected groups.

ANOVA was used to analyse the competitive status of the individual trees of the sample tree selection. An error-bar plot in Figure 12 (a) shows significant differences in the displacement of the stem position from the Voronoi centre of gravity between irregular and regular competitive status trees. This was confirmed by a Welch's t-test. Additionally, histograms of the trees within irregular and regular groups (n=60) were created to evaluate the spread of diameter classes in both groups (Figure 12b). The two group means differ in both compartments.

4.1.2 Sample stand information

A summary of the quadratic mean diameter (D_q) and mean height (H_q), as well as the dominant diameter (D_{dom}) and height (H_{dom}) of each compartment is shown in Table 13. The information is shown by compartment, as well as by competitive status.

Table 13: Characterisation of mean diameter, dominant diameter, mean height and dominant height of the sampled compartments H18b and J37.

Compartment	Competitive status	D_q	D_{dom}	H_q	H_{dom}
H18b	Regular	24.8cm σ 3.8cm	29.4cm σ 1.9cm	21.2m σ 1.5m	22.0m σ 0.6m
	Irregular	29.7cm σ 4.8cm	36.2cm σ 3.6cm	21.0m σ 1.7m	22.2m σ 1.2m
	All trees	27.3cm σ 5.3cm	33.7cm σ 2.4cm	20.9m σ 2.3m	22.5m σ 1.5m
J37	Regular	36.7cm σ 5.4cm	43.6cm σ 1.6cm	27.9m σ 2.9m	31.0m σ 4.0m
	Irregular	39.4cm σ 6.0cm	48.0cm σ 4.1cm	27.9m σ 1.6m	28.7m σ 1.4m
	All trees	38.8cm σ 6.1cm	46.2cm σ 3.1cm	27.4m σ 2.7m	28.5m σ 1.7m

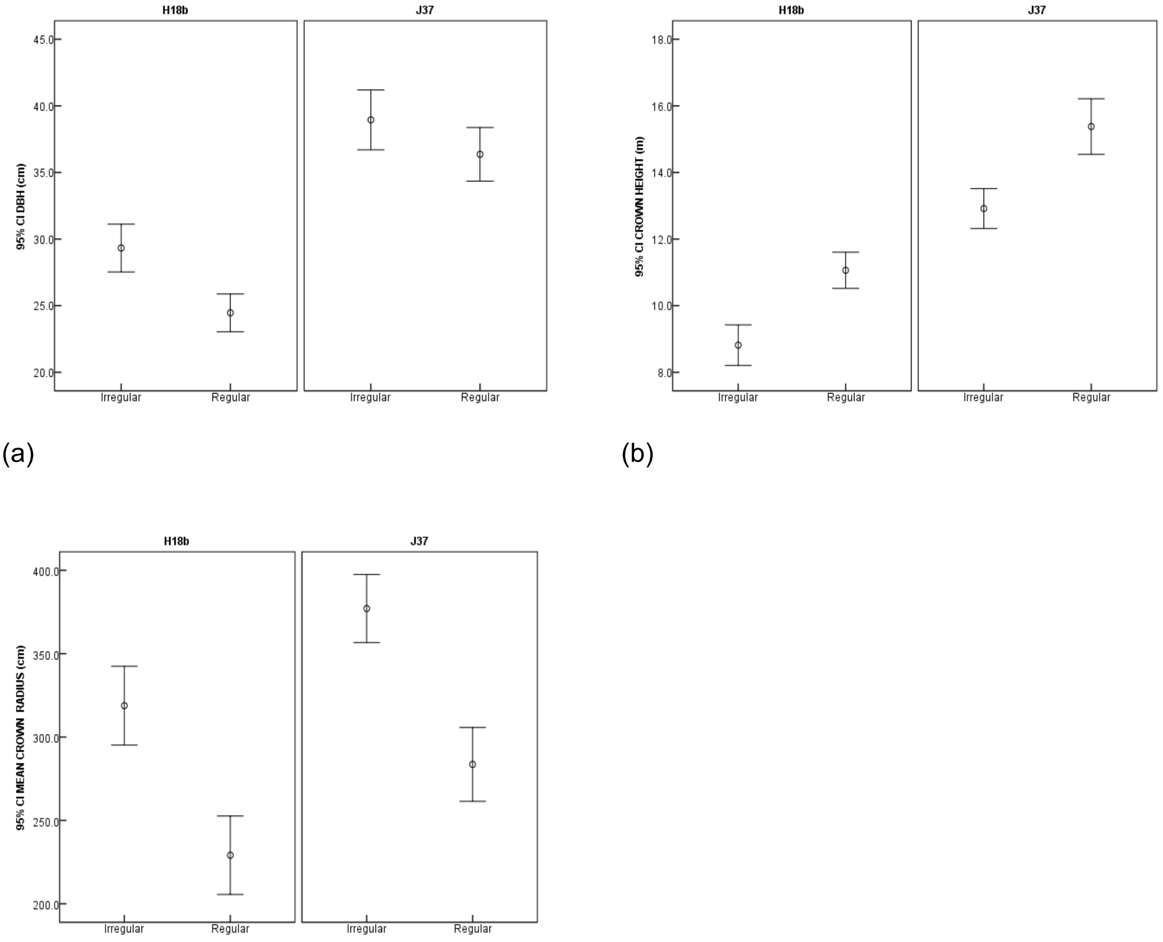
4.1.3 DBH, crown height and mean crown radius

Table 14 and Figure 13 illustrate the results obtained by ANOVA to test the differences between DBH, crown height and crown radius in irregular and regular competition. In compartment H18b it was found that DBH, crown height and mean crown radius where all significantly different.

Table 14: ANOVA analysis showing results for DBH, crown height and mean crown radius between irregular and regular competition in compartments H18b and J37 ($p<0.05$).

Compartment			Sum of Squares	Df	Mean Square	F	Sig.
H18b	DBH	Between Groups	354.78	1	354.78	18.91	<0.001
		Within Groups	1088.31	58	18.76		
		Total	1443.09	59			
	Crown height	Between Groups	75.94	1	75.94	31.88	<0.001
		Within Groups	138.16	58	2.38		
		Total	214.10	59			
	Mean crown radius	Between Groups	120776.38	1	120776.38	30.24	<0.001
		Within Groups	231669.33	58	3994.30		
		Total	352445.71	59			
J37	DBH	Between Groups	100.36	1	100.36	3.08	0.085
		Within Groups	1892.14	58	32.62		
		Total	1992.51	59			
	Crown Height	Between Groups	90.90	1	90.90	23.98	<0.001
		Within Groups	219.83	58	3.79		
		Total	310.73	59			
	Mean Crown Radius	Between Groups	131124.89	1	131124.89	40.34	<0.001
		Within Groups	188518.42	58	3250.32		
		Total	319643.30	59			

The same results were obtained in compartment J37 for crown height and mean crown radius. DBH was, however, not significantly different at the 95% confidence level.



(a)

(b)

(c)

Figure 13: Error bar plots showing the relationship between irregular and regular competitive status on (a) DBH, (b) crown height and (c) mean crown radius in compartments H18B and J37.

4.1.4 Crown plasticity and eccentricity

Table 15 and Figure 14 show the results of the differences between irregular and regular competition on crown plasticity and eccentricity.

Table 15: Results of the analysis of crown plasticity and eccentricity in compartments H18b and J37 between regular and irregular competitive status (p<0.05).

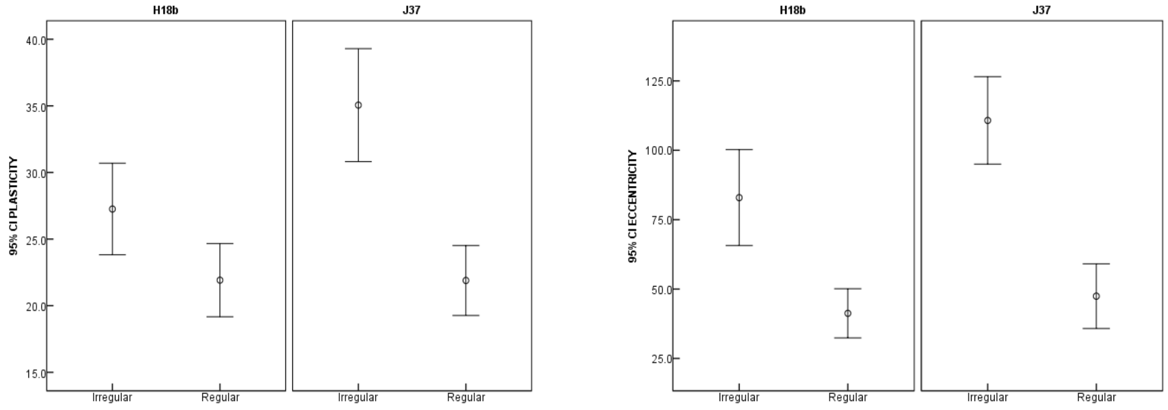
Compartment			Statistic*	Sum of Squares	df1	df2	Mean Square	F	Sig.
H18b	***Plasticity	Between Groups		427.52	1		427.53	6.17	0.02
		Within Groups		4021.82	58		69.34		
		Total		4449.34	59				
	**Eccentricity		19.23		1	43.31			<0.001
J37	**Plasticity		29.18		1	48.38			<0.001
	***Eccentricity	Between Groups		60096.07	1		60096.07	43.68	<0.001
		Within Groups		79807.58	58		1375.99		
		Total		139903.65	59				

* Asymptotically F distributed

** A Welch's t-test was used instead of t-test, where a Levene test had revealed a lack of variance homogeneity.

*** ANOVA analysis used

The analysis revealed significant differences in crown plasticity and crown eccentricity between irregular and regular competitive status in H18b and J37.



(a) (b)

Figure 14: Error bar plot of (a) plasticity and (b) eccentricity between irregular and regular competitive status in compartments H18b and J37.

4.1.5 Branch length and diameter

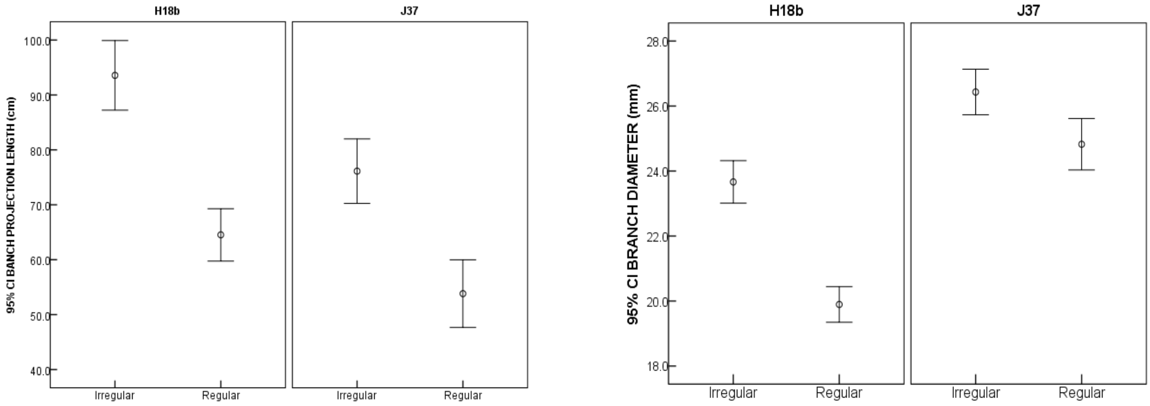
Table 16 and Figure 15 show the results of the differences between irregular and regular competitive status on both branch projection length and branch diameter using a Welch's t-test.

Table 16: Results of branch projection length and branch diameter in compartment H18b and J37 between regular and irregular competitive status (p<0.05).

Compartment		Statistic*	df1	df2	Sig.
H18b	Branch Projection length (cm)	47.001	1	1252.615	<0.001
	Branch Diameter (mm)	74.79	1	2033.823	<0.001
J37	Branch Projection length (cm)	23.738	1	856.119	<0.001
	Branch Diameter (mm)	8.895	1	2020.756	0.003

* Asymptotically F distributed

In both H18b and J37 significant differences between regular and irregular competitive status on branch projection length and diameter were found.



(a) (b)

Figure 15: Error bar plot of (a) branch projection length and (b) branch diameter in irregular and regular competitive status in compartments H18b and J37.

4.1.6 Space-use efficiency

Significant differences between irregular and regular competitive status trees were found in terms of their space-use efficiency in both compartments (Table 17).

Table 17: ANOVA analysis showing results of space-use efficiency between irregular and regular competitive status in compartments H18b and J37 ($p < 0.05$).

Compartment		Sum of Squares	Df	Mean Square	F	Sig.
H18b	Between Groups	0.02	1	0.02	7.44	0.02
	Within Groups	0.04	13	0.00		
	Total	0.07	14			
J37	Between Groups	0.01	1	0.01	4.78	0.05
	Within Groups	0.03	13	0.00		
	Total	0.04	14			

4.1.7 Summary of results

A summary of the mean values for each of the hypotheses tested appear in Table 18, along with particular alternative hypotheses tested for each.

Table 18: Calculated quadratic means for all competitive status diagnostics analysed

Comp	Competition	DBH (cm)	Crown Height (m)	Crown Radius (cm)	Space-use efficiency	Crown Plasticity	Crown Eccentricity	Branch Diameter (mm)	Branch Proj. Length (cm)
Connected Hypothesis		A_1			A_2	A_3		A_4	
J37	Regular	36.75 σ 5.38	15.54* σ 2.34	289.51* σ 59.3	0.17* σ 0.05	22.96* σ 7.63	56.48* σ 31.68	27.36* σ 12.68	163.96* σ 124.61
J37	Irregular	39.40 σ 6.02	13.01* σ 1.6	380.88* σ 54.63	0.11* σ 0.03	36.79* σ 11.35	118.26* σ 42.44	30.19* σ 13.44	211.42* σ 106.63
H18b	Regular	24.75* σ 3.88	11.16* σ 1.45	237.36* σ 63.16	0.20* σ 0.08	23.08* σ 7.35	47.42* σ 23.78	21.85* σ 9.79	131.06* σ 93.70
H18b	Irregular	29.71* σ 4.8	8.96* σ 1.63	324.86* σ 63.29	0.11* σ 0.03	28.72* σ 9.20	94.61* σ 46.3	26.01* σ 10.55	174.14* σ 92.63

* Significant differences between trees in regular and irregular growing situation ($P < 0.05$)

4.2 Harvesting thinnings from optimised stand structure

4.2.1 Determining the optimal tree geometry

The planting geometry selection process in Chapter 3 found the planting geometries 2.5m x 2.9m, 2.3m x 3.1m and 2.4m x 3.0m (Table 19), to be suitable alternatives for the conventional 2.7m x 2.7m geometry; i.e. the control.

Table 19: Acceptable planting geometries based on; rows removed, machine trail length and closest tree distance.

Planting geometry (m x m)	Machine Trail width (m)	Distance to furthest tree (m)	Row removed (machine trail)	Spacing between trails (m)*	Trail length.ha^{-1} (m)	Number of rows removed. Ha^{-1}
2.7x2.7	5.4	9.45	7th	18.9	599.4	6
2.5x2.9	5	10	9th	22.5	500	5
2.3x3.1	4.6	9.2	9th	21.6	504	5
2.4x3	4.8	9.6	9th	20.7	506	5

* Measured from the mid-point of the machine trails

The alternatives over the control geometry reduced the length of machine trail ha^{-1} by between 99.4 and 93.4 meters ha^{-1}. The number of tree rows removed per hectare was reduced by adjusting the width between the skid trails in all cases. In all the proposed planting geometries the distance to the furthest tree was within the maximum reach of the harvester boom (10m).

4.2.2 Compartment thinning

Results of the virtual thinnings are detailed in Table 20 and Table 21.

Table 20: Trees remaining before first and second thinning

Planting geometry (m x m)	Initial tree number in compartment subset	After first thinning (trees.ha^{-1})	After Second thinning (trees.ha^{-1})
2.7m x 2.7m	1189	717	476
2.5m x 2.9m	1229	691	462
2.4m x 3m	1193	684	456
2.3m x 3.1m	1223	699	455

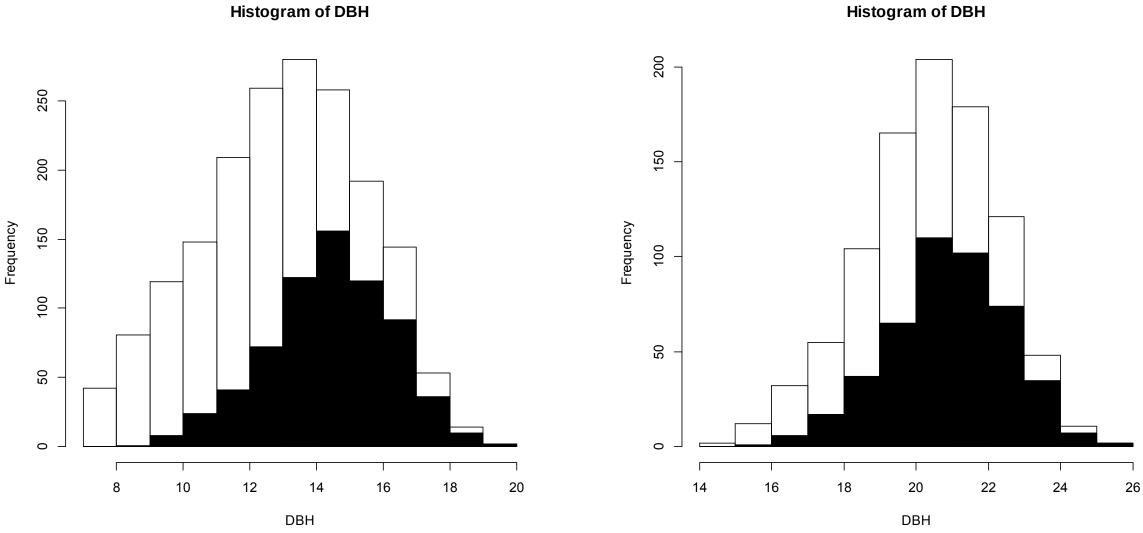
The reduction in SPHA from the initial numbers of tree to tree count after each thinning are of a subset (snapshot) one hectare sample of the 1.5 ha compartment used as input to the simulator (Table 20). The DBH and height information before and after thinning are shown in Table 21.

Table 21: DBH and height means before and after first and second thinning

Thinning	Planting geometry (m x m))	Before thinning				After thinning			
		DBH (cm)	σ	Height (m)	σ	DBH (cm)	σ	Height (m)	σ
First	2.7 x 2.7	13.28	2.44	10.2	1.04	14.41	1.94	10.70	0.77
	2.5 x 2.9	13.21	2.40	10.17	1.04	14.49	1.86	10.73	0.77
	2.4 x 3	13.29	2.43	10.20	1.04	14.56	1.86	10.75	0.75
	2.3 x 3.1	13.30	2.40	10.20	1.03	14.62	1.71	10.70	0.67
Second	2.7 x 2.7	20.19	1.94	15.17	0.78	20.94	1.51	15.47	0.57
	2.5 x 2.9	20.27	1.86	15.20	0.77	20.76	1.77	15.40	0.70
	2.4 x 3	20.32	1.71	15.21	0.67	20.89	1.57	15.44	0.59
	2.3 x 3.1	20.40	1.86	15.26	0.75	21.01	1.65	15.50	0.63

This result shows an overall increase in DBH and height after each of the subsequent thinning operations.

Figure 16 shows examples of histograms of tree removal and remaining diameter classes before and after first and second thinning.



(a) (b)

Figure 16: DBH range according to diameter class of trees removed (clear) and remaining (black) for (a) first and (b) second thinning.

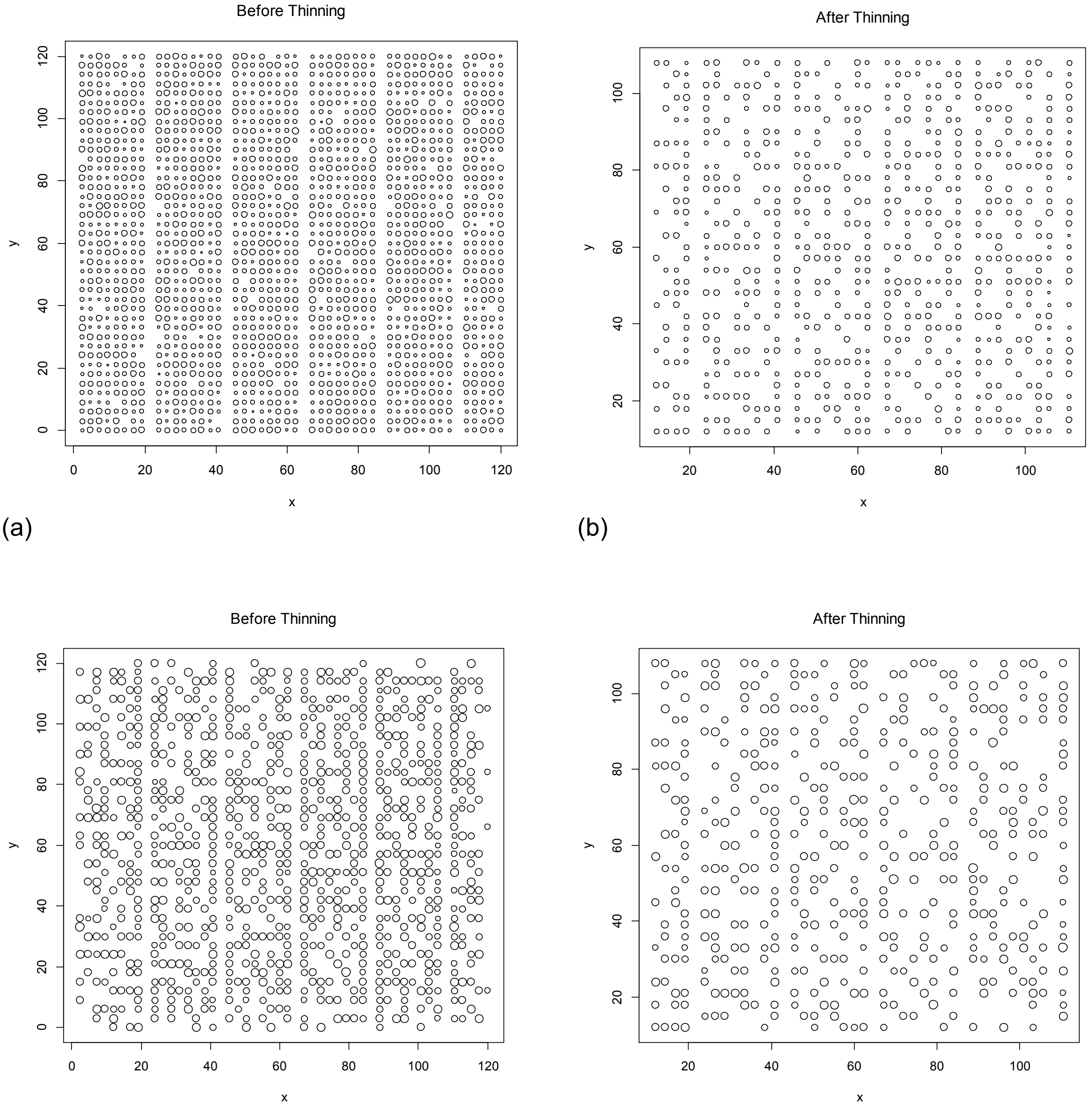
It can be seen that the total stem count is reduced and the mean diameter of the remaining trees increases. This result is representative for all proposed planting geometries as well as the control geometry.

In order to test the efficacy of the thinning in maintaining an evenly distributed tree structure a Clark and Evan aggregation (R) index was carried out on the tree distributions before and after thinning. The results of this analysis appear in Table 22.

Table 22: Clark and Evans (R) index for compartments before and after thinning

Thinning	Planting geometry (m x m)	Clark and Evan aggregation index (R)	
		Before thinning	After thinning
First	2.7m x 2.7m	1.863	1.098
	2.5m x 2.9m	1.760	1.132
	2.4m x 3m	1.701	1.124
	2.3m x 3.1m	1.641	1.156
Second	2.7m x 2.7m	1.425	1.126
	2.5m x 2.9m	1.398	1.100
	2.4m x 3m	1.386	1.196
	2.3m x 3.1m	1.641	1.156

Examples of graphical illustrations of the thinned stand structure from before thinning, after first and after second thinning are illustrated in Figure 17.



(a) (b)

(c) (d)

Figure 17: Example of the resulting tree distribution after thinning simulation; before (a) and after (b) first thinning and before (c) and after (d) second thinning subset stand structure.

4.2.3 Virtual harvesting of sample stands

Harvested volume data of the virtually thinned stands are shown in Table 23.

Table 23: Harvested data before initial thinning and after first or second thinning

Thinning	Planting geometry (m x m)	Total volume ($m^3 \cdot ha$)		Means per harvesting stop			
		Removed	Remaining	Volume (m^3)	σ	Distance (m)	σ
First	2.7 x 2.7	30.37	46.96	0.41	0.08	7.91	0.14
	2.5 x 2.9	27.66	48.13	0.26	0.03	5.19	1.02
	2.4 x 3	30.27	46.96	0.42	0.08	7.23	0.72
	2.3 x 3.1	28.56	47.46	0.51	0.05	9.05	0.43
Second	2.7 x 2.7	35.85	93.89	0.91	0.17	12.85	1.28
	2.5 x 2.9	35.31	90.87	0.76	0.2	10.38	1.39
	2.4 x 3	35.98	89.91	0.88	0.12	11.64	2.03
	2.3 x 3.1	39.02	90.57	1	0.12	11.86	1.12

The results show the removed and remaining volume after each thinning, mean volume harvested at each harvesting stop and the mean distance between the harvesting stops.

The mean differences between the different planting geometries (control and suggested potential scenarios) and the abovementioned criteria were further compared.

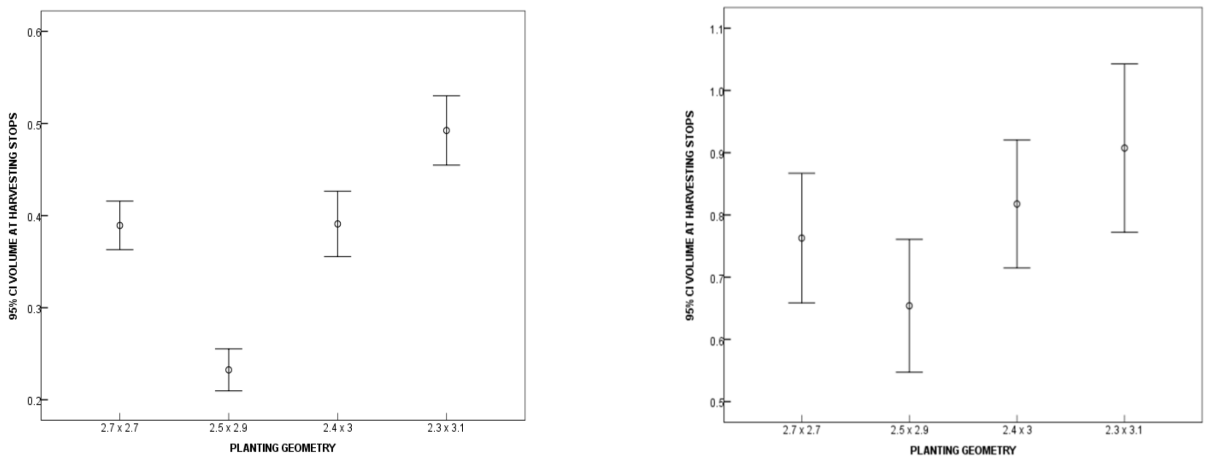
4.2.3.1 Volume harvested per stop for each planting geometry

ANOVA analysis results for differences between the mean volume harvested at each harvesting stop on machine trails for each planting geometry are shown in Table 24 and Figure 18.

Table 24: ANOVA results indicating the mean differences between volume harvested per stop for different geometries for both first and second thinning ($p<0.05$).

Thinning		Sum of Squares	Df	Mean Square	F	Sig.
First	Between Groups	3.06	3	1.02	57.78	<0.001
	Within Groups	5.70	323	0.02		
	Total	8.77	326			
Second	Between Groups	1.63	3	0.54	3.71	0.013
	Within Groups	26.96	184	0.15		
	Total	28.59	187			

Analysis of the data indicates that there were significant differences ($p<0.05$) between mean harvested volume at each harvesting stop for both first and second thinning.



(a) (b)

Figure 18: Mean volume harvested for each stop (a) first thinning and (b) second thinning for each planting geometry.

A post hoc analysis using a Bonferroni multiple comparison test found that there were significant differences (p<0.05) between volume harvested at each stop for all of the geometries in the first thinning, except for the control and 2.4m x 3m planting geometry. In the second thinning there were no significant differences (p>0.05) between volume harvested at each stop for all of the geometries, except for a significant difference between 2.5m x 2.9m to 2.3m x 3.1m geometries.

4.2.3.2 Distance between harvesting stops for each planting geometry

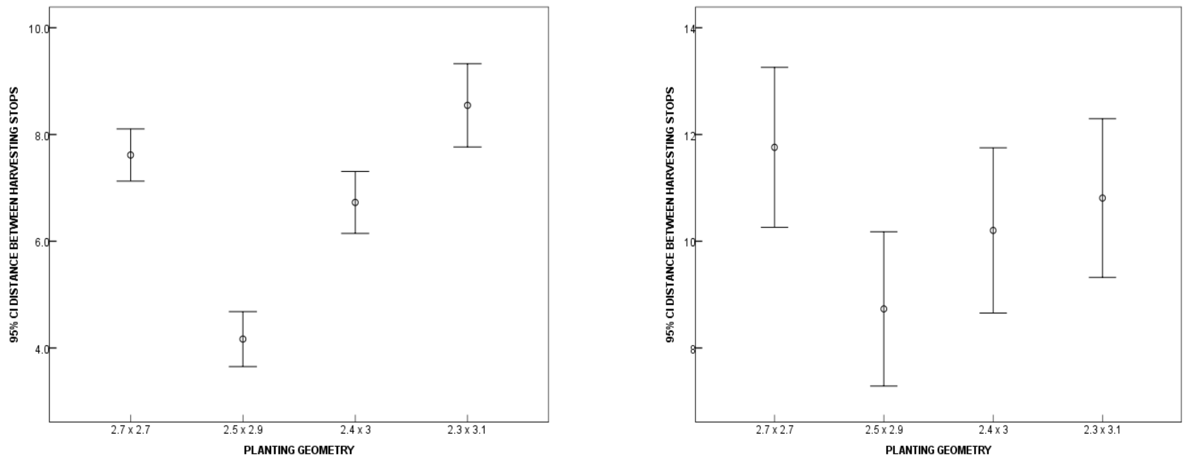
A Welch t-test showed differences between the mean distances between harvesting stops on machine trails for each of the planting geometries (Table 25, Figure 19).

Table 25: Welch test results indicating significant differences between harvesting stop position in both first and second thinning (p<0.05)

Thinning	Statistic*	df1	df2	Sig.
First	42.764	3	159.45	<0.001
Second	2.979	3	101.18	0.035

* Asymptotically F distributed.

The results of this test show that there were significant differences (p<0.05) between the distances between harvesting stops in both first and second thinning.



(a) (b)

Figure 19: Mean distance traveled between harvesting stops for (a) first thinning and (b) second thinning for each planting geometry.

A Tamhane T2 multiple comparisons were done and results of this test indicate significant differences between all the geometries except for the control and 2.4m x 3m and the control and 2.3m x 3.1m planting geometries in first thinning. In the second thinning there were no significant differences between any of the combinations except for the control and 2.5m x 2.9m planting geometry.

4.2.3.3 Harvesting time per harvesting stop for each planting geometry.

ANOVA analysis was done on the first thinning data, the second thinning data necessitated a Welch t-test on this data (Table 26 and Figure 20).

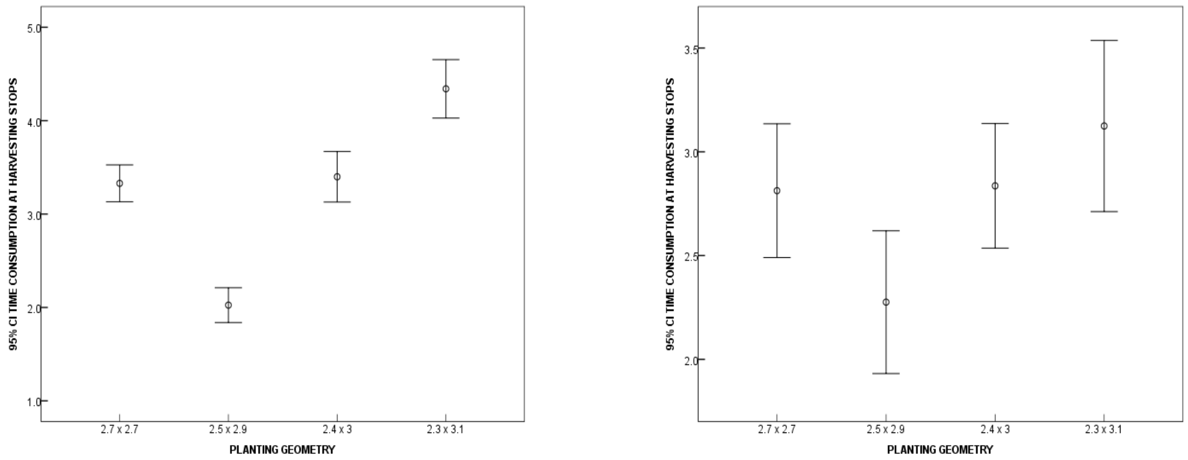
Table 26: Results of mean harvesting time per harvesting stop for first and second thinning (p<0.05)

Thinning		Statistic*	Sum of Squares	df1	df2	Mean Square	F	Sig.
First	Between Groups		236.62	3		78.87	71.03997	<0.001
	Within Groups		358.62	323		1.11		
	Total		595.24	326				
Second**		3.78		3	100.71			0.013

* Asymptotically F distributed.

**A Welch’s t-test was used instead of t-test, where a Levene test had revealed a lack of variance homogeneity.

The results show that there were significant differences between the mean harvesting times at each harvesting stop. Significant differences were also found between all of the planting geometries in first thinning operations except for the control and the 2.4m x 3m planting geometry (Bonferroni multiple comparison test). The second thinning showed no significant differences between the geometries, except between the 2.5m x 2.9m and the 2.3m x 3.1m geometries (Tamhane T2 multiple comparison test).



(a) (b)

Figure 20: Mean time consumption to harvest trees for each harvesting stop for first thinning (a) and second thinning (b) for each planting geometry.

4.2.4 Time study and cycle times

Harvester cycles, volume and production achieved in the two thinning operations for each planting geometry are shown in Table 27. The number of cycles depended on the number of harvesting stops determined by the harvesting simulator.

Table 27: Harvester total cycles, time taken, volume, productive machine hours (PMH) and volume per PMH for each geometry and thinning

Thinning	Planting geometry (m x m)	Cycles	Time	Volume	PMH	$m^3 \cdot PMH^{-1}$
First	2.7x2.7	78	259.66	30.75	4.33	7.11
	2.5x2.9	119	240.95	28.22	4.02	7.03
	2.4x3	72	244.74	28.5	4.08	6.99
	2.3x3.1	58	251.79	28.84	4.2	6.87
Second	2.7x2.7	47	132.2	35.7	2.2	16.2
	2.5x2.9	54	122.88	35.61	2.05	17.39
	2.4x3	44	124.78	36.2	2.08	17.41
	2.3x3.1	43	134.34	39.24	2.24	17.53

In the first thinning there was a reduction in production between the control and the remaining planting geometries. While in the second thinning the opposite was true where an increase was evident between the control and the other planting geometries.

Forwarder cycles (Table 28) were limited by the load capacity of the forwarder, and in most cases only one full load was possible ($18.86m^3$) followed by a partial load. However, in the second thinning on the 2.3m x 3.1m geometry, the additional volume (from the thinning simulation) to the machine trail lead to two full loads and one partial third load being forwarded.

Table 28: Forwarder cycle times and volumes per cycle for each thinning and geometry and total time and volume per hour

Thin.	Planting geometry (m x m)	Cycle one		Cycle two		Cycle three		Total		PMH	$m^3 \cdot PMH^{-1}$
		Time	Vol.	Time	Vol.	Time	Vol.	Time	Vol.		
First	2.7x2.7	144.78	18.86	101.02	11.89	NA	NA	245.8	30.75	4.1	7.51
	2.5x2.9	233.07	18.86	116.65	9.36	NA	NA	349.72	28.22	5.83	4.84
	2.4x3	137.5	18.86	88.97	9.64	NA	NA	226.47	28.5	3.77	7.55
	2.3x3.1	115.84	18.86	64.93	9.98	NA	NA	180.77	28.84	3.01	9.57
Second	2.7x2.7	85.11	18.86	107.22	16.84	NA	NA	192.33	35.7	3.21	11.14
	2.5x2.9	107.31	18.86	112.9	16.75	NA	NA	220.21	35.61	3.67	9.7
	2.4x3	97.94	18.86	81.67	17.34	NA	NA	179.61	36.2	2.99	12.09
	2.3x3.1	89.09	18.86	81.31	18.86	15.09	1.52	185.5	39.24	3.09	12.69

The lowest production was with the 2.5m x 2.9m planting geometry, there was, however, a general increase in production from the control to the remaining planting geometries.

4.2.5 Machine and systems costing

The results of the machine costing and system costing are shown in Table 29.

Table 29: Results of machine costing for first and second thinning for harvesting and forwarding operations.

Thinning	Planting geometry (m x m)	Harvester cost ($R \cdot m^{-3}$)	Forwarder cost ($R \cdot m^{-3}$)	Total system cost ($R \cdot m^{-3}$)
First	2.7x2.7	153.06	99.86	252.92
	2.5x2.9	154.81	154.95	306.76
	2.4x3	155.69	99.33	255.02
	2.3x3.1	158.41	78.37	236.78
Second	2.7x2.7	67.18	67.32	134.50
	2.5x2.9	62.58	77.32	139.90
	2.4x3	62.51	62.03	124.54
	2.3x3.1	62.08	59.10	121.18

In both the first and second thinning the most expensive thinning operation (total costs) was for the 2.5m x 2.9m planting geometry (R306.76 and R139.90$\cdot m^{-3}$). In the first thinning, the cheapest system was that of the 2.3m x 3.1m planting geometry (R236.78 m^{-3}). The second thinning showed a reduction in cost trend between the control and the remaining planting geometries.

5 Discussion

5.1 Irregular stand structure and tree form

The following hypotheses, testing the differences between regular and irregular competitive status in both compartments, could be accepted (The means and associated hypotheses for each of these indices are shown in Table 18):

A_1: for DBH, crown height and crown radius

A_2: for crown plasticity and eccentricity

A_3: for branch diameter and projection length

A_4: for space-use efficiency

The majority of the relationships tested yielded significant differences between the regular and irregular competition. It was, however, found that DBH did not differ significantly between regular and irregular competitive situations on the 5% level but only on the 10% significance level ($p=0.086$) in the older compartment J37. A possible explanation could be the diameter range being of an insufficient sample size. It can therefore be hypothesised that it would be significantly different on the 5% level if the sample size was increased. Based on the results it can be stated that trees grown in regular and irregular spatial competition differ significantly in their dimensions and branch properties, as well as their efficiency in space use.

5.1.1 DBH, crown height and crown radius

The DBH in both compartments H18b and J37 differed between trees in regular and irregular competitive situations (Table 18). As expected, trees in both compartments exhibited increasing diameter growth when trees were under less competitive stress, along machine trails and at gap edges for example.

Crowns in both compartments were significantly longer for trees in an irregular competitive status (Table 18). As with DBH this was also supported by Cancino (2005), who did work on *P. radiata* growing at compartment edges. This can be related to the mean crown radius of the trees under irregular competitive status having significantly larger crown radii than those in regular competitive status (Table 18). Further evidence on the influence of geometric one-sided competition on crown length and crown extension was provided by

Seifert (2003) with a dynamic simulation model for Norway spruce (*Picea abies*) justifying the detected reaction pattern in the current work.

Based on the findings it can be stated that *P. patula* exhibits a considerable ability to extend its crown into areas of less competition i.e., trees growing on compartment edges, on machine trails or at the edge of gaps in the compartment. These trees had longer crowns compared to trees in regular all-sided competition. The latter would have the living crown reduced due to a stronger natural pruning as a consequence of competition for light and mechanical abrasion (Seifert, 2003).

5.1.2 Crown eccentricity and plasticity

Both crown eccentricity and plasticity measure the ability of the crown to extend into areas of less competition and space, primarily to intercept light. Umeki (1995b) found similar characteristics in broad-leaved plants. Crown eccentricity particularly indicates the extent to which the crown grows off-centre in relation to the stem of the tree in order to improve light interception. These indices are significantly influenced by the silvicultural management of stands (Weiskittel et al. 2007). Longuetaud et al. (2008) showed in a study on *Quercus petraea* that crown eccentricity and plasticity stabilised with time after thinning and consequently led to more regular spatial crown distribution. This study found a similar effect pattern in *P. patula* since the differences in eccentricity decreased in the older stand (Table 18).

5.1.3 Branch diameter and length

Branch diameters and branch projection lengths were larger with trees in spatially irregular competition than those in regular competition (Table 18). This is closely associated with most of the other defined indices, since crown radius, crown plasticity, crown eccentricity and space-use efficiency are closely correlated with branch length. A well-known positive allometric relationship exists between branch length and branch diameter (Seifert, 1999 and 2003). This was also found in this study, where longer branches also had larger diameters. Cregg et al. (1993), Seifert (2003) and Weiskittel et al. (2007) showed that one-sided competition (irregular competition) resulted in longer branches of larger diameter. Studies by Samson (1993) and Lemieux and Beaudoin (1999) established further relations from branch diameter at the stem surface to knot diameter in the stem. It can be concluded that large branches are detrimental to saw timber quality (Kromhout & Bosman, 1982; Seifert, 2003).

Based on the findings from this study further assumptions can be made on trees grown in spatially asymmetric competitive status. The association of longer, thicker and heavier branches leads to an increase in crown length, and crown area creates a disproportional mass to one side of the tree. The tree in turn naturally attempts to maintain itself spatially upright. This in turn could lead to stem lean or sweep and mechanical stress in the wood with the consequence of eventual reaction wood in the stem (Kromhout & Bosman, 1982; Bredenkamp; 1984; Cancino, 2005).

5.1.4 Space-use efficiency

A concern in terms of stand volume growth is that space-use efficiency in irregularly spaced trees is less than those of regularly spaced trees. These results are supported by work done on *P. taeda* by Sterba and Amateis (1998) and on aerial crown photography related to tree volume by Akça (1979), where narrower tree crowns were found to be more efficient in volume production than wider tree crowns. Similar results were found by Hamilton (1969), and Webster and Lorimer (2003) in mixed conifer forests.

This information is important, as quantifying space-use efficiency has not yet been investigated in South Africa. To grow trees in irregular stand structures can thus lead to a substantial loss of overall volume production because those trees will compete for the additional space with higher growth rates to a certain degree but will not grow as efficiently as regularly spaced trees.

Ultimately, irregular stand structures in *P. patula* may significantly influence tree volume growth and wood quality.

5.2 Harvesting thinnings from optimised stand structure

The following research questions posed in Chapter 1 were found to be true.

A change in planting geometry will;

- reduce machine trail length per hectare but still maintain suitable access to harvesting machines.
- maintain compartment tree spacing regularity when simulated thinning is done.
- allow for improved harvesting productivity.
- allow for reduced harvesting system cost.

5.2.1 Planting geometry changes

The alternative planting geometries analyzed (Table 19) resulted in a 16% reduction in machine trail length per hectare (from 599.4m to 500m. ha^{-1}) when compared to the standard 2.7m x 2.7m planting geometry; the control. This is a significant advantage over the traditional planting geometry.

A reduction in machine trail length has a number of advantages. Large gaps in the canopy created by the cutting out of rows for machine trails in standard planting geometries were reduced in size or limited. Furthermore, the likelihood of damage to residual trees during harvesting, purely because there are fewer trails, is also reduced (Hunt & Krueger, 1960; Ohman, 1970; Kromhout & Bosman, 1982; Vasiliauskas, 2001). One could assume, based on works of Warkotsch et al. (1994) and Bettinger et al. (1998), that fewer trails also resulted in reducing the potential of soil damage in terms of soil compaction and displacement.

CTL system harvesting as applied in this study, generally shows reduced stand impact over tree-length and full-tree length harvesting systems (Wang et al. 2005). There are also advantages of carrying wood rather than dragging tree-lengths along the ground in terms of wood quality and fibre damage.

5.2.2 Stand regularity after thinning

Alternative planting geometries, and a thinning algorithm were developed to provide realistic thinning output while maintaining stand regularity. As reported in Chapter 4, the thinning algorithm produced an accurate thinning from below result in terms of stem reduction and diameter class increment. Secondly, an aggregation index, (R) (Clark & Evans 1954) showed that the thinning algorithm was effective in terms of maintaining regular stand spacing.

However, the stem counts after each thinning (Table 20) did not fully reflect the required number of stems, as per current working circle prescriptions (Table 2). This is possibly due to the thinning algorithm over- thinning at the sample stand edges and that the sub-set used for the simulation was merely a snapshot of the center of the compartment. Depending where the subset was taken, tree counts could be more or less than was prescribed. A similar result would have been found if a subset had been randomly taken from any part of the compartment. The algorithm is still in the development stage and has not been optimised for compartment edges.

The results of simulation were, however, acceptable as the full set of trees were thinned in proportion to these prescriptions. Furthermore, the requirements of the thinning, in terms of the study were to produce a harvestable volume and not to test the exact number of stems removed. Results in this study showed that the thinning simulator performed this operation effectively.

The aim of the simulator was to avoid clustering of the trees and to maintain a (R) value higher than 1.0. All the aggregation index results were higher than this threshold (Table 22). This illustrates that the stands were thinned to a random distribution with no clustering.

5.2.3 Harvesting and forwarding productivity

Following the virtual thinning of the stands, calculations and comparison of harvesting production volumes, time models and movement distances were completed.

5.2.3.1 Harvester

As expected, volumes per harvesting stop on machine trails increased when less machine trail rows were removed. This was also closely associated with the distance between harvesting/loading stops and the time consumption for harvesting at each stop. In all of these cases, the 2.5m x 2.9m planting geometry consumed less time than the control (2.7m x 2.7m) and all other alternatives. Due to the lower volume per stop and shorter distances between stops. There were, however, many more stops per hectare than for the other geometries.

There was an overall increased time consumed at each harvesting stop in the first than compared to the second thinning. This was due to higher stem numbers (of lower piece volume) in the younger stand harvested. The individual tree volume, in this simulation, did not influence time consumption. The harvester boom movement related activities were the main driver of this. In other words, due to the individual tree volume being less in first thinnings, the multiple boom movements did not translate into a potentially higher volume harvested, a fact highlighted in a study by Eliasson and Lageson (1999) and Talbot et al. (2003). This phenomenon will potentially decrease productivity of the system in first thinnings as was evident in Belbo (2010).

The data showed that the distance a harvester moved between harvesting stops and the volumes harvested at each stop influenced each other. A balance between these two factors, in order to optimise machine working time and movement time, would greatly increase the productivity. This can be backed up by results in other studies that provide evidence where travel distances do significantly affect the productivity of harvesters seen here (Talbot et al. 2003).

When deciding on a feasible alternative to the control (2.5m x 2.9m, 2.4m x 3m and 2.3m x 3.1m), the productivity results for the harvester were inconclusive in the first thinning (Table 27). One would assume that the spacing geometries with the highest volume per harvesting stop, the shortest distance between stops and lowest total harvesting time consumption would appear to be the best alternative. These factors, however, only had a greater influence in the second thinning.

In term of results, harvester productivity decreased by 3% in the first thinning and increased by 8% in the second thinning, this can, however, be seen as a net increase in productivity over the rotation of the stand. Planting geometries 2.4m x 3m and 2.3m x 3.1m showed an increase in productivity when compared with the control. It is evident that these were the best suited alternatives at this point.

5.2.3.2 Forwarder

Forwarder productivity depends on the distance travelled between loading points and the volume available at each stop. The grapple size influences the number of times the boom has to be deployed to load the available volume. While this movement of the boom influenced the time consumed loading the forwarder as with the harvester, the travel time did not have a great effect on the productivity in this simulation. The main influence of productivity, evident from this study, was the increase in forwarder productivity when volume per harvesting stop increased.

Similar travelling distances between harvesting stops were found in the simulation between the control, 2.4m x 3m and 2.3m x 3.1m, showing the importance of the volume per stop as a factor was driving productivity increases. Overall productivity increases of by 21% with the first thinning and 12% in the second thinning could be achieved by using different planting geometries to the traditional 2.7m x 2.7m spacing. Similar to that of the harvester, 2.4m x 3m and 2.3m x 3.1m were the most productive planting geometries for the forwarder.

5.2.4 Harvesting system cost

Harvest system costing is seen as one of the most important decision making tools available to forest engineering planning (Hogg et al. 2012). The cost of a harvesting system is dependent on the productivity of the individual machines in the system. In general, there was a decrease in cost·m^{-3} between the control and the alternative planting geometries.

The planting geometries that led to the lowest costs were 2.4m x 3m and 2.3m x 3.1m in both first and second thinning operations. These two systems yielded an overall reduction in cost of 7% (R16.14·m^{-3}) and 10% (R14.32·m^{-3}) in second thinning respectively. As discussed previously, these two planting geometries did not significantly differ from each other in terms of volume per harvesting stop, distance between harvesting stop and time consumption per harvesting stop. However, a reduction of R18.24·m^{-3} and R3.66·m^{-3} could be realised in first and second thinning operations respectively when choosing between 2.4m x 3m and 2.3m x 3.1m planting geometries, the latter being the cheapest.

The financial benefit of adopting alternative planting geometries to the control is evident in the results. First thinnings are usually marginal in terms of cost and productivity. However, by changing the planting geometry the potential cost reduction can make these thinnings more competitive for the current systems.

6 Conclusion

From the data presented in this thesis, it is clear that irregular stand structure affects tree growth in the following ways.

Firstly in growing situations of irregular stand structure;

- crowns are larger in diameter and extend to the area of less competition disproportionately.
- branches are longer and thicker.
- Stem diameters at breast height are larger in individual trees grown in irregular competition due to increased growing space. However, on the other hand the space-use-efficiency, i.e. ability of the tree to translate crown area into stem volume, is significantly reduced, which may lead to volume losses at the stand level.

Secondly, when optimising the planting geometries for mechanised thinning operations it was also found that;

- a thinning simulator can effectively maintain stand regularity thus proving the efficacy of the method for the purpose of this study
- overall system productivity could be increased by up to 8% and 21% in harvester and forwarder productivity, respectively, if the planting geometry was changed.
- rectangular geometries were superior to standard quadratic planting geometries.
- cost reductions of up to 7% in first and 10% in second thinnings can be achieved.

The planted plantation area in South African has been significantly reduced over the past few years mainly due to conservation issues (DAFF 2001). Consequently the Industry needs to maintain or increase production on what is a diminishing land area to maintain the required production.

Due to long saw timber working circle rotations, this necessitates a more efficient use of the existing plantation area. However, investigations into tree growth in relation to irregular stand structures has not been explored extensively in South Africa.

A major finding of this study is that the space-use efficiency of regularly spaced trees is higher – a result not yet reported in South Africa. Results that are often thought of as common knowledge; the relationship between DBH, crown height, crown radius, branch diameter and branch length have been further quantified for *P. patula*. The use of indices such as crown plasticity and crown eccentricity in *P. patula* have also led to a greater understanding of tree reactions to different competitive situations and can thus provide a quantitative background for optimised forest management.

In the second part of the study, adding to the understanding of stand characteristics, the development and application of a computer based harvesting simulation model has once again highlighted the power of simulation techniques in providing answers to these complex issues. Financial decisions to implement changes in stand management require the ability to test these without the associated risks involved by trial and error applications. Even though the quantifiable results may vary in real-life, proven benefits are set and should translate well into the actual situation. However, in more extensive simulation studies, accuracy can be improved by including factors that mimic stand and operational variability even better.

The study has highlighted the effects of irregular stand structure on tree growth. There is, however, a need to manage effective marking for thinning tied to operational harvesting planning in order to limit irregularity and effectively manage the resources to maximise future yields. This work has also attempted to change mind-sets by exploring alternatives to standard, square planting geometries by showing that small adjustments can potentially improve overall harvesting productivity and costs and reduce impact on the stands. By not remaining within the constraints of current planting and management prescriptions, the change in planting geometries has proved its benefit.

6.1 Recommendations for future work

The identified further research needs can be divided into three parts. Firstly, investigation into wood quality, knots and reaction wood, should be undertaken in order to determine the financial effects these have on the final saw timber products. Secondly, financial opportunity cost analyses, quantifying the effects of the decrease in space-use efficiency of trees due to an irregular stand structure, would be useful to the viability of saw timber production. Although there was no quantification of the costs involved by not maintaining stand regularity in the first part of the study, the increase in branch size, increase of reaction wood and the sub-optimal volume increment can be expected to, hypothetically, negatively impact the return of investment of the stand.

Lastly, the simulation of the thinning operations conducted in this study proved how effective this technique is in testing multiple scenarios without having to implement them in reality. The logistics, cost benefit and time saving of this form of Operations Research are clearly apparent. Investigations need to be done in developing the thinning and harvesting simulator, improving its user-friendliness and improving the accuracy of the results.

6.2 Impact on forestry research

It is evident that row thinning is going to remain standard practice in Southern African forestry well into the future. The benefit of maintaining stand regularity in terms of tree growth characteristics and volume increment is evident. Furthermore, the objective of implementing other planting geometries while maintaining stand regularity has also shown to improve harvesting productivity and reduce overall harvesting system cost in a simulation environment.

Marrying the thinning and harvesting simulator with stand and tree distance dependent growth simulators would provide scenario testing for the whole forestry value chain. This would ensure that parts of this unique value chain do not work in isolation but provide detailed feedback throughout the chain. This research has made a start at developing this interaction, where aspects of Operations Research are not seen in isolation but as a combined field for all forestry disciplines. Developing these links and interactions between silviculture, growth and yield and harvesting will benefit the forestry industry and increase its overall competitiveness.

7 References

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