The variation and prediction of structural timber properties of standing *Pinus patula* trees using non-destructive methods

by
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DECLARATION

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This dissertation includes three original papers published in peer-reviewed journals and two unpublished papers currently in preparation for submission to an accredited scientific journal. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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Abstract

Pinus patula is the most intensively planted conifer in the tropics and sub-tropics. In South Africa *Pinus patula* plantations are the main saw-log resource for structural lumber production. Improved intensive silvicultural practices and tree breeding have resulted in marked increases in the rate of growth. To reap the financial benefits of the faster growth, plantation managers are more and more inclined to reduce rotation ages, which inevitably results in the production of higher proportions of juvenile wood at final harvest, and lumber which often does not meet the minimum requirements for stiffness for structural lumber. Knowledge of the variation and the accurate prediction of the mechanical properties of the timber of standing trees can have various benefits for growers and processors of trees. It can be used for tree allocation to different processing facilities, for processing production planning, and to assist tree breeders to screen and select for superior breeding material.

The objectives of this study were (1), to examine the within- and between-tree variation in wood properties of young South African grown *Pinus patula* trees known to have important impacts on the suitability of sawn lumber for structural purposes and (2), to develop empirical prediction models for the flexural lumber properties from standing *Pinus patula,* based on variables that could be assessed non-destructively from standing trees.

Sample material was obtained from 170 trees (16-20 years old) established in 17 compartments along the Mpumalanga escarpment of South Africa. A large number of variables which could be obtained non-destructively from the trees while they were still standing, were measured. The trees were subsequently felled and two logs, 2.1 m in length, were extracted from each tree at two height positions. The 340 logs were processed into 1402 pieces of lumber for further measurements and destructive testing.

Results showed that the mean modulus of elasticity measured on edge (MOE_{edge}) was far below the limits set for structural grade softwood timber in South Africa. All the desirable properties for structural lumber improved with distance from the pith with the exception of the 5^{th} percentile value for modulus of rupture (MOR), which was higher at the pith than for the boards processed adjacent to the pith. Boards processed from the lower part of the stem were superior in most of the important properties compared to those higher up in the stem.

Separate multiple regression models for predicting the average dynamic MOE (MOE_{dyn}) of individual boards, trees and compartments were developed. The models managed to explain 68%, 60% and 95% of the variation in MOE_{dyn} respectively. The models developed for MOR explained 40% and 42% of variability at board and tree level respectively. At compartment level, 80% of the variation in the 5^{th} percentile MOR value could be explained by the model. Sensitivity analyses showed that site index at base age of 10 years, acoustic time-of-flight, wood density and ring width were the most influential variables in the MOE models. The models indicated that tree slenderness during early growth seems to play a major role in determining the dynamic MOE and MOR of lumber. This is in agreement with Euler's buckling theory and the bending stress theory.

Microfibril angle (MFA) and density were measured on radial strips taken from a sub-sample of trees with the Silviscan 3 technology. The mean microfibril angle per year ring in *Pinus patula* varied between 7^{o} and 29^{o}. In general MFA decreased with distance from the pith and height above ground level. A multiple regression model including microfibril angle, density and ring width explained 71% of the variation in the dynamic MOE of boards. Sensitivity analysis on the model showed that microfibril angle and density had roughly equal influences on predicting the MOE_{dyn} of *Pinus patula* boards.

Opsomming

Pinus patula is die mees aangeplante naaldhoutspesie in die tropiese en sub-tropiese areas van die wêreld. Dit is die grootste bron van saagblokke vir die produksie van strukturele hout in SA. Intensiewe boskultuurpraktyke en boomteling het gelei tot 'n merkbare verhoging in die groeitempo van die spesie. Plantasiebestuurders is gevolglik geneig om rotasie-ouderdomme te verlaag, wat lei tot 'n groter persentasie jeughout wat nie aan die minimum styfheidvereistes van strukturele hout voldoen nie. Kennis van die variasie en die akkurate voorspelling van die meganiese eienskappe van staande bome kan voordele inhou vir beide die verbouers en verwerkers van bome. Dit kan byvoorbeeld van hulp wees met die toewysing van bome aan verwerkingsfasiliteite, vir produksiebeplanning, en vir ondersteuning met die keuse van teelmateriaal vir boomtelers.

Die doelwitte van hierdie studie was (1), om die binne– en tussenboomvariasie in die houteienskappe, wat 'n bepalende invloed het op die geskiktheid van jong Suid Afrikaanse *Pinus patula* bome vir strukturele hout produksie, te ondersoek en (2), om empiriese modelle vir die voorspelling van die buigeienskappe van planke te ontwikkel, gebaseer op veranderlikes wat nie-destruktief op staande *Pinus patula* bome ge-evalueer is.

Monsters vir die studie is verkry vanaf 170 bome (16-20 jaar oud), geplant in 17 vakke op die Mpumalanga platorand van Suid Afrika. 'n Groot aantal veranderlikes is nie-destruktief gemeet op die staande bome waarna die bome gevel is en twee saagblokke, 2.1m in lengte, is op twee hoogte posisies uit elke boom verwyder. Die 340 blokke is verwerk tot 1402 planke vir verdere metings en destruktiewe toetse.

Resultate het getoon dat die gemiddelde modulus van elastisiteit gemeet op die dwarskant (MOE_{edge}) aansienlik laer was as wat vereis word vir strukturelegraad hout in Suid Afrika. Al die gewenste eienskappe het toegeneem met afstand vanaf die murg behalwe die 5de persentiel breekmodulus (MOR), wat hoër was vir murgplanke as vir aangrensende planke. Planke afkomstig van die laer dele van die stam het oor die algemeen beter eienskappe gehad as planke afkomstig van die hoër dele.

Veelvuldige regressiemodelle kon 68%, 60% en 95% van die variasie in die gemiddelde dinamiese MOE (MOE_{dyn}) op die vlak van onderskeidelik individuele planke, bome en vakke verklaar. Die modelle vir MOR kon 40% en 42% van die variasie op onderskeidelik plank- en boomvlak verklaar. Die model vir 5de persentiel MOR van vakke kon 80% van die variasie verklaar. 'n Sensitiwiteitsanalise het aangetoon dat groeiplekindeks op ouderdom 10, akoestiese vlugtyd, digtheid en jaarringwydte die belangrikste veranderlikes was wat MOE_{dyn} beïnvloed het. Die modelle het aangetoon dat die slankheid van bome tydens vroeë groei vermoedelik 'n belangrike invloed op die MOE_{dyn} en MOR van planke het. Dit is in ooreenstemming met Euler se knikteorie en die buigsterkteteorie.

Die mikrofibrilhoek en digtheid van 'n steekproef van die bome is gemeet met die Silviscan 3 apparaat. Die gemiddelde mikrofibrilhoek per jaarring het tussen 7^{o} en 29^{o} varieer. Hierdie variasie was hoofsaaklik afhanklik van boomhoogte en aantal jaarringe vanaf die murg. 'n Veelvuldige regressiemodel wat mikrofibrilhoek, digtheid en jaarringwydte insluit, kon 71% van die variasie in MOE_{dyn} verklaar. 'n Sensitiwiteitsanalise op die model het aangetoon dat mikrofibrilhoek en digtheid ongeveer ewe belangrik was wat betref hulle invloed op die voorspelde MOE_{dyn} van *Pinus patula* planke.

Acknowledgements

I want to thank God, the creator of trees, for providing me with this opportunity for such an interesting and rewarding study.

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Finally, I dedicate this thesis to Zerilda, Jurie and Malan – *my skadubome.*

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Chapter 1. Introduction

Planted forests are rapidly expanding on a global scale at about 5 million ha per year and currently accounts for about 7% of the total afforested area worldwide (FAO, 2013). In 1980 there were 18 million ha of planted forests, compared to 187 million ha in 1990 and 264 million ha in 2012 (Carle et al., 2002; FAO, 2013). Carle and Holmgren (2008) estimated that in 2005 about two thirds of the global industrial wood supply originated from commercial plantations.

Pinus patula is the most intensively planted conifer in the tropics and sub-tropics. It is estimated that more than one million hectares are planted with this species with about half of that in Africa (Wright, 1994). *Pinus patula* is also planted in the Andean countries of South America with potential to increase the area under this species in the high altitude areas in Brazil (Hodge and Dvorak, 2012). In South Africa it is the most important commercial plantation softwood resource with a total of 338 923 ha planted with *Pinus patula* trees (DAFF, 2009). The Mpumalanga escarpment is the largest saw log growing area in South Africa with *Pinus patula* the main species planted.

South Africa was one of the first countries to establish plantation forestry on a large scale, starting in the late nineteenth century. By 1960 the forestry area had increased to about 1 million ha (Owen and Van der Zel, 2000). Due to a shortage of suitable land available for afforestation, as well as competition from agriculture and water catchment, the area under forest plantations in South Africa has since stabilised. To meet the country's growing needs for wood this resulted in increasing emphases in the forest and wood processing industries on improved volume production per unit area through improved silvicultural practices and genetic improvement, as well as improved wood product yield and quality.

However, the increased size of the corewood zone, and the bigger proportion of corewood that results when rotations ages are shortened to reap the financial benefits of the faster growth, has become a wood quality factor of growing concern worldwide (Cown, 2006; Malan, 2010). Cown (2006) states that "researchers around the world have confirmed that aggressive silvicultural regimes have caused a significant reduction in mechanical properties" of plantation grown pines. Studies in South Africa have shown sharp reductions in some of the mechanical properties of pine lumber processed from material harvested at a younger age, as trees reach merchantable size much earlier due to faster growth rates (Burdzik, 2004; Wessels et al., 2011). While the financial importance of increased volume production of plantations is undisputed, it is increasingly important that forest managers and researchers take into consideration the adverse effects of their actions and efforts on end-product quality.

More than 70% of the solid sawn lumber produced in SA is sold as structural or building timber (Crickmay and Associates, 2011), a wood product category which has to comply to very strict strength and stiffness requirements. Given the challenges caused by an increasing proportion of juvenile wood in the timber resource, there is a growing need to better understand the variation in the mechanical properties of the lumber from plantation grown trees. There is also a need for non-destructive methods capable of accurately predicting these properties from standing trees. Amongst others, such information can be used to assist in decisions related to the allocation of trees to different processing facilities (Matheson et al*.* 2002; Cown 2006; Wang et al*.* 2007), for processing production planning (Uusitalo 1997; Wessels et al. 2006), to study the effect of site and silviculture factors on wood quality (Wang 2000b; Grabianowski et al*.* 2004; Wang et al*.* 2005) and to assist tree breeders to screen and select for superior breeding material (Ivković et al*.* 2009; Lindström et al*.* 2002; Launay et al*.* 2002).

The objectives of this study were:

- To examine the within- and between-tree variation in wood properties of young South African grown *Pinus patula* trees known to have important impacts on the suitability of sawn lumber for structural purposes;
- To develop empirical prediction models for the flexural properties of lumber produced from young *Pinus patula* trees, based on related variables that could be assessed non-destructively on standing trees.

Structure of the dissertation

This dissertation consists of an introduction (Chapter 1), followed by three published and two unpublished papers, each addressing a specific topic within the scope of this study (Chapters 2 to 6). The two unpublished papers are currently in preparation for submission to an accredited scientific journal. Chapter 7 contains a full summary of all the research results.

Appendix A contains signed declarations by the candidate and co-authors regarding the nature and extent of the contributions of the different authors.

The study was performed on sample material obtained from 170 *Pinus patula* trees (16-20 years old at the time of sampling) established in 17 compartments on the Mpumalanga escarpment of South Africa. A brief summary of each paper's contribution towards meeting the objectives of this study, are presented below.

Chapter 2

Wessels CB, Malan FS, Rypstra T. 2011. A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. Eur J Forest Res 130(6): 881-893.

- This paper reviewed the current literature on new and existing non-destructive or limited destructive property measurement methods on standing trees that can assist with the prediction of, in most cases, the modulus of elasticity and modulus of rupture of timber.

Chapter 3

Dowse GP, Wessels CB. 2013. The structural grading of young South African grown *Pinus patula* sawn timber. Southern Forests: A Journal of Forest Science 75 (1): 7–17.

- In this paper the efficiency of the current visual and mechanical grading rules on young *Pinus patula* sawn lumber were assessed and the potential of some indicator properties to be used as structural grading parameters were evaluated.
- In terms of the objectives of this dissertation, the most important results reported in this paper were the correlations between basic wood and lumber properties and the stiffness and strength of lumber.

Chapter 4

Wessels CB, Malan FS, Nel DG, Rypstra T. In press. Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*. Southern Forests: A Journal of Forest Science 76.

- This paper described the within- and between-tree variation in modulus of rupture, modulus of elasticity, density, and twist of lumber from the *Pinus patula* trees.
- Apart from the strength and stiffness variation, the variation in the relationship between strength and stiffness, which is important for efficient structural grading, was also investigated.

Chapter 5

Wessels CB, Seifert T, Louw JH, Malan FS, Rypstra T. Unpublished. The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees.

- The paper described empirically based models for predicting the flexural properties of the wood produced by the *Pinus patula* trees.
- Models were based on the properties of standing trees and their effectiveness was evaluated on board, tree and compartment levels.

Chapter 6

Wessels CB, Malan FS, Kidd M, Rypstra T. Unpublished. The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber.

- This study was performed on a sub-sample of 30 trees (out of 170 trees), hence it forms a separate study and was not included as a part of Chapter 5. The reason for the smaller sample was the cost associated with measuring microfibril angle and density on the Silviscan 3 apparatus.
- The paper described the variation in microfibril angle and the determination of the relationship between microfibril angle and the dynamic modulus of elasticity of sawn *Pinus patula* lumber.

The format of the papers appearing in Chapters 2-6 were as required for the journals they appeared in or will be submitted for review – hence the differences in format between chapters.

Chapter 2.

A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber

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Abstract

The accurate prediction of the mechanical properties that can be expected from timber from standing trees has many benefits for the growers and processors of trees. It includes support in tree breeding selection, tree processing allocation decisions, site and silvicultural research and processing production planning. A number of methods have been developed over the last few decades with significant interest in the recent past in especially acoustic methods, near infrared spectroscopy methods and the Australian multi-property measurement system known as Silviscan. This paper reviews the current literature on new and existing non-destructive or limited destructive property measurement methods on standing trees that can assist with the prediction of, in most cases, the modulus of elasticity and modulus of rupture of timber.

Keywords: *non-destructive; mechanical properties; standing trees; review*

Introduction

The mechanical properties of sawn timber play an important role in many applications. It is particularly relevant for structural timber – that is timber used in load bearing structures. In South Africa roughly 70% of all sawn timber is classified as structural or building timber (Crickmay and Associates 2009). For growers and processors of trees intended for structural timber production, the accurate prediction of the mechanical properties of the timber of standing trees have various benefits. Amongst others, such information can be used to assist in decisions related to the allocation of trees to different processing facilities (Matheson et al*.* 2002; Cown 2006; Wang et al. 2007), for processing production planning (Uusitalo 1997; Wessels et al. 2006), to study the effect of site and silviculture factors on wood quality (Wang 2000b; Grabianowski et al. 2004; Wang et al. 2005) and to assist tree breeders to screen and select for superior breeding material (Ivković et al. 2009; Lindström et al. 2002; Launay et al. 2002).

There are three important issues involved in predicting the mechanical properties of products from standing trees:
1. One must be able to identify and prove a meaningful relationship between measureable properties of a tree and the mechanical properties of timber from that tree.
2. One must be able to measure the relevant properties in a limited destructive or preferably a non-destructive way.
3. In order to make whole-tree and stand-based property predictions from limited sampling points in a tree and stand, knowledge is required on the relationship between properties at the sampling points in a tree and stand and the property variation through the rest of the tree and stand.

This paper will focus mainly on the second issue viz. measurement methods which can be used in the prediction of the mechanical properties of timber of standing trees. Literature on existing and new methods of measurement will be reviewed and discussed.

The review will focus specifically on the properties relevant to structural timber performance, namely longitudinal stiffness and the six ultimate stress values of timber products used in timber design codes. Included are measurement of underlying or basic properties that influence structural timber performance, such as density and microfibril angle. Although other properties may also play a role in the various timber strength grading systems i.e. discolouration and deformation, only mechanical properties are considered here. Measurement of randomly occurring defects in tree stems that have an influence on mechanical properties like resin cracks, decay and reaction wood is not considered in this review.

Properties influencing the mechanical behaviour of timber

The mechanical behaviour of timber is a result of the basic physical, anatomical and chemical characteristics of the raw material. In many cases concomitant properties to the actual characteristics of interest are measured and used to evaluate or predict the likely performance of products from a standing tree. An understanding of the relationship between the basic characteristics of timber and the mechanical behaviour are required in order to discuss most of the measurement methods used for prediction purposes. The relationships between various concomitant properties to strength and stiffness have been well documented in research on structural grading systems.

Knots, annual ring width, modulus of elasticity (MOE) and density of sawn timber form the basis of many structural timber grading systems and are generally accepted as properties that can be used to predict the strength and stiffness of timber. Johansson (2003) compared the coefficient of determination (r^2) obtained in six different studies between knot properties, annual ring width, density and MOE as independent variables and sawn timber strength (tensile and bending) as dependent variable of Norway spruce (Johanssen et al. 1992; Hoffmeyer 1984; Hoffmeyer 1990; Lackner 1988; Glos et al. 1982, Johansson 1976). In all cases MOE was found to be a better predictor of tensile or bending strength of timber ($0.53 \le r^2 \le 0.74$) than the other three properties used individually ($0.16 \le r^2 \le 0.44$). Using combinations of these properties to predict strength of timber pieces increased the coefficient of determination somewhat. Where knot data is combined with MOE for prediction of strength of Norway spruce and Southern Pine timber, the coefficient of determination increased by 0.1 to 0.17 compared to using only MOE (Johansson et al. 1992; Johansson et al. 1998; Orosz 1969).

Microfibril angle has been shown in many studies to be as influential as density, and sometimes even more so, especially in juvenile wood, for the prediction of stiffness of clear wood samples. Cave and Walker (1994) argued that microfibril angle is the only property that can explain the large variation in MOE of *Pinus radiata* from the pith outwards. Evans and Ilic (2001) found that density alone accounted for 70% of the variation in the MOE of *Eucalyptus delegatensis* clear wood samples and microfibril angle alone accounted for 86% of variation. Microfibril angle and density together accounted for 96% of variation in MOE. Megraw et al*.* (1999) found that density and microfibril angle together explained 93% of variation of MOE in small clear wood samples of *Pinus taeda*. The relative importance of each property in explaining variation in MOE change with location in the tree – at the base of the stem microfibril angle had a larger influence than density on MOE values, with the opposite to be true at 5m stem height. The strength and stability properties of juvenile wood have also been found to be affected more by differences in microfibril angle than wood density, while in mature wood density tends to play a more dominant role (Cave and Walker 1994). Due to the cumbersome methods used in the past to measure the microfibril angle, a number of workers explored the relationship between tracheid length and the microfibril angle and derived formulas to predict microfibril angle from tracheid length (Preston 1948; Wardrop and Dadswell 1950; Echols 1955; and Smith 1959, as cited in Cave and Walker 1994). In Smith's study, tracheid length accounted for 58% of the variation in microfibril angle, whereas in Echols' study 91% of variability was accounted for by differences in microfibril angle (as quoted in Huang et al*.* 2003).

Spiral grain has an influence on some mechanical properties of wood. As wood is an orthotropic material, its strength properties are significantly different in the three mutually perpendicular directions or axes. Therefore, when the grain orientation is not parallel to that of the stem, the actual strength values will be a combination of parallel-to-grain and perpendicular-to-grain characteristics. Spiral grain in tree stems is one of the main causes of grain deviation in sawn products, as cutting normally takes place parallel to the stem axis. For properties such as MOE (longitudinal), bending strength and tensile strength parallel to grain, grain deviation results in strength reductions.

Wilson (1921) tested the strength properties of clear pieces of White ash, Sitka spruce and Douglas fir with various levels of grain deviation. He found an average bending strength loss of 11% with a grain angle of 3.8 degrees, 19% with a grain angle of 5.7 degrees, and 45% with a grain angle of 11.3 degrees. Dinwoodie (2000) stated that longitudinal tension strength is affected more severely by grain deviation than longitudinal bending strength and compression strength. Hankinson (1921) developed an equation to calculate the strength of timber at any grain angle when the parallel-to-grain and perpendicular-to-grain strength values are known. The negative effect of grain deviation on wood strength is widely accepted and, as a result, restrictions are included in many structural timber grading standards i.e. EN 518 (1995), SANS 1783-2 (2005) and AS 2858 (2003).

Many randomly occurring defects in the tree stem also play a role in the mechanical performance of timber. Restrictions on the occurrence of these defects are usually contained in structural grading rules and can also include resin splits, biological decay, ring splits and reaction wood. Measurement and prediction of these random defects in standing trees is not discussed in this paper.

Mechanical tree stiffness measurement

Several workers developed mechanical tree bending apparati to determine the MOE of standing trees (Vafai and Farshad 1979; Koizumi and Ueda 1986; Launay et al*.* 2000; Launay et al*.* 2002). The basic mechanism in all these systems is the application of a bending moment on the tree trunk and measurement of deflection at a specific point (Fig 1). The longitudinal MOE of the trunk can be calculated using the results from these tests. Launay et al*.* (2000) argued that this approach gives better estimates of the mechanical properties of timber products from trees than localised measurements of basic properties, such as density, since it covers a vertical range in the stem and include the effect of branches or knots. Launay et al*.* (2000) found a moderate correlation coefficient (r = 0.54) between the tree MOE and average board MOE of Douglas-fir and Larch trees. These methods, however, are fairly time consuming as only 20-50 trees can be measured per day depending on the apparatus being used (Launay et al*.* 2000).

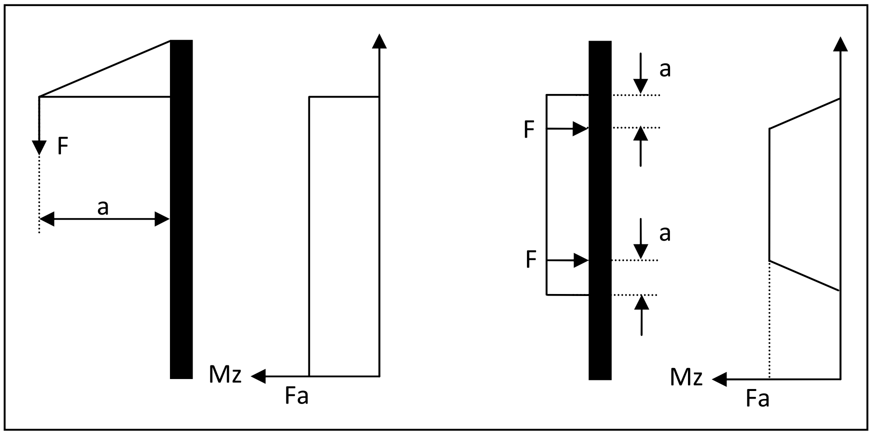

Fig. 1 Principle of two bending tests on standing trees (adapted from Launay et al. 2002)

Branch and knot assessment methods

Visual tree grading methods were developed in the past to evaluate the potential of a tree to produce specific products. Branching and knot characteristics are usually the main criteria for evaluation in such systems. Schroeder et al*.* (1968), as reported in Clark and McAlister (1998), developed tree grading rules for Southern Pine based on the evaluation on the number of clear faces in the bottom 4.9 m of the stem. Biological and mechanical damage, sweep and crook were also considered. Equations were developed to predict structural timber grades, given the tree grade, age and diameter. A similar tree grading system was developed by Brisbin and Sonderman (1971) for Eastern White Pine in the United States. According to Clark and McAlister (1998) the Southern Pine tree grading system is effective in grading older mature Southern Pine trees but not so effective in grading younger trees. As a consequence new tree grading rules were developed and tested on *Pinus taeda* and *Pinus echinata* trees of ages varying from 22 to 73 years. The main evaluation criteria included branch properties (number, size, live / dead) for specific height sections, diameter at breast height, age, straightness, seams, cankers and decay. The highest grade trees (Grade 1) produced relatively higher proportions of the best visually graded structural grades (No. 1 and better) than the lowest grade trees (Grade 3). Prestemon and Buengiorno (2000) developed a model to predict Southern Pine tree grades and subsequently timber grades directly from tree and stand-level variables (diameter, height, stand basal area, site quality, ownership). However, they concluded that the model had “low explanatory power”.

In a study by Bier (1985) on New Zealand grown radiata pine, trees and logs were graded according to “branch index”, which is the average of the largest branch diameter from each log quadrant as well as the basic density of the logs. Boards sawn from these logs were destructively tested in bending and the relationship between bending properties and the log variables was determined. It is interesting to note that the basic density of a log showed a stronger correlation with both the average MOE and modulus of rupture (MOR) of boards from that log than with the branch index. However, the branch index of the log showed better correlation with the minimum MOE and MOR obtained from boards from a log than basic density. This is a significant finding since the weakest and lowest stiffness timber is what determines mechanical grade stresses and not average values (Madsen 1992). In another study by Bier (1986) it was shown that for low branch index logs and trees no structural grading for individual boards is required since all the timber from such logs will be above the minimum New Zealand stress grade. The disadvantage of such an approach is that no higher stress grade products can be recovered from a tree.

Uusitalo (1997) stated that knot properties in Scots pine are by far the most important quality indicators of the timber. He developed a model to assess the quality of standing Scots pine which could be used in sawmill production planning. The variables measured on a sample of trees from each stand included diameter, height to first dead branch, crown height and tree height. However, these characteristics were not directly compared with the mechanical properties of timber.

In intensively managed softwood plantations, pruning of the lower section of the stem produces clear timber in the outer sections of the bottom log. This practice is aimed mainly at producing high value appearance grade timber but will also have an effect on the mechanical properties of timber, since it changes the knot properties. In certain market conditions sawmillers may choose to convert pruned logs to structural timber. In New Zealand, Park (1989 and 1994) developed a pruned log index which can be used to evaluate a compartment of trees in terms of the potential to produce clear grade timber. A limited destructive sample is required to evaluate the size of the knotty defect core of a compartment of trees. A similar limited destructive evaluation system was developed in South Africa and can be used for sawmill production planning and for the prediction of timber grades to expect from a specific compartment (Wessels et al*.* 2006). Neither of these studies explored the relationship between the defect core size and mechanical properties of timber from the pruned section of the stem.

Methods for measuring spiral grain

Measurement of spiral grain of trees from pith to bark (or across the radius) is relatively simple to perform on disk sections taken from a tree stem but unfortunately it involves destructive sampling (Brazier 1965; Kromhout 1966). A number of methods were developed to measure the grain angles from increment cores, which is less destructive. However, precautions need to be taken to avoid or minimise twisting of the cores during boring. It is also important that the in-tree orientation of a core is marked accurately to ensure that the measurements taken on the core reflect grain orientation at the point of sampling precisely.

Noskowiak (1968) proved that increment cores from 4.5 mm borers were unsuitable for grain angle measurement because torsional stresses during boring exceeded the elastic limit of the core, causing the cores to become permanently twisted. Cores from 12 mm borers, however, did not deform permanently, provided that the borer was turned uniformly. Noskowiak's method requires mounting the samples in aluminium cubes, extruding the core, and microscopic examination of cores under incident light. Harris (1984) proposed a method where bark windows are cut in opposite sides of the stem and the grain angle measured on the stem surface within each window. An increment core is then removed across the entire diameter – from one window to the next. Grain angles can be measured at different growth rings relative to a planed surface on the core. By taking readings for a growth ring on opposite sides of the pith and getting an average for each growth ring, the influence of a core which is not removed at right angles in relation to the stem axis, is eliminated. Angle readings can also be corrected using the readings taken at the core surfaces on the standing tree.

Buksnowitz et al*.* (2008) evaluated the use of X-ray diffractometry for measuring grain angle over radial samples of Norway spruce, using the Silviscan system. A good relationship between goniometric measurements (similar method to that of Brazier 1965) and X-ray diffractometry was found ($r^2 = 0.87$). The Silviscan apparatus was designed to accommodate increment cores.

Gindl and Teischinger (2002) used partial least square analysis of visible and near infrared reflectance spectra on Larch blocks to predict the grain angle. Coefficients of determination of 0.77

and 0.80 were obtained respectively. Although sanded wood blocks were used in this study it was assumed that a sanded surface on an increment core will yield similar results.

A method based on the fact that the dielectric constant of wood is about 1.5 times higher parallel to grain than across the grain is often used to predict grain angle in sawn boards (McLauchlan et al. 1973; Samson 1984; McDonald and Bendtsen 1986; Samson 1988; Samson et al. 1993). However, none of these studies mention the potential of using this method for small samples or increment cores.

An apparatus reported to be effective and fast is the Spiralometer, a device making use of the tracheid effect (Brashaw et al. 2009). A laser is focussed on a rotating increment core and maximum transmission occurs when the laser beam and longitudinal axis tracheids are aligned. The device is designed to take a grain angle reading every 1 mm.

A number of studies evaluated the use of microwaves for the detection of grain angle (James et al. 1985; Ghodgoankar et al. 2000, Kaestner and Bååth 2005; Schajer and Orhan 2006). None of the studies discussed the applicability of these methods on small samples or increment cores. One study (James et al. 1985) examined the use of polarization angle of a transmitted microwave for predicting of grain angle. It is important, however, that the test sample must be of sufficient thickness (not quantified) to ensure accurate prediction of the grain angle. This suggests that the method might not be suitable to measure grain orientation in increment cores.

When accurate models for grain angle from pith to bark exist, only grain angle measurement under the bark is required. Two fairly simple methods to obtain such measurements are described by Hallingbäck (2010). In the first one a section of bark must be removed and the exposed cambium scribed so that the grain angle on the cambium can be measured mechanically. Alternatively, a small wedge can be pushed into the outermost annual rings of the wood. As it is pushed in it is forced to align parallel to the tracheid cells, so the grain angle can be simply quantified by measuring the inclination angle between the orientation of the wedge and that of the stem axis.

Density and growth ring assessment methods

Density has long been considered as one of the most important wood properties, if not the most important, in terms of its effect on the quality of solid wood products. Zobel and Van Buijtenen (1989) concluded "therefore, specific gravity largely determines the value and utility of wood and overshadows the importance of other wood properties". Although this view is challenged by some (Cave and Walker 1994), many structural grading studies confirmed that density plays an important role in determining some mechanical properties of wood (Johansson 2003). Seen at the anatomical level, density is the combined result of a number of characteristics including cell wall thickness, cell diameter, growth ring width, amount of ray and vessel elements, and the ratio of earlywood to latewood in a growth ring. Strength and stiffness prediction methods using the width of growth rings are, therefore, also included as a density dependent prediction method.

From the 1960's the use of increment borers to collect samples from standing trees for density determination became more common (Cown 2006). There are several methods to determine density from increment core samples. Gravimetric methods for density determination make use of the accurate determination of the volume and mass of the sample at a specific moisture content (Yao 1968). A relatively easy and popular way of determining the density of small samples, like those from increment cores, is the maximum moisture content method developed by Diana Smith (1954). This method uses the mass of a sample when saturated with water, its oven-dry mass and the absolute density of wood cell wall material (1,53 g/cm^3), to determine the basic density of small sections. In some wood species, extractives, which is not part of the wood substance and which contribute nothing to wood strength, need to be extracted from the wood to ensure more reliable density values for predictive purposes (Tsoumis 1991).

Several indirect measurement methods have been developed in the past to predict density and growth ring properties from increment cores. Spectroscopic studies or radiation densitometry is one of the most widely used methods to measure the density of wood from increment cores. One of the earliest methods involved the use of X-ray radiographs of wood samples (Polge 1966). Using a calibration wedge, optical densities are converted into wood density. Later methods, also referred to as "direct radiation densitometry", measure the amount of radiation absorbed by wood to calculate the linear attenuation coefficient and density. Different sources of radiation are used for these i.e. X-rays, beta rays and gamma rays (Polge 1978; Cown and Clement 1983; Malan and Marais 1992; Divos et al. 1996). A recent development in densitometry was the development of the Silviscan system, which is a multi-property measuring device which can use increment cores and perform X-ray densitometry, X-ray diffraction for microfibril measurement and image analyses of microscopic images of cells (Evans et al. 1998). Microwaves have also been used in numerous studies for density determination, mainly with timber grading studies (Schajer and Orhan 2006; Tiuri et al. 1980; James et al. 1985; Martin et al. 1987; Leicester and Seath 1996).

Densitometry allows for a high resolution measurement of density so that both inter-ring and intra-ring density variation analysis can be performed (Fig 2). The method lends itself to automation and the relatively fast measurement of large numbers of samples (Polge 1978). In terms of standing trees the most laborious and time-consuming part of this method is the collection of increment cores from the trees and the accurate preparation of the samples for densitometry.

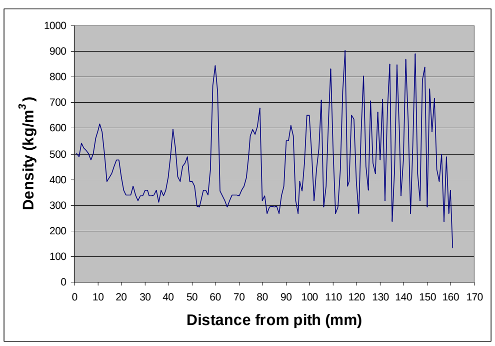

Fig. 2 A density profile measured with a gamma ray densitometer

Recently portable X-ray computed tomography (CT) systems were developed for the scanning of standing trees (Habermehl et al. 1999). These systems use gamma rays as a source of radiation and use the scanned data to reconstruct a three dimensional internal density image of a standing tree trunk. Applications of such systems include inspection of park and street trees (Habermehl et al. 1999), growth ring assessment (Onoe et al. 1984), and moisture content studies of living trees (Tognetti et al. 1996). No literature were found where mobile CT scanners were used for predicting mechanical properties of standing trees, although the density data will obviously be useful for such purposes.

An indirect density measurement method that uses increment cores is the laser sandblasting method (Lesnino 1994). Radial increment cores are sandblasted and the depth profile measured with a laser measurement technique. A correlation (r) of 0.86 between density measured with a stereogravimetric method and the laser sandblasting technique was obtained. The big advantage of this method, according to the author, is that samples require less preparation than stereogravimetric and radiation densitometry methods and measurements can be automated easily.

In order to obtain more rapid results, some indirect density measurement methods on tree stems have been developed where no increment cores are required. The Pilodyn wood tester was developed in Switzerland and injects a spring-loaded striker pin into the stem of a tree (Cown 1978). The penetration depth can be used as an indirect measure of the density of the outer section of the stem. The relationship between density results of the outer portions of a tree stem and Pilodyn readings was found to be relatively strong with a correlation coefficient of 0.97 for radiata pine of different ages (Cown 1978). In another study Cown et al*.* (1998) reviewed sixteen other studies where the Pilodyn tester was used and compared to outerwood basic densities of standing trees. The results of these studies in terms of the correlation coefficients between density and Pilodyn readings varied between 0.47 and 0.96. According to Cown et al*.* (1998) the general consensus is that the Pilodyn method is not sufficiently accurate for the determination of density of an individual tree but can be very cost effective and accurate for comparing groups of trees, such as in genetic trials.

Another indirect method used to predict density makes use of the Torsiometer which measures the torque when an increment borer is turned into a tree. In Cown's study (1978) the Pilodyn method was also compared to Torsiometer results. Apart from the fact that a Torsiometer was slower than the Pilodyn, the correlation with density was also worse. A modern and improved version of the Torsiometer is a resistance drill, known as the Resistograph, which measures variations in drilling resistance of a thin needle when driven into a tree at a constant force (Rinn *et. al.* 1996). Variations in power consumption is measured electronically and is directly related to variations in density. Chantre and Rozenberg (1997), as reported in Isik and Li (2003), evaluated this tool and although they reported a significant correlation with the mean radial density of Douglas Fir strips, their results showed that it cannot be used for accurately predicting density variation within a trunk. Isik and Li (2003) found it an effective tool for density selection of trees in a *Pinus taeda* tree improvement program.

Near infrared spectroscopy is an indirect method for density determination that has been studied by several researchers and that can be used on increment cores from standing trees. Schimleck et al*.* (2001) obtained a coefficient of determination of 0.93 between density and NIR data for the calibration set of *Eucalyptus delegatensis* samples. Via et al*.* (2003) obtained coefficients of determination exceeding 0.71 when predicting the density of *Pinus palustris* samples using various statistical models. Similar results were obtained in other studies (Hoffmeyer and Pedersen 1995; Hauksson et al*.* 2001; Schimleck and Evans 2004). Koch et al*.* (1998) found that density can also be predicted using the far-infrared spectroscopy method which, according to the authors, has safety advantages over other techniques.

Wimmer (1995), reported a method of estimating wood density by microscopically measuring anatomical cell features. A correlation coefficient of 0.85 was obtained between estimated density values and measured values.

Microfibril angle measurement methods

Microfibril angle of wood refers to the orientation of cellulose microfibrils in the secondary cell wall in relation to the longitudinal axis of the cell. Most techniques for measuring the microfibril angle can use increment cores for these measurements.

Huang et al*.* (1998) and Barnett and Bonham (2004) provided reviews on the measurement techniques of microfibril angle. There is a range of techniques, including the following (taken from Barnett and Bonham, 2004): Polarization microscopy was the first technique for measuring microfibril angle. The problem of light passing through two walls of a tracheid or fibre, in which the fibrils form opposite sides of the spiral, was solved in different ways by Preston (1934), Page (1969) and Donaldson (1991). Another optical technique that has been applied makes use of the fact that natural or induced checks and splits in the cell wall follows the direction of the microfibrils in the S2-layer. The angle of these checks and splits normally serves as a reasonable accurate measure of the average MFA (Preston 1947; Huang 1995). Similar techniques utilise iodine infiltration of the cell wall, which crystallizes in the checks or splits between the microfibrils, and assist with measurement of check orientation (Bailey and Vestal 1937; Senft and Bendtsen 1985). The orientation of the oval aperture of cross-field pits has also been used to measure microfibril angle (Pillow et al*.* 1953; Donaldson 1998). The microfibril angle can also be determined by using decay cavities caused by soft-rot fungi, which align themselves along the microfibrils in the S2layer (Anagnost et al*.,* 2000). Small angle and wide angle X-ray scattering are other techniques that have been used for many years (Wardrop 1952; Meylan 1967). Techniques used in recent years, and discussed by Huang et al*.* (1998), include the following: Micro Raman spectroscopy (Pleasants et al*.* 1997), transmission ellipsometry (Ye et al*.* 1994) and confocal microscopy (Verbelen and Stickers 1995; Batchelor et al*.* 1997). Huang et al*.* (1998) concluded that measuring pit apertures is the simplest method for use in field, whilst iodine staining, complemented with ultrasonic checking, is suitable for more accurate measurement.

The method of choice, according to Barnett and Bonham (2004) remains X-ray diffraction. The advantages of X-ray diffraction over other methods have been discussed by Cave (1997*a, b*) and include the speed of determination and accuracy of X-ray diffraction as well as the fact that the average microfibril angle can be determined for a large sample of tracheids. Silviscan 2 uses X-ray diffraction to obtain microfibril angles directly from increment cores (Evans et al*.* 1998).

Recently, near infrared spectroscopy (NIR) was used in several studies to determine microfibril angles of wood specimens (Schimleck and Evans 2004; Kelley et al*.* 2004b; Zbonak and Bush 2006). All these studies indicated relatively high correlation coefficients between the NIR predicted microfibril angle and the measured angle for the calibration datasets ($r > 0.8$). The correlation coefficients, however, for independent test -or prediction datasets were considerably lower ($r < 0.6$).

Barnett and Bonham (2004) concluded that it is axiomatic among those working in the field of microfibril measurement that the results obtained for a single sample can vary widely according to the method used.

Acoustic measurement methods

Jayne (1959) proposed the hypothesis that the energy storage and dissipation properties of wood are controlled by the same mechanisms that determine static behaviour of the wood. As a consequence useful relationships between the acoustic and vibrational properties, and static elasticity and strength are attainable. For instance, a strong relationship exists between the microfibril angle, an important determinant of wood stiffness, and the acoustic velocity in wood. Wang et al*.* (2007) reported a coefficient of determination (R^2) value of 0.855 between acoustic velocity and microfibril angle of radiata pine and Evans and Ilic (2001) an R^2 value of 0.86.

There are a number of techniques that can be used to measure these energy storage and dissipation properties of timber but the possibilities for standing trees are more limited. The method of choice in standing trees is the measurement of stress wave speed through the stem of a tree. In a typical setup (Fig 3) a transmitter probe and receiver probe is inserted in the sapwood of a tree stem and a stress wave is induced by tapping the transmitter probe with a light hammer (Wang and Ross 2002). The time-of-flight (TOF) of the wave is measured between the transmitter and receiver probe. The TOF can be used to calculate the wave speed and the dynamic modulus of elasticity (MOE_d) in either the longitudinal or radial direction of the stem. The MOE_d is calculated directly from the wave speed and the green density of timber, which normally relates well to to the static MOE. Wielinga et al. (2009) found that green wood density of *Pinus radiata* varies within such a small range that it can be considered a constant value in the case of standing trees, meaning that MOE_d is almost directly related to velocity.

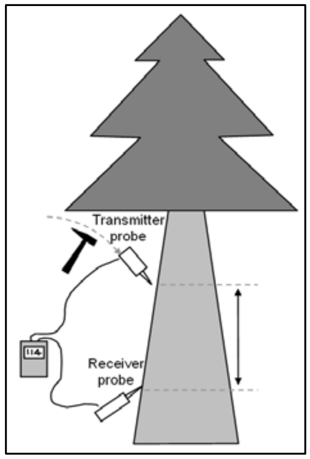

Fig. 3 A typical stress wave measurement setup

Wang et al. (2007) stated that “the precision of acoustic technology has been improved to the point where tree quality and intrinsic wood properties can be predicted and correlated to structural performance of the final products”. Wang and Ross (2002) reviewed a number of studies that explored the relationship between standing tree stress wave properties (radial and longitudinal) and some mechanical properties of logs, sawn timber and clear wood from these trees. Correlation coefficients between standing tree acoustic measures and the static modulus of elasticity (MOE_s) of defect-containing timber from these trees varied from 0.33 to 0.64 (Ikeda and Arima 2000; Matheson et al. 2002; Ishiguri et al. 2006). In studies relating MOE_d of standing trees with MOE_s and MOR of clear pieces of wood from those trees the authors obtained correlation coefficients of 0.63 – 0.69 for MOE_s and 0.36 - 0.65 for MOR (Wang et al. 2000a; Wang et al. 2001; Ivković et al. 2009). Other studies explored the relationship between standing tree acoustic measurements and the MOE of clear wood or timber determined dynamically or with transverse vibration methods (Huang 2000; Wu et al. 2000; Wang et al. 2005; Grabianowski et al. 2006).

Ilic (2003) proposed a method of using impact-induced resonance vibrations on small longitudinal beams of 20x2x150 mm that can be obtained from the outerwood of standing trees. Results showed an excellent correlation (r = 0.98 softwoods and 0.97 hardwoods) between the dynamic MOE_d of these small beams and dynamic MOE_d of standard clear specimens. In a different study, the dynamic MOE_d of radiata pine of these small longitudinal beams were found to be good predictors of both the static MOE_s (r^2=0.71) and MOR (r^2=0.61) of clear samples from trees of one of the study sites. However, on another site MOE_d proved to be only a poor predictor of MOE_s (r^2=0.31) and MOR (r^2=0.03) (Ivković et al. 2009). A rapid method for removing such beams from a standing tree was not discussed in these articles.

In a slightly different approach for predicting standing tree wood stiffness, Bucur (1983) determined ultrasonic wave speeds through 5 mm increment cores to obtain three stiffness moduli and three shear moduli for the increment cores. These ultrasonically determined moduli were compared to statically determined clear wood moduli from the same trees. Moderate correlations between the various ultrasonically determined moduli and statically determined moduli were obtained i.e. correlation between dynamic longitudinal stiffness of an increment core and static longitudinal stiffness of a standard clear specimen was 0.67.

Ultrasonic imaging or tomography is a technique used to reconstruct the material under inspection from global wave propagation data (Bucur, 2003). This technique can also be used on standing trees. As with CT scanning a cross-sectional property-image can be obtained which can be expanded, with enough cross-sectional images, into a three-dimensional internal image of the material. Ultrasonic imaging on standing trees is mostly used for decay studies (i.e. Comino et al. 2000). According to Bucur (2003) the elastic constants of sawn lumber was calculated using ultrasonic imaging in a study by Chazelas et al (1988). It is assumed that the same might be possible for standing trees – making ultrasonic imaging a potential method for predicting the mechanical properties of timber from standing trees.

Near infrared spectroscopy

Near infrared (NIR) spectroscopy involves the study of the interaction of electromagnetic radiation in the near infrared region, which is the infrared region closest to the visible region with materials (Fig 4). The NIR region extends from 780 to 2500 nm in which the spectra may be characterized by the assignment of the absorption bands to overtones and combinations of fundamental vibrations associated with C-H, O-H and N-H bonds. As NIR spectroscopic results on their own are of limited use, multivariate analysis techniques need to be employed to analyse the significance of relationships between NIR measurements and other properties of interest in wood. Since NIR spectroscopy is relatively fast, cheap and easy to perform, it is an ideal method to predict related wood properties which are time-consuming and costly to obtain (So et al. 2004).

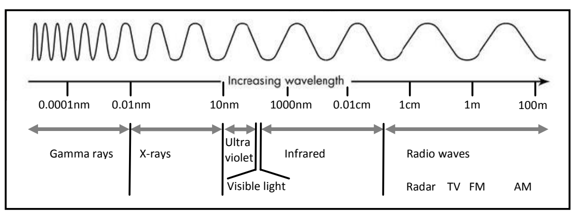

Fig. 4 The electromagnetic spectrum

NIR data can be obtained from increment cores from standing trees. The analysis normally involves calibration using a part of the samples (calibration set) to quantify the relationship between the NIR results and the property of interest. The remaining samples, the test or prediction set, are used to test the reliability of the relationship that was obtained (Schimleck et al*.* 2001).

Various workers investigated the potential of NIR spectroscopy to predict mechanical properties like MOE and MOR of small clear wood samples. Schimleck et al*.* (2001) found coefficients of determination of 0.90 and 0.77 for the relationships between NIR data and MOE and MOR respectively for clear *Eucalyptis delegatensis* samples of the calibration set. Similar results were obtained in other studies (Gindl and Teischinger 2001; Thumm and Meder 2001; Kelley et al*.* 2004a; Kelley et al*.* 2004b). Via et al*.* (2003) found whole-tree regression coefficients of determination larger than 0.84 for both MOE and MOR of clear *Pinus palustris* samples employing different statistical analysis techniques. They found, however, that when only pith-wood was considered, the predictive ability of the models decreased significantly. Hoffmeyer and Pedersen (1995) investigated the ability of the NIR method to predict the MOR of full-sized defect-containing timber but the coefficient of determination for the prediction set was fairly weak (r^2 = 0.29).

Discussions and conclusions

It is clear from the existing work on property measurement methods that the objective of predicting mechanical properties from standing trees will play an important role in selecting the most appropriate method of study. For instance, several authors mentioned that a certain method may be sufficient for genetic trials, but not for individual tree predictions (e.g. Cown et al. 1998; Isik and Li 2003). In order to make predictions of the mechanical properties of defect-containing timber from standing trees, a species- and resource-specific approach will have to be followed. For a specific forest resource, a good starting point should be an investigation into the relative strength of correlations between properties measurable on sawn boards and the mechanical properties of these boards (e.g. Johansson 2003), which will give an indication of standing tree properties that need to be considered.

An important aspect to keep in mind when trying to predict the mechanical properties of structural timber and specifically the recovery of structural grades from a standing tree resource, is that the characteristic strengths or design strengths of a grade is determined by the 5th percentile strength values (Fig 5) – in other words the weak portion of the strength distribution curve (Madsen 1992). This means that it is essential for any property and method used in such a study to be an accurate predictor of the weak portion of the strength distribution curve. With a few exceptions (e.g. Bier 1985; Via et al. 2003) most studies referred to above, evaluated methods or properties that can be used for strength prediction purposes using the relationship of that specific property with strength over the full strength distribution curve. For stiffness, however, design codes often use both 5th percentile and average MOE values - making predictions of the full stiffness distribution necessary (i.e. CSA O86-01, 2001).

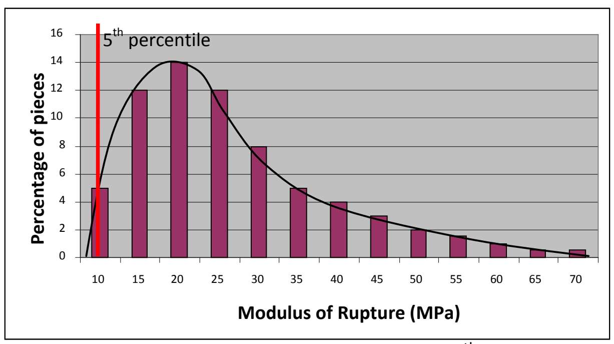

Fig. 5 A typical histogram of the MOR of timber with the 5th percentile value indicated

Although the use of clear and defect-free timber in structural applications is very limited, by far the most of the studies used clear and defect-free timber to evaluate standing tree property measurement methods. It is obvious that the defect-free strength and stiffness will also have an effect on the properties of defect-containing timber pieces, but in some cases defects might overshadow the importance of certain properties, especially in the important weak portion of the strength distribution curve. An area that has received limited attention from scientists in recent years is that of knot and branch assessment methods. Since knots play an important role in timber mechanical properties (Johanssen 2003), and especially in the weak portion of the strength distribution curve (see for instance the study of Bier 1985), consideration of this property in predictive studies might be advantageous for some species.

The efficiency of standing tree property measurement methods have been evaluated, almost exclusively in the literature reviewed, in terms of bending strength (MOR) and longitudinal stiffness (MOE). Design codes generally specify six characteristic strength values as well as longitudinal stiffness values for structural design applications. The assumption in proof grading or mechanical stress grading, where only one value like MOE is often measured, is that a good relationship exists between the different strength and stiffness values. For any tree resource this assumption will have to be validated.

In some cases a combination of methods and properties might be required to obtain the required accuracy of prediction. A technique which can be used to determine which is the best measurement method for a specific forest resource, is to perform a path analysis (Downes et al. 2002 and Ivković et al. 2009). Results are represented in path diagrams to help the researcher to decide what method or combination of methods is the best for a specific study (Fig 6).

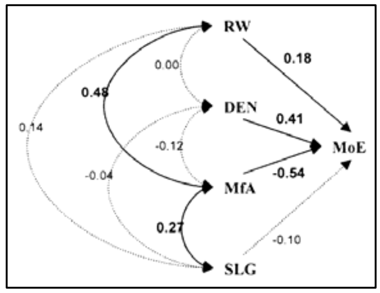

Fig. 6 Path analysis for MOE of radiata pine. Correlation coefficients indicated for each effect. DEN=density, RW=ring width, MfA=microfibril angle, SLG=spiral grain (from Ivkovic et al. 2009).

Although it is difficult to compare standing tree property measurement methods without specific project or study objectives in mind, one can draw some general conclusions from the literature surveyed. A number of methods have been developed over the last few decades. More recently the focus was primarily on acoustic and NIR spectroscopy methods, as well as on multi-property measurement systems such as Silviscan. Each method has specific applications and advantages, but they all require a relatively low labour input, resulting in relatively low manpower cost. Acoustic methods, such as the stress wave timer, are the fastest and lowest cost methods as a single operator can obtain a reading within a matter of seconds. Various studies found significant correlations between acoustic stress wave properties and the MOE and MOR values of clear wood and timber. NIR spectroscopy methods have the advantage of being able to predict many different basic properties like density, microfibril angle, spiral grain as well as MOE and MOR of clear wood from increment cores. However, this approach requires a process of calibration as it is not a direct measurement method of any property. Silviscan uses an automated measurement process of increment cores to obtain density, microfibril angle and cell dimensional properties. Spiral grain angle can also be obtained from Silviscan results. These basic properties have been shown to have a significant relationship with some mechanical properties of wood.

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Chapter 3.

The structural grading of young South African grown *Pinus patula* sawn timber

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Abstract

In this study sawn timber from 16-20 year-old *Pinus patula* trees were obtained from a wide variety of sites along the Mpumalanga escarpment in South Africa. The objectives of this study were to assess the efficiency of the current visual and mechanical grading rules on this timber and to evaluate the potential of some indicator properties to be used as structural grading parameters on this resource. A large number of non-destructive measurements were performed on all the samples (i.e. X-ray density scanning, acoustic frequency measurement, year-ring measurements, stiffness measurement) before it was destructively tested in bending and tension. The young *P. patula* timber tested in this study had good bending strength (MOR) properties with higher characteristic grade values than required. The timber, however, had low stiffness and did not comply with the SANS 10163-1 requirements for mean MOE_{edge} for any of the structural grades. Dynamic MOE (MOE_{dyn}), calculated from acoustic frequency tests on the timber, was found to be the best single predictor of MOE_{edge}, MOR and tension strength. Multiple regression analysis showed that a combination of MOE_{dyn}, density and knot parameters can be used to improve the predictability of some of the strength and stiffness characteristics of the timber.

Keywords: structural grading, non-destructive evaluation, young *Pinus patula*,

Introduction

About 34% of the area under commercial forestry plantations in South Africa is managed for sawlog production. *Pinus patula* is the most important South African commercial plantation softwood resource with a total of 338 923 ha planted with this species (DAFF, 2009). Of the total South African sawmill product output, nearly 70 percent is classified as structural or building timber (Crickmay and Associates, 2009). Structurally graded timber in South Africa is being used mainly in roof trusses of residential houses where the safety of the inhabitants, builders and maintenance workers is at stake. Tree breeding programmes in South Africa emphasise a high growth rate. Together with a reduction in rotation ages of sawlog trees this results in logs with a relatively high proportion of juvenile wood. It is a well established fact that the properties of juvenile wood can differ quite dramatically from that of mature wood (Kennedy, 1995; Zobel and Sprague, 1998). The current structural grading rules and the grade design properties of South African pine was established in the early 1980's (Knuffel, 1983, 1984) when the composition of the sawlog resource was probably different in terms of the relative juvenile wood content of logs. The question is whether the current structural grading rules are still effective in separating this resource according to its actual strength and stiffness properties.
The objectives of this study were to assess the efficiency of the current visual and mechanical grading rules on young *Pinus patula* sawn timber and to evaluate the potential of some indicator properties that could be used as structural grading parameters on this resource.

For structural grading systems it is important that the indicator properties used to grade the timber have a strong relationship with timber strength and stiffness. There are many studies where the strength of this relationship has been determined for different properties and species and only a selected few will be discussed here.

Table 1 summarises the results of six studies on the species *Picea abies* (as summarised by Johansson, 2003). From Table 2 it can be observed that modulus of elasticity (MOE) is the single best predictor of both bending and tension strength. Where knot data is added to MOE, the R^2 values improved. Knot, density, and ring width data are, on their own, poor predictors of both bending and tensile strength. When locations of knots are taken into account, prediction values can improve slightly (Johansson, 2003). Knuffel (1984) found from laboratory data that visual grading of South African pine could be improved by placing more emphasis on knot data than on density.

Table 1: Degrees of determination (R^2) from various investigations of the relationship between strength and other properties of Norway spruce timber (Picea abies) – the sources of the investigation are numbered from 1 to 6 (Johansson,2003)

Characteristics that can be measured non-destructively	**Degree of determination** R^2						
	MOR				**Tension**		
Source	[1]	[2]	[3]	[4]	[1]	[5]	[6]
Knots	0.27	0.2	0.16	0.25	0.36	0.42	0.30
Annual ring width	0.21	0.27	0.2	0.44	0.36	0.33	0.28
Density	0.16	0.3	0.16	0.4	0.38	0.29	0.38
MOE, bending	0.72	0.53	0.55	0.56	0.70	0.69	0.58
MOE, flatwise, short span							0.74
Knots + annual ring width	0.37	0.42	0.39		0.49		
Knots + density	0.38		0.38		0.55	0.61	0.64
Knots + MOE	0.73	0.58	0.64		0.70	0.76	0.78

[1]. Johansson et al. (1992), [2]. Hoffmeyer (1984), [3]. Hoffmeyer (1990),
[4]. Lackner and Foslie (1988), [5]. Glos et al. (1982), [6] Johanssen (1976)

Table 2: Degrees of determination (R^2) for MOR predictions by different indicator properties (Glos, 2004).

Characteristics that can be measured non-destructively	**Degree of determination** R^2
Knots	0.15 – 0.35
Density	0.20 – 0.40
Frequency, ultrasonic speed	0.30 – 0.55
MOE	0.40 – 0.65
Knots & density	0.40 – 0.60
Knots & MOE	0.55 – 0.75
Knots & density & frequency	0.55 – 0.80

Glos (2004) quoted similar results to that of Table 1 but his results were not species-specific and acoustic resonance frequency measurements were included (Table 2). Of interest in Glos' data is that a combination of knot properties, density and acoustic resonance frequency results, can increase the degree of determination for predicting strength to 0.80. Modern grading systems are able to measure all these properties within a single system.

The results reported by Gaunt (1999) are very relevant to this study since comparisons of the relationship between MOE and MOR were done between "old crop" and young 19-year-old radiata pine from New Zealand. Flatwise stiffness values (MOE_p) were related to MOR as well as MOE_{edge} values for the two samples. The R^2 values found are shown in Table 3. The author concludes that the relationship between MOR and MOE for radiata pine in New Zealand has deteriorated to such an extent as a result of shorter rotation ages that it makes machine stress grading based on stiffness often unreliable and inefficient in terms of grade recoveries. A weakness of this study is that the differences between old crop and 19-year-old radiata results cannot be ascribed solely to the crop age differences, as the 19 year old crop was tested at the position of lowest MOE, while the old crop was tested with random defect placement.

Table 3: Comparison of old and new crop R^2 values for New Zealand radiata pine (Gaunt, 1999)

	Old crop	**19 year old crop**
MOE_p vs. MOR	52.4	15.03
MOE_p vs. MOE_{edge}	68.37	47.87

Ishengoma et al. (1995) found that the basic density at different heights of the juvenile wood of *Pinus patula* varies between 353-376 kg/m^3 and for mature wood between 433-495 kg/m^3. The mean MOE of clear sections of juvenile wood was 4793 MPa versus 8939 MPa for mature wood.

Burdzik (2004) tested structural timber from four sawmills in "low density regions" in South Africa, and found that only one sawmill's timber made the grade requirements for bending and tensile strength. None of the sawmills' graded timber made the requirement for mean modulus of elasticity (MOE). It was not mentioned whether young tree resources were used at these sawmills.

Methods and Materials

The logs used for this study were obtained from 17 different compartments of 16-20 year-old *Pinus patula* trees in the Mpumalanga escarpment, South Africa (see Table 4). The compartments varied between 810 and 1930 m above sea level, had a mean annual rainfall of between 840 and 1640 mm and a mean annual temperature of between 13.7 and 19.4 ºC. The sample consisted of 170 trees (ten trees per compartment) which were processed firstly into 340 logs and finally into 1402 boards. Two 2.1m-long logs were removed from each tree – one from the pruned section of the stem at 2.3m height and one from the unpruned section at 7m height. The logs were processed at a local sawmill using frame-saws and a cant sawing pattern (Figure 1). Only boards from the cant section were used for this study. In practice this is often the case in South Africa where the side or wing boards are sawn to industrial grade dimensions and only the cant contains structural grade dimensions. The secondary breakdown saw used a curve-sawing device so that the grain of the boards was predominantly parallel to the longitudinal direction. The boards were kiln dried using a medium temperature schedule.

Table 4. General data for each compartment and the mean diameter at breast height (DBH) and height of the ten sample trees per compartment.

Compartment ID	Plantation	Age (yrs)	Mean DBH (cm)	Mean height (m)	Site Index$_{10}$ (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
A (E66)	Nelshoogte	17	36	20.9	14.3	1061	16.0
B (E28a)	Nelshoogte	19	33.8	21.8	14.5	1036	16.1
C (G21)	Nelshoogte	16	26.2	18.4	15.5	1057	16.1
D (D1)	Uitsoek	17	32.7	22.3	15.7	944	17.4
E (D88)	Uitsoek	17	30.2	18.4	15.3	942	17.3
F (E55a)	Uitsoek	20	32.3	20.1	14.6	1151	13.7
G (E36c)	Uitsoek	19	31.9	23.0	16.8	902	14.0
H (E22)	Uitsoek	17	27.6	20.8	16.5	840	14.2
I (E5)	Berlin	19	36.5	23.8	16.7	1284	16.1
J (E15)	Berlin	19	37.4	23.8	17.6	1082	15.9
K (E35)	Berlin	16	29.1	18.0	16.5	1006	17.2
L (C22)	Blyde	20	34	27.0	18.5	1156	16.1
M (E3)	Morgenzon	17	31.4	20.6	13.5	1015	14.3
N (D74)	Morgenzon	19	26.9	16.4	9.6	997	16.2
O (A1a)	Morgenzon	16	27.8	19.0	13.6	862	15.1
P (D11)	Wilgeboom	18	29.4	22.8	19.6	1242	19.4
R (J20)	Wilgeboom	19	33.4	24.0	16.8	1299	18.5
Mean		**18**	**31.6**	**21.2**	**15.6**	**1052**	**16.1**

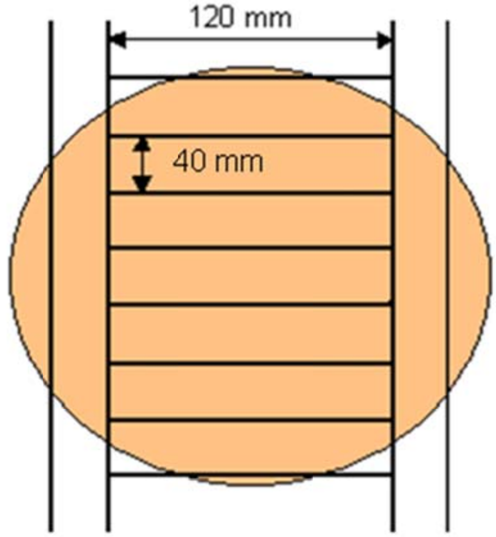

Figure 1: The cant sawing pattern used

X-ray density scanning and knot parameters

After drying, the boards were scanned with a commercial Goldeneye-702 X-ray scanner from Microtec. Figure 2 shows an example of a scanned board. The Goldeneye scanner has a number of sensors including optical cameras, a laser scanning device and an X-ray density scanning device to measure a number of knot parameters including knot location and quality, board dimensions, board warp, presence of pith, density, cracks, resin pockets and bark. Only knot location and size measurements from the scanner and density variation per board were used for further analysis. The density calibration of this machine was not done as specified by the manufacturer and it was decided to use the manually determined absolute density values. The variation in density within a single board (X-dev) measured by the scanner was used for further analysis.

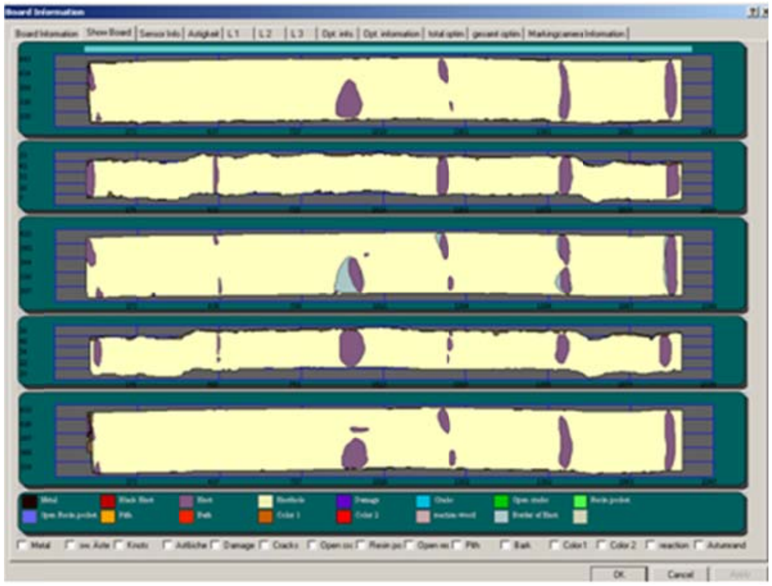

Figure 2: Example of scanned board showing optical and X-ray views

By using the knot information gathered from the x-ray scanner, the following knot parameters were determined:

# Knots	is the number of knots on a single piece of timber;
Knot average (knot avg.)	is the mean area (mm^2) covered by individual knots on a particular piece of sawn timber. X-ray scanning evaluated each board from the vertical direction when a board is laying flat on its width face. The area measurement is similar to the knot-covered area one will see if you look from above at a knot in a transparent board. Take note that this is different to the knot area ratio (KAR) often used in research studies;
Knot area / board	is the total area (as detected by the X-ray scanner) of the piece of timber that contains knot material (mm^2);
Knot maximum (knot max)	is the area (as detected by the X-ray scanner) covered by the biggest knot on a piece of timber (mm^2);
KSC	is a calculated parameter developed for this study. It is the product of knot size and the stress index of a specific knot. The stress index is a ratio of the bending stress at a specific knot to the maximum bending stress in a piece of timber. The maximum bending stress will be PL/bh^2 with the test setup used (see Figure 3 for definitions of variables). The stress index will be higher at the upper and lower edges of a board and lengthwise in the centre third (mm^2);
$KPar_f$, $KPar_c$	are two knot parameters calculated by the Microtec scanner software. Explanations and calculations for these parameters were not available to us.

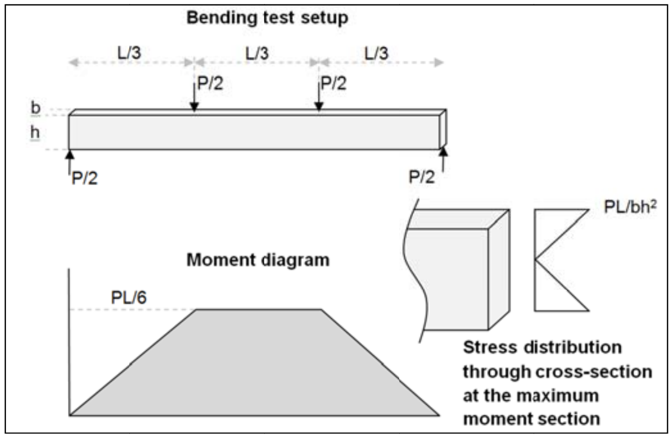

Figure 3: The stress distribution in a board was used to calculate a stress index at a specific knot.

Annual ring measurements

The ends of the boards were sanded to provide clearly visible annual rings. The number of annual rings on each board was counted and numbered from the pith outwards. The cambial age (mean, maximum and minimum) of the wood within each board was therefore known. The cambial age is the age by ring count from the pith. A line drawn from the pith to the bark and perpendicular to the growth rings (Figure 4) was used to do ring width measurements using a dial calliper. The line was drawn to include the maximum number of rings in each board. Measurements were rounded to the nearest 0.1 mm. For each board the minimum, maximum, and mean ring width was calculated.

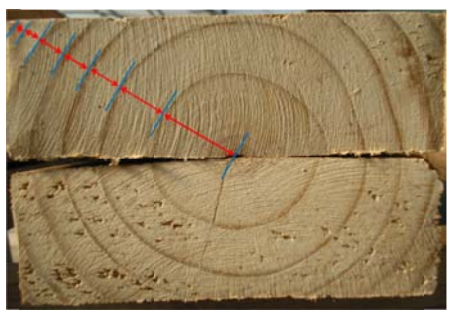

Figure 4: Annual ring-width measurements taken perpendicular to annual rings

Acoustic resonance frequency

The acoustic resonance frequency of each board was measured using the A-Grader Portable software from Falcon Engineering. The boards were placed on two polystyrene supports, 450 mm from each end, to provide clearance between the boards and the table (Figure 5), as well as to prevent frequency channelling through the table. A hit was then made with a wooden hammer which sends a vibration through the board. The sound caused by the resonance of the wave was recorded with a microphone on the opposite end of the board. Each board was tested twice to ensure the correct reading. During testing a 5% trigger level was used with a 5512 Hz frequency range. The dynamic MOE was then determined from the frequency and the density, measured by use of mass and volume, with the following formula:

$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)^2$ where:

MOE_{dyn}	is the dynamic modulus of elasticity, in MPa;
ρ	is the density of the test specimen at the moisture content at the time of testing, in kg/m^3;
l	is the length of the test specimen in meters to the closest mm; and
f	is the frequency of the test specimen, in Hertz.

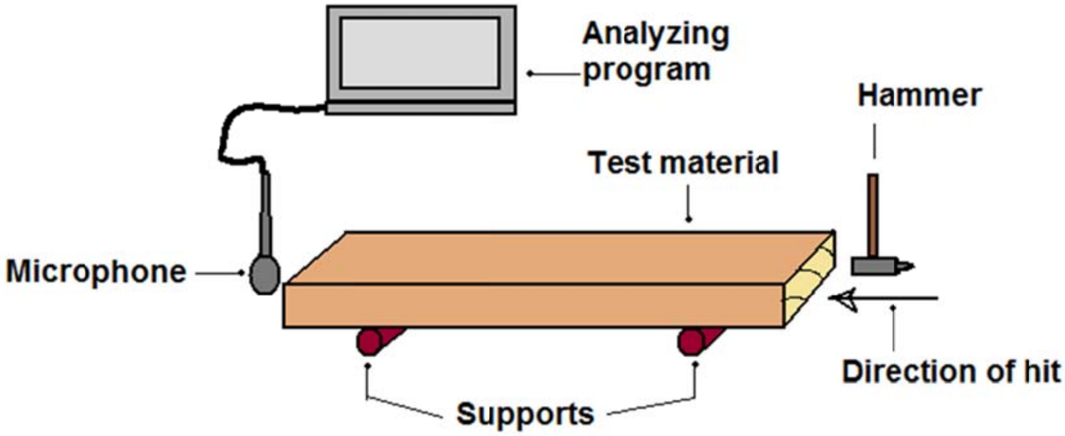

Figure 5: Frequency testing setup

Mechanical grading

Static flatwise mechanical grading on all the samples were performed using a TRU-grader according to SANS10149 (2002) – see Figure 6. The modulus of elasticity calculated from this grading process was referred to as MOE_{flat}. During the mechanical grading there were about 14 boards that failed under the test load. These boards could not be used for further testing.

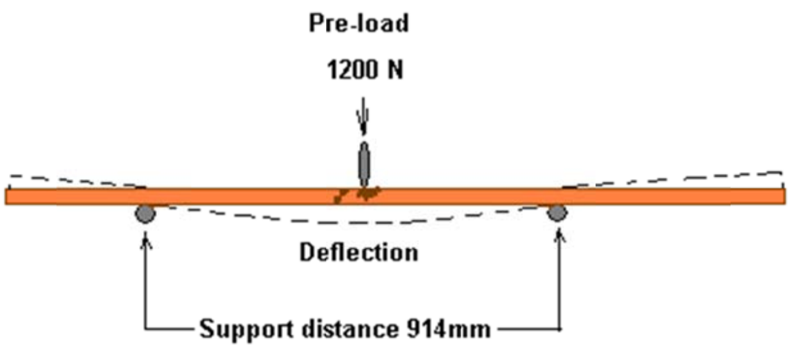

Figure 6: Flatwise mechanical grading of test material

Visual grading

Visual grading of all of the boards was done by a SANAS (South African National Accreditation System) accredited professional visual grader from the independent company SATAS (South African Timber Auditing Services). The boards were graded according to SANS 1783-2 (2005) visual grading rules. For analytical purposes the boards were allocated a grade considering all the defects (as would be the case in a mill setup). The reason for downgrade of each board was also noted i.e. density, warp (twist, spring and bow) and defects (knots, mechanical damage etc.). During visual grading for this study, a separate grade allocation was documented for each board in 3 categories. These categories included the grades allocated according to density, knots (sizes and distribution) and other defects including wane, warp, resin and mechanical damage.

Warp, moisture content and density measurements

Warp (twist, bow, spring) of each board was manually measured according to SANS 1783-1 (2004). The moisture content was measured with a resistance moisture meter. Density was calculated from the weight and dimensional data and where required in the data analysis process it was corrected for moisture content. Note that the warp measurement was not part of the visual grading process and was performed by a different operator.

Destructive tests

The sample material was divided into two groups based on the board position and a random allocation function. Pith boards were marked 0, the two boards on each side of the pith boards 1, the two boards further removed from the pith boards 2 etc. A random function was used to allocate the boards from the same position in a log (i.e. the two 1 boards) into the two different groups. One group was tested in bending and the other in tension. During the sawmilling and drying process some boards were lost and a few boards were broken during mechanical grading so that a total of 1345 boards out of 1402 boards were destructively tested.

Bending and tension tests were performed according to SANS 6122 (1994) with a few exceptions which will be explained below. Due to test equipment limitations, the bending test span was 1950 mm which is slightly less than the required 18:1 span to depth ratio. The tests were performed at a rate of deformation of 14 mm/min which was higher than prescribed. Research from Madsen (1992) suggests that the testing speed for timber only starts to play a role with material stronger than 35 MPa, which is stronger than normal commercial timber and far higher than the characteristic strength of any South African pine grade. Of the total bending sample of 699 only 683 tests were completed due to samples that twisted out of the test setup. Another 9 sample results were discarded due to numbering errors leaving a total sample size of 674. Eight of the boards tested were of slightly shorter lengths than 1950 mm, and the calculations of the strength and stiffness properties were adjusted accordingly.

Due to test machine limitations, specimens for the tensile tests had to be cut to a length of 1060 mm to fit into the testing setup with a span of 880 mm which is lower than the 9 x depth prescription in SANS 6122 (1994). The test load was limited to 100 kN which is the maximum value that can be tested with the load cell. A test speed of 15 mm/min was used, which is very moderate compared to other literature (Madsen, 1992; Rayda, 2003) but higher than that required by SANS 6122 (1994). The tension tests on the stronger portion of the timber proved problematic as the surface area of the machine grips in contact with the timber was too small. This caused the strong test pieces to break prematurely at the grips. The maximum load capacity of the load cell, which was 100 kN, was also not high enough to test the strongest pieces to failure. The tension test results might, therefore, be somewhat lower for some of the stronger pieces of timber than what it would have been if a better test setup was possible. Of the total tension sample of 623 only 611 tests were completed due to samples which slipped.

Bending strength, tension strength, MOE and 5^{th} percentile values were calculated according to SANS 6122 (1994). The modulus of elasticity calculated from the destructive tests was referred to as MOE_{edge}.

Statistical evaluation

For single correlation analysis, simple Pearson correlations were performed on all the variables in order to achieve a correlation matrix which includes all the possible indicator properties. Cook's distance was used to determine some outliers from the testing process. Simple scatterplots were drawn up for selected variables using a Least Squares approach with a linear model fitted ($Y = a + b \cdot X$).

When performing multiple regressions, a summary of best subsets, Mallows' Cp (Mallows, 1973) and forward stepwise regression was done in order to quantify co-linearity between the different variables and to decide which variables were significant enough to add to the multiple regression statistics. The Mallows' Cp number assesses the fit of a regression model and attempt to address the issue of overfitting.

Results and discussion

The results for the non-destructively evaluated (NDE) properties from the timber in this study are depicted in Table 5. The table also shows the yield percentage of structural grades if grading was based on only the specific property evaluated.

Table 5: NDE properties of the 1345 sawn 38x114x2100 mm Pinus patula boards

Property	Mean	Standard deviation	Maximum	Minimum	Grade yield according to specific property (%)			
					XXX	**S5**	**S7**	**S10**
Density* (ρ_m) (kg/m^3)	428	41.2	640	332	2.23	49.4	36.8	11.6
MOE_{flat} (MPa)	5320	1934	14490	1961	49.6	35.8	12.6	2.4
MOE_{dyn} (MPa)	8732	2295	16937	4251	-			
Annual ring width (mm)	10.3	4.73	41.8	0.60				
Bow (mm)	2.24	2.6	45.0	0	0.24	99.8		
Spring (mm)	2.62	2.11	23.0	0	0.16	99.8		
Twist (mm)	13.3	8.13	45.0	0	56.9	43.1		
Moisture content (%)	8.72	0.96	12.0	4.00	-			

*Density was determined at the kiln dried moisture content of each board and corrected as per SANS 1783-1 (2004)

Density has always been considered an important timber property in the prediction of some timber quality and strength properties. Based on density alone 2.23% of the boards were rejected, 49.4% fell into the S5 class (≥360 kg/m^3), 36.8% into the S7 class (≥425 kg/m^3) and 11.6% into the S10 class (≥475 kg/m^3). The fact that very few boards were rejected for structural use due to density is probably because this resource would already have been improved through tree breeding selection based on density. Density was still an important grade determining property for this resource, allowing less than half of the timber to be in the S7 and S10 grades according to the current structural grading rules.

The absolute values for MOE_{dyn}, which is the dynamic modulus of elasticity calculated from the natural frequency and density, was not really important on its own but was used as predictor of the other strength and stiffness properties. It was, however, noted that the values were higher than MOE_{flat}, and MOE_{edge}. MOE_{dyn} is an elastic property influenced by the total material make-up of a board, while both MOE_{flat} and MOE_{edge} are primarily influenced by localised weak points in areas where stresses are highest during a bending test.

The values for bow, spring and twist are used in structural grading due to the practical requirements for relatively straight timber when manufacturing products from it. It does not directly influence the timber strength and stiffness properties. It can be noticed that the values for bow and spring were much lower than the allowable bow of 21mm and allowable spring of 15mm (SANS 1783-2, 2005).

However, the mean twist was 13.36 mm which was above the allowable twist of 10mm according to SANS 1783-2 (2005). Based on twist alone, 56.9% of the boards were rejected.

Destructive test results

Results from the destructive tests according to the SANS 1783 (2005) visual and SANS 10149 (2002) mechanical grade allocation of timber (including warp and other non-structural requirements of the grading rules) are shown in Table 6. The table also contains the characteristic stress values for South African pine (SANS 10163-1, 2003).

Table 6: Timber strength and stiffness properties determined by means of destructive tests. Visual grading in accordance to SANS 1783 (2005) and mechanical grading in accordance to SANS 10149 (2002)*. The 5th percentile MOE values were obtained from the draft SANS 10163-2 document.*

Property	**SANS visual grade**	**Visual grading**					**Mechanical grading**					**Grade potential (%)**	**SANS 10163-1 requirement**	
		N	**Mean (MPa)**	**5th percentile (MPa)**	**Yield (%)**	**Yield excl. warped timber (%)**	**N**	**Mean (MPa)**	**5th percentile (MPa)**	**Yield (%)**	**Yield excl. warped timber (%)**			
MOR	**All**	674	30.1	15.1	-	-	674	30.1	15.1	-	-	-	-	
	XXX	345	28.0	14.7	51.2%	17.1%	455	26.9	13.9	67.5%	50.0%	1.0%	-	
	S5	241	28.8	14.5	35.8%	59.2%	167	33.6	17.9	24.8%	35.2%	5.2%	11.5 (5th)	
	S7	67	39.8	17.7	9.9%	17.2%	44	46.3	17.7	6.5%	12.5%	25.0%	15.8 (5th)	
	S10	21	49.5	27.2	3.1%	6.5%	8	51.5	-	1.2%	2.4%	68.8%	23.3 (5th)	
Tension	**All**	605	12	7.8	-	-	611	12.0	7.8	-	-	-	-	
	XXX	286	10.9	6.6	47.3%	16.8%	392	10.5	6.9	64.2%	48.8%	2.9%	-	
	S5	228	11.3	7.2	37.7%	59.5%	155	13.1	7.9	25.4%	33.1%	43.7%	6.7 (5th)	
	S7	67	16.5	9.7	11.0%	16.6%	58	17.7	10.1	9.5%	15.1%	52.9%	10 (5th)	
	S10	24	18.4	11.6	4.0%	7.1%	6	20.0	-	1.0%	3.1%	0.5%	13.3 (5th)	
MOE_{edge}	**All**	**674**	5888	3835	-	-	674	5888	3835	-	-		-	
	XXX	**345**	5566	3795	51.2%	17.1%	455	5451	3713	67.5%	50.0%	24.4%	-	
	S5	241	5750	3786	35.8%	59.2%	167	6419	4415	24.8%	35.2%	27.1%	4630 (5th)	7800 (mean)
	S7	67	7381	5126	9.9%	17.2%	44	7935	5052	6.5%	12.5%	28.4%	5700 (5th)	9600 (mean)
	S10	21	8081	5031	3.1%	6.5%	8	8732	-	1.2%	2.4%	20.1%	7130 (5th)	12000 (mean)

Table 7a: Pearson's correlation coefficient (r) between destructive and non-destructively tested values. Shaded areas has no significant correlation (p>0.05).

Coefficient of variation	MOE_{edge}	MOR	Tension	MOE_{dyn}	MOE_{flat}	ρ_m	ρ_s	Ring max	Ring min	Ring mean
MOE_{edge}	1	-	-	-	-	-	-	-	-	-
MOR	0.695	1	-	-	-	-	-	-	-	-
Tension	-	-	1	-	-	-	-	-	-	-
MOE_{dyn}	0.797	0.701	0.800	1	-	-	-	-	-	-
MOE_{flat}	0.760	0.659	0.696	0.866	1	-	-	-	-	-
ρ_m(Density manual)	0.593	0.404	0.580	0.668	0.599	1	-	-	-	-
ρ_s (Density scanner)	0.419	0.371	0.519	0.573	0.536	0.880	1	-	-	-
Ring max (Maximum ring width)	-0.502	-0.402	-0.480	-0.601	-0.490	-0.398	-0.315	1	-	-
Ring min (Minimum ring width)	-0.418	-0.337	-0.512	-0.513	-0.413	-0.441	-0.385	0.617	1	-
Ring mean (Mean ring width)	-0.523	-0.429	-0.562	-0.653	-0.537	-0.486	-0.414	0.854	0.906	1
Board position	0.443	0.333	0.474	0.524	0.502	0.247	0.199	-0.513	-0.328	-0.479
X-dev	-0.320	-0.181	-0.373	-0.340	-0.374	-0.189	-0.275	0.340	0.168	0.297
Knot avg (Avg. knot area)	-0.318	-0.368	-0.378	-0.345	-0.338	-0.210	-0.195	0.190	0.136	0.200
Knot max (Max. knot area)	-0.438	-0.428	-0.486	-0.460	-0.437	-0.187	-0.207	0.338	0.211	0.324
Knot Area /Board	-0.507	-0.454	-0.516	-0.570	-0.508	-0.238	-0.227	0.418	0.258	0.393
# Knots	-0.304	-0.147	-0.258	-0.294	-0.250	-0.040	-0.053	0.296	0.150	0.244
KSC (Knot stress calculation)	-0.293	-0.420	-0.272	-0.256	-0.248	-0.069	-0.081	0.073	0.016	0.050
$KPar_f$ (Knot parameter full board)	-0.373	-0.391	-0.371	-0.391	-0.390	-0.062	-0.032	0.268	0.194	0.275
$KPar_c$ (Knot parameter centre third)	-0.326	-0.367	-0.296	-0.316	-0.354	-0.069	-0.038	0.243	0.143	0.232

Table 7b: Pearson's correlation coefficient (r) between destructive and non-destructively tested values. Shaded areas has no significant correlation (p>0.05)

Coefficient of variation	**Board position**	**X-dev**	**Knot avg**	**Knot max**	**Knot Area / Board**	**# Knots**	**KSC**	**$KPar_f$**	**$KPar_c$**
X-dev	-0.592	1	-	-	-	-	-	-	-
Knot avg (avg. knot area)	-0.191	-0.019	1	-	-	-	-	-	-
Knot max (Max. knot area)	-0.461	0.421	0.587	1	-	-	-	-	-
Knot Area / Board	-0.562	0.401	0.519	0.700	1	-	-	-	-
# Knots	-0.485	0.577	-0.380	0.169	0.477	1	-	-	-
KSC (Knot stress calculation)	-0.159	0.025	0.273	0.242	0.397	0.122	1	-	-
$KPar_f$ (Knot parameter full board)	-0.381	0.095	0.427	0.508	0.488	0.102	0.205	1	-
$KPar_c$ (Knot parameter centre third)	-0.274	0.121	0.360	0.412	0.413	0.112	0.291	0.715	1

Bending strength (MOR) results

The grade potential column shows that 93.8% of all the timber pieces could potentially be Grade S7 or S10 based on MOR values alone. The 5^{th} percentile values for both visual and mechanical structural grades were much higher than required by SANS 10163-1 (2003). Even if the full ungraded sample was considered, the 5^{th} percentile value was still 15.1 MPa which is fairly close to the required value for grade S7 timber. It is clear that this young *Pinus patula* resource has very good bending strength properties. Downgrading to the XXX grade was mainly due to warp and the 5^{th} percentile values for the XXX grade of both mechanical and visual grading were well above that required for Grade S5.

The 5^{th} percentile value for bending strength is usually strongly influenced by knot related properties such as the local grain deviation around a knot. For a young resource the branches in a tree will be smaller than for mature trees which will also result in smaller knots. It is hypothesized that the bending strength of the mature resource used to establish the grade properties for South African pine might have been worse because of the larger knots that would have been present in such a resource and subsequent larger grain deviations around these knots. Even though the visual grading process will limit the size of knots allowed in a board the grain deviation caused by such a knot might on occasion still be present in a board even when only a section of the knot goes through the board.

Tension strength results

Most of the boards that were tension tested failed at the grips, which would negatively affect the strength values. Normally these values would have been discarded, but since grip-failures included most of our sample it was decided that they should be included. The tension grips made use of a wedge effect to increase the clamping force at the grips as the tension load increased. The wood at the grips compressed and failure was usually due to a combination of the tension stress and the grip compression. Even though the absolute failure values of most of the samples would have been lower than those which could have been achieved with no grip failures, the test results still provided useful information. Most importantly, with no grip-failures, values would have been higher so the results provided a conservative picture of tension strength. The tension values should, therefore, in reality be better for the higher grades, since this was where grip-failures and upper load limitations mostly occurred. For visual grading the 5^{th} percentile values for Grades S7 and S10 were below that required from SANS 10163-1 (2003). This would most probably be due to the test setup limitations which often caused grip failures for higher strength material. The 5^{th} percentile value for Grade S7 mechanically graded timber was higher than required. Despite the limitations of the testing method, the grade potential column shows that 97.1% of all the samples fell within either grade S5, S7 or S10. Although one cannot draw firm conclusions from these results due to test setup limitations, it seems as if the tension strength of this resource might be adequate.

Modulus of elasticity

The mean MOE_{edge} for the full sample (5888 MPa) was about 25% lower than required for Grade S5 timber. Table 6 shows that the mean MOE_{edge} values for all the grades were well below that required by SANS 10163-1 for both visual and mechanical grades. Although the grade potential column shows that only 24.4% of the timber would have been rejected based on MOE_{edge} it should be noted that for this column only the 5^{th} percentile MOE_{edge} requirement listed in the current draft version of SANS 10163-1 were considered and not the mean MOE_{edge} requirement per grade (which is not possible in this context). From these results it is clear that this young *Pinus patula* resource had very poor stiffness properties.

Mechanical grading was, for obvious reasons, better at separating timber according to stiffness. The mean MOE_{edge} of mechanically graded rejects (XXX) was lower than that of visually graded timber whereas for the structural grades it was higher. The variation of MOE_{edge} values is important for structural grading of timber since there is a mean MOE_{edge} requirement in SANS 10163-1 (2003) - unlike strength properties where only the 5^{th} percentile value is used to describe a property. It can be deduced that this young *Pinus patula* resource had much lower stiffness than the resource which was used to develop the visual and mechanical grading rules for South African pine in the past. Hence the current grading rules were not effective in meeting the requirements for stiffness of the various structural grades. The reason for the low stiffness was most probably the larger average microfibril angles associated with juvenile wood.

Visual and mechanical grade yields

The grade yield of this resource according to visual grading standards was quite poor with roughly only half the timber suitable for structural grades in both the bending and tension sample. Most of the downgrading with visual grading was due to the high twist values in the timber (Note: the measurements for the warp values and grade recoveries in the previous Table 5 were performed separately from the visual grading by a different operator – therefore the fact that according to Table 5 there was 56.9% of the timber rejected when only twist was taken into account whereas Table 6 shows that the total reject yield in both the bending and tension sample were less than that value). When warp was not taken into account in visual grading (in the “Yield excluding warped timber” column), only 17.1% of the bending sample and 16.8% of the tension sample were rejected. Better drying practices can lower warp in timber, and, with modern finger jointing operations the problem of twist can be reduced by simply cross-cutting twisted pieces and joining them again – although there are some recovery losses and significant extra costs involved in such an operation. With mechanical grading the yields were significantly poorer than with visual grading and 67.5% of the timber was not suitable for structural purposes. Even when warp was not taken into account, the yield was still only 50% for structural grades.

A concern with this timber resource is that despite the low grade yields for mechanical grading it still did not fulfil the current MOE_{edge} requirements for structural South African pine (SANS 10163-1, 2003). In practice it means that if border values of indicating properties for mechanical and visual grading are increased so that MOE_{edge} requirements are met, the grade yields will be even lower. At the same time the bending strength 5^{th} percentile values for structural grades were much higher than required. This indicates that the relationship between various properties such as the ratio of MOR:MOE for this resource is very different to what it was when the characteristic values for South African pine was determined three decades ago.

Defect placement with in-grade testing

The current South African in-grade testing standard (SANS 6122, 1994) prescribe biased placement of the worst defect in destructive testing of a sample. The 2.1 m log lengths effectively meant that there was little option with defect placement and that defect placement can be viewed as random placement of the worst defect for bending tests. For tensile test samples with a testing span of 880 mm the test results can be viewed as “limited” biased testing since the 2.1 m board length was much shorter than is normal for South African structural products. The Australian and New Zealand in-grade testing standards (AS/NZS 4063, 1992) and the ISO 13910 (2005) standard prescribe random placement of defects. Madsen (1992) is of the view that random placement of the sample is the more correct method for in-grade testing since that is what occurs during construction of timber structures – the worst defect is not always, and never deliberately, placed in the highest stressed area. The advantage of random placement of defects is that higher 5^{th} percentile MOR values are obtained. A change to the current SANS 6122 standard should be considered – although other factors should also be taken into account such as the required sample sizes which might be higher for random placement of defects.

Correlations between measured properties

All correlation coefficients (r) between the measured properties are shown in Tables 6a and b.

MOE_{edge} vs. MOR

One of the most widely used relationships in timber grading is that between stiffness and bending strength. Gaunt (1999) found that younger *P. radiata* material has a much lower MOE vs. MOR correlation than older material. A low correlation makes the determination of efficient grading rules more difficult, as timber with high stiffness does not necessarily have a high MOR. However, the coefficient of determination obtained in this study (R^2 = 48.2%) was within the expected range (see Table 2 and Figure 7).

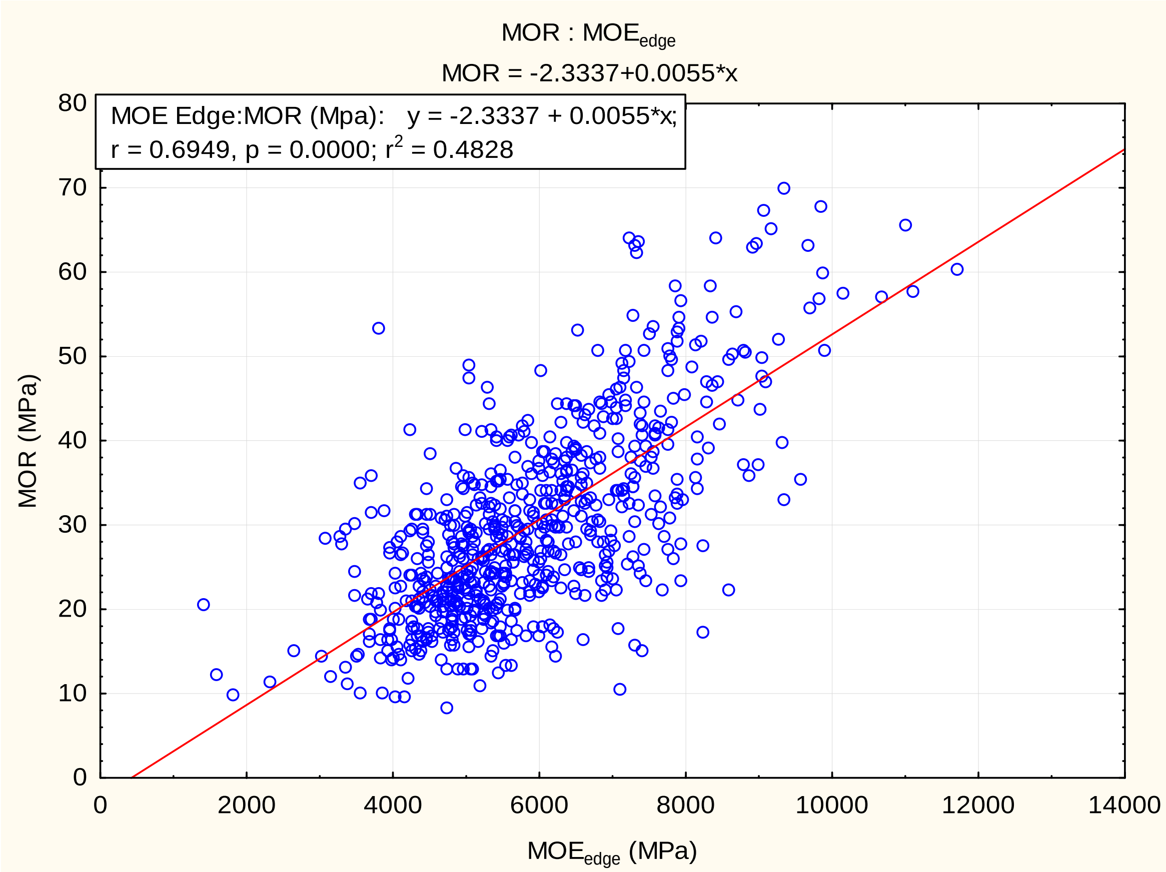

Figure 7: Scatterplot of MOR against MOE_{edge}

Density vs. MOR, MOE_{edge} and tension

The correlations of MOE_{edge}, MOR and tension with density (Table 7a) were comparable with results found in other studies where R^2 values of between 20-30% were obtained (Glos, 2004).

MOE_{edge} vs. MOE_{flat}

A surprising result was the low correlation between MOE_{edge} and MOE_{flat} (r = 0.76) from Table 7a. The low correlation might be explained by the fact that the MOE_{flat} value was determined at the weakest point of the timber and on flat, probably including a big knot percentage, as opposed to the random test setup for the determination of MOE_{edge}.

MOE_{dyn} vs. MOE_{edge} / MOR / Tension

A very encouraging NDE property measured was that of MOE_{dyn}. MOE_{dyn} was the best single predictor for MOE_{edge}, MOR and tension (Table 7a). The correlation values were even better, although not by much, than the correlation with MOE_{flat} which was calculated from flatwise bending on the weakest point of the samples. The higher correlation values of MOE_{edge} and MOR with MOE_{dyn} compared to MOE_{flat} shows promise when taking into consideration that MOE_{dyn} measurements are probably a lower cost method at high production speeds compared to the measurement of MOE_{flat}.

Other properties

The other variables that were deemed to be statistically influential were: annual ring widths (*ring max, ring min and ring avg*.), the position of the timber piece within the tree (*position*) and knots (*knot avg. knot max, knot area /board, KSC, $KPar_f$ and $KPar_c$*). It was noticed that the ring average, which is the mean width of the annual rings on each board, had a better correlation with both MOE_{edge} and tension than the individual knot parameters. This was not such a surprising result for MOE_{edge}, as the knots do not play such a big role as would be expected for MOR and tension. It was, however, surprising that the single knot parameters did not play a bigger role in the prediction of tension strength. This might have been due to the limitations in the tension testing discussed earlier. The correlation between MOR and ring width average was also only slightly lower when compared to MOR vs. knot area per board (Tables 6a and b). The best predictor for MOE_{edge}, MOR and tension, between the different knot measurements taken, was the total knot area per board. This seems to be a better predictor than the maximum knot size in a board. The knot stress calculation and knot parameters, which was formulated by combining knot sizes and positions, did not show good correlations.

Using combinations of properties to predict strength and stiffness

Multiple regression analysis was used to determine how well combinations of NDE properties can predict the strength and stiffness of the young *P. patula* timber. A combination of the best subsets, Mallows Cp and forward stepwise regression methods were used to identify properties to include in prediction models. Table 8 depicts the degrees of determination between the destructively tested properties and combinations of indicator properties. These were the indicator properties with the highest influence on the characteristic strength properties of timber. By means of statistical analysis of the co-linearity only the properties that were determined to be influential in the destructive test results were displayed in the table. Note that the r-values for single properties might be slightly different to that in the correlation table (Tables 6a and b) due to higher sample numbers possible when only individual correlations were considered.

Table 8: Coefficients of determination values (percentages) between destructive tests and both single and combined indicator properties. Pearson's correlation used for single predictors and forward stepwise regression for multiple predictors

Predictors	**MOE_{edge}** R^2	**MOR** R^2	**TENSION** R^2
MOE_{dyn}	63.57	46.55	62.93
MOE_{flat}	57.82	47.32	53.69
ρ_m(Density manual)	35.10	23.83	33.71
$KPar_f$, KSC, Knot max	23.21	33.67	31.14
ρ_m, $KPar_f$, KSC	43.49	42.53	45.91
MOE_{dyn}, ρ_m, $KPar_f$, KSC	62.59	54.26	64.38

Knot parameters, comprising of knot size and calculated parameter values ($KPar_f$, KSC, Knot max), showed a degree of determination of 33.67% for MOR. This is in the upper range of values found by

Glos (2004). Various combinations of timber properties were statistically evaluated and also tested for co-linearity as explained in the methods and materials section of this report. Combining MOE_{dyn} with density and knots increased the predictability of MOR by almost 7% over the use of MOE_{dyn} alone.

The best prediction values for MOE_{edge}, MOR and tension were obtained by combining knot parameters, density and MOE_{dyn}. Statistical analysis showed that the density contributes very little to this prediction value and that the addition of the knot parameters to MOE_{dyn} in the prediction of MOR has a roughly 6% increase compared to MOE_{dyn} on its own. MOE_{dyn} is, however, the best individual predictor of $MOE_{edge,}$ MOR and tension.

When comparing the R^2 values in this study with that obtained by Glos (2004), it shows that the predictability of MOR using combinations of properties for this resource is quite low. Glos mentions R^2 values of between 55-80% and with a combination of properties the best R^2 value obtained was 54.26%. The predictability of tension strength (despite the limitations in our test setup) was relatively good at 64.38%.

Conclusions and recommendations

The young *P. patula* timber tested in this study had good bending strength (MOR) properties with higher characteristic grade values than required. The tension strength values were similar to the requirements as specified in the SANS 10163-1 (2003) document for all the structural grades. There were, however, some limitations in our tensile test setup which caused the results to be lower than it should have been if a correct test setup was possible. The timber had low stiffness and did not comply with the SANS 10163-1 (2003) requirements for mean MOE_{edge} for any of the structural grades.

Of all the individual non-destructive predictors of strength and stiffness, the dynamic modulus of elasticity (MOE_{dyn}) showed the best correlation with MOR, MOE_{edge} and tension strength. When combinations of NDE properties were used to predict stiffness and strength the degree of determination could be increased in some cases over only using a single predictor such as MOE_{dyn} or MOE_{flat}.

It is recommended that in-grade testing programs be conducted at sawmills which use a predominantly young *Pinus patula* resource. If not compliant to the current strength and stiffness requirements, new grading methods such as acoustic grading should be considered.

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Chapter 4.

Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*

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Abstract
The objective of this study was to examine the variation in and inter-correlation among wood properties determining the suitability of 16-20 years old South African grown *Pinus patula* trees for structural timber. A total of 1112 sawn boards from 340 logs, 170 trees and 17 different compartments were examined. Sawlogs were taken from two height levels from each tree. The mean modulus of elasticity measured on edge (MOE_{edge}) was far below, and the mean twist higher than the limits set for structural grade softwood timber in South Africa. All the desirable properties for structural timber improved with distance from the pith with the exception of the 5th percentile value for modulus of rupture (MOR) which was higher at the pith than for the boards processed adjacent to the pith. Boards processed from the lower part of the stem were superior in most of the important properties compared to the properties higher up in the stem. The correlation between the dynamic modulus of elasticity (MOE_{dyn}) and MOR of boards processed from the logs taken higher up in the stem was much weaker than in the case of the boards processed from the log taken from the lower part in the stem, suggesting that indirect (non-destructive) prediction of MOR decreased in reliability with increase in height in trees. A relatively strong negative correlation was found between the mean growth ring widths of the pith boards and the mean MOE_{dyn} values per compartment, suggesting that slower initial growth in a compartment resulted in increased mean stiffness of boards from that compartment.

Keywords
Pinus patula, structural timber, modulus of elasticity, modulus of rupture, twist

Introduction

Pinus patula is the most intensively utilised conifer in the tropics and sub-tropics, where it is widely planted as an exotic. It is estimated that more than one million hectares are planted to this species with about half of that in Africa (Wright 1994). In South African it is the most important commercial plantation softwood resource with a total of 338 923 ha planted with *Pinus patula* trees (DAFF 2009). A substantial portion of that area is managed for saw log production. Of the total solid sawn timber production in South Africa more than 70% is sold as structural or building timber (Crickmay and Associates 2011). This timber is mainly used in roof trusses and other building components where the safety of the inhabitants, builders and maintenance workers is at stake. It follows that the mechanical properties of *Pinus patula* timber are of major importance to the sawmilling industry in South Africa.

Pine plantations managed for saw log production were traditionally harvested at about 30 years of age. In the last few years, however, the rotation age for saw timber plantations in South Africa has been reduced by many growers and the average rotation age has fallen from about 30 years in 1994 to less than 23 years in 2004 (Crickmay et al. 2005). The reason for this reduction in rotation age can largely be attributed to the increase in growth rate of trees through tree breeding and improved silvicultural practices, to meet the increased demand for sawn timber and the growing need to enhance the productivity of our existing forestry resource. Unfortunately the shortening of rotation age to reap the financial benefits of the faster growth, has a direct impact on wood quality as it causes an increased proportion of juvenile wood in the raw-material entering the processing industry. Juvenile wood is known to be structurally different and considerably more variable in virtually all wood properties compared to mature wood, resulting also in higher variability in it's performance and behavioural characteristics (Kennedy 1995; Malan 2010; Zobel and Sprague 1998; Xu and Walker 2004).

For structural timber producers and users, two aspects are important. In the first instance the absolute values of the strength and stiffness properties of sawn timber from a specific timber resource should be such that an acceptable percentage of timber meets the requirements for the various structural grades as set out in SANS 10163-1 (2003). Secondly, the ability to predict these strength properties non-destructively is also very important for a specific wood resource since it ensures reliable strength and stiffness properties (after grading) for users of structural timber.

Burdzik (2004) performed mechanical tests on visually graded timber that passed the lowest South African structural grade (S5) from four sawmills from "low wood density" areas in South Africa. It was found that none of the sawmills produced graded timber that conformed to the strength or stiffness requirements of SANS 10163-1 (2003). The result thus suggested that in some areas in South Africa, the relationship between the visual grading criteria and strength and stiffness properties of South African pine was not the same as in the past when the currently applied grading rules were developed. Burdzik (2004) provided no information on the pine species and age distribution of the logs processed by these sawmills, but speculated that an increased proportion of juvenile wood may have been the main reason for the low strength and stiffness experienced by these mills.

Stiffness, or MOE, is one of the best and most widely used non-destructive predictors of timber strength (Johansson, 2003). In New Zealand, Gaunt (1999) investigated the relationship between MOE and bending strength of juvenile and mature *Pinus radiata.* He concluded that this relationship was so weak for juvenile *Pinus radiata* that machine stress grading using this relationship, became unreliable and inefficient.

An understanding of the within- and between-tree, and between-site variation in strength and stiffness of South African pine, and the ability to quantify and predict these variation patterns, especially in the corewood section of trees, would provide saw log growers and processors with a reliable information base for the development of much needed processing decision support tools. It can be expected that in South Africa the need for such tools will grow in importance with the continuous changes in the quality of the South African pine timber resource.

The objective of this study was to examine the within- and between-tree variation in wood properties of young South African grown *Pinus patula* trees known to have important impacts on the suitability of sawn timber for structural purposes. Apart from the strength and stiffness variation, the variation in the relationship between strength and stiffness, which is important for efficient structural grading, was also investigated. Although warp does not have a direct effect on wood strength and stiffness, it was nevertheless included in the study as sawn timber needs to be relatively straight to be utilisable in a structure.

Materials and methods

Tree sampling

Saw logs were obtained from 17 different *Pinus patula* compartments in the Mpumalanga forest area of South Africa. The compartments varied in age from 16 to 20 years, altitudes from 810 to 1930 m above sea level, mean annual rainfall from 840 to 1299 mm and a mean annual temperature range of 13.7 to 19.4 °C. Site indices at base year 10 ranged from 9.6 to 19.6 (Table 1).

Compartment identification	Plantation	Age (yrs)	Mean DBH (cm)	Mean height (m)	Site Index$_{10}$ (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
A (E66)	Nelshoogte	17	36	20.9	14.3	1061	16.0
B (E28a)	Nelshoogte	19	33.8	21.8	14.5	1036	16.1
C (G21)	Nelshoogte	16	26.2	18.4	15.5	1057	16.1
D (D1)	Uitsoek	17	32.7	22.3	15.7	944	17.4
E (D88)	Uitsoek	17	30.2	18.4	15.3	942	17.3
F (E55a)	Uitsoek	20	32.3	20.1	14.6	1151	13.7
G (E36c)	Uitsoek	19	31.9	23.0	16.8	902	14.0
H (E22)	Uitsoek	17	27.6	20.8	16.5	840	14.2
I (E5)	Berlin	19	36.5	23.8	16.7	1284	16.1
J (E15)	Berlin	19	37.4	23.8	17.6	1082	15.9
K (E35)	Berlin	16	29.1	18.0	16.5	1006	17.2
L (C22)	Blyde	20	34	27.0	18.5	1156	16.1
M (E3)	Morgenzon	17	31.4	20.6	13.5	1015	14.3
N (D74)	Morgenzon	19	26.9	16.4	9.6	997	16.2
O (A1a)	Morgenzon	16	27.8	19.0	13.6	862	15.1
P (D11)	Wilgeboom	18	29.4	22.8	19.6	1242	19.4
R (J20)	Wilgeboom	19	33.4	24.0	16.8	1299	18.5
Mean		**18**	**31.6**	**21.2**	**15.6**	**1052**	**16.1**

Table 1 General data for each compartment and the mean diameter at breast height (DBH) and height of the ten sample trees per compartment.

A stratified sampling procedure in terms of tree diameters was followed so that the sample trees represented the productive timber volume available from the compartments. In each compartment one tree was randomly selected from the first quartile (small diameter), two trees from the second quartile, three trees from the third quartile and four trees from the fourth quartile (large diameters), giving a total of ten sample trees per compartment, thus 170 trees for the entire investigation.

Board preparation
Two 2.1m-long logs were removed from each tree – the bottom log from the pruned section of the stem at 2.3 m thick-end height and the top log from the unpruned section at 7 m thick-end height (Figure 1). The logs were processed at a local sawmill using frame-saws and a cant sawing pattern. The cross-sectional dimension of all the boards was 38 x 114 mm. Only boards from the cant section were used for this study as it provided test material that represented the full radius of each log. Boards were consecutively numbered from the pith towards the outside, starting with 0 to indicate boards containing pith tissue, followed by the numbers 1 and 2 (Figure 1). When two boards from the same log contained pith tissue (which was often the case), both were marked as 0.

Boards were kiln-dried using a medium temperature schedule to a target moisture content of 12%.

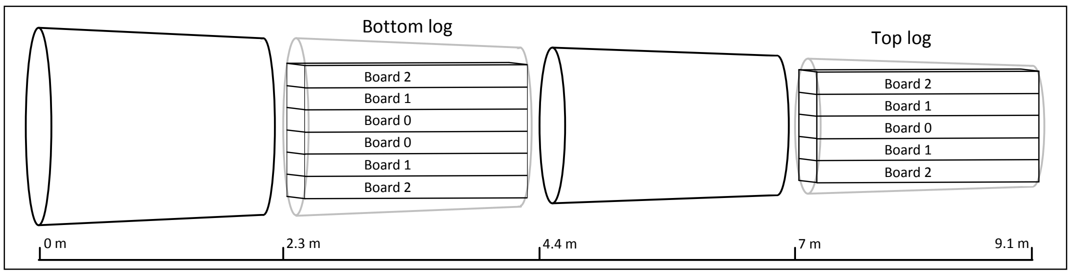

Fig. 1 Position of logs and boards sampled from the tree stem. Note that board position 0 signifies boards that contained pith. Sometimes there was only one pith-containing board in a log (see top log above) and sometimes two pith-containing boards (see bottom log above)

Board evaluation
Dried boards were scanned with a commercial Goldeneye 702 X-ray scanner from Microtec. This scanner is fitted with a number of sensors including optical cameras, a laser scanning device and an X-ray density scanning device. For the purpose of this study only knot location and size data from the scanner were used for further analyses.

The following knot characteristics were calculated and analysed:

- Total knot area (mm^2): The total area of the board that contained knots. X-ray scanning evaluated each board from the vertical direction when a board was laying flat on its width face. The area measurement is similar to the knot-covered area seen when looked from above at a knot in a transparent board.
- Maximum knot area (mm^2): The area covered by the largest knot or combination of knots on a piece of timber.

Individual board densities were determined by weighing and calculating the volume of each board from dimensional data, corrected for moisture content according to SANS 1783-1 (2004). The moisture content was measured with a resistance moisture meter. Warp (twist, bow, spring) of each board was measured according to SANS 1783-1 (2004).

The number of annual rings on each board was counted and numbered from the pith outwards. The cambial age or year ring number (mean, maximum and minimum) of the wood within each board was therefore known. The cambial age is the age by ring count from the pith. Ring width, from start of earlywood to end of latewood, were measured to the nearest 0.1 mm (Figure 2). For each board the minimum, maximum, and mean ring widths were determined.

Fig. 2 Radial ring-width measurements taken perpendicular to annual rings

The acoustic resonance frequency of each board was measured using the A-Grader Portable software from Falcon Engineering. Two measurements were taken per board to ensure correctness. During testing a 5% trigger level was used with a 5512 Hz frequency range. The dynamic MOE was determined from the resonance frequency and the density with the following formula:

$$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)^2$$

where:

MOE$_{dyn}$ is the dynamic modulus of elasticity, in MPa;
ρ is the density of the test specimen at the moisture content at the time of testing, in kg/m^3;
l is the length of the test specimen in meters to the closest mm; and
f is the resonance frequency of the test specimen, in Hertz.

The test boards were divided into two groups by randomly allocating the two boards at each radial position to a different group. Boards in one group were earmarked for bending tests and the boards in the other group for tension tests parallel to grain. Where only one board was available for a specific position, it was allocated to the bending test sample.

Bending and tension tests were performed approximately according to the prescriptions outlined in SANS 6122 (1994). Due to equipment limitations the test span used for carrying out the bending tests was 1950 mm, which was slightly shorter than the required 18:1 span-to-depth ratio. The tests were performed at a rate of deformation of 14 mm/min.

Of the 699 boards available for bending tests, 683 were successfully tested as some of the boards twisted during the test process, rendering them unsuitable for further testing. The test results of another 9 boards were eliminated from the dataset due to numbering errors.

Due to test equipment limitation, the specimens for tensile testing had to be cut to a length of 1060 mm to fit into the testing machine. This resulted in a test span of 880 mm, which is shorter than the 9:1 span-to-depth ratio prescribed by SANS 6122 (1994). A test load of 100 kN, which is the maximum load capacity of the load cell, and a test speed of 15 mm/min were used.

Tension tests on the stronger boards proved problematic as some of the stronger boards broke prematurely at the grips. The maximum load capacity of the load cell (100 kN) was also not high enough to test the strongest boards to failure. The tension test results might therefore have been higher for stronger boards if a better test setup had been possible. Of the total tension sample of 623 boards, 611 were tested due to samples which slipped.

Bending strength, tension strength and MOE_{edge} values were calculated according to SANS 6122 (1994).

In the final analysis all boards with more wane than allowed in SANS 1783-2 (2005) were also discarded leaving a total of 1112 boards.

Statistical analysis

In the statistical analysis, three-way cross classification ANOVA's were done using compartment, log position, and board position as factors. The effect of these factors were analysed on MOR, MOE, tension strength, density and twist. If the three-way interaction was significant it was investigated with Bonferroni multiple comparisons. Otherwise the significant two-way interactions were interpreted. Where a factor was not included in any significant interactions, the main effect was interpreted. If enough data was not available for a three-way ANOVA, successive two-way ANOVA's were done.

Results and discussion

The variation in the most important properties of full sized boards within a tree can be seen in Table 2.

Description		Board 0		Board 1		Board 2		All boards
		Bottom log	Top log	Bottom log	Top log	Bottom log	Top log	
No. of boards (n)		232	203	253	193	117	61	1112
Year ring no.	Mean	3.0	3.2	5.5	5.4	8.1	7.9	4.9
	95% Conf. Int	2.8-3.2	3.0-3.4	5.2-5.7	5.2-5.7	7.7-8.5	7.5-8.4	
Year ring width (mm)	Mean	13.1	12.2	10.4	10.4	7.9	8.4	10.8
	95% Conf. Int	12.6-13.6	11.8-12.7	10.0-10.9	9.9-10.9	7.4-8.3	7.8-9.1	
Density (kg/m^3)	Mean	417.4	411.5	426.6	420.0	450.2	436.1	424.4
	95% Conf. Int	413-421	407-416	422-431	415-425	443-458	428-445	
Bow (mm)	Mean	2.0	2.0	2.4	2.4	2.0	2.0	2.2
	95% Conf. Int	1.7-2.3	1.8-2.3	1.9-2.8	2.0-2.8	1.6-2.3	1.6-2.4	
Spring (mm)	Mean	2.8	2.6	2.5	2.6	2.4	2.2	2.6
	95% Conf. Int	2.5-3.2	2.3-2.9	2.3-2.8	2.3-2.8	2.1-2.7	1.8-2.6	
Twist (mm)	Mean	17.4	18.5	12.1	11.7	8.6	8.9	13.7
	95% Conf. Int	16.3-18.5	17.4-19.7	11.3-13.1	10.7-12.7	7.5-9.7	7.2-10.6	
Total knot area (mm^2)	Mean	16513	15024	11728	11830	6614	8725	12622
	95% Conf. Int	15731-17296	14332-15716	11095-12362	11213-12447	5736-7492	7835-9614	
Max. knot area (mm^2)	Mean	4505	4522	2983	3272	2094	2812	3548
	95% Conf. Int	4254-4755	4235-4810	2792-3175	3060-3485	1869-2319	2602-3023	
MOE_{dyn} (MPa)	Mean	7170	7372	8650	8457	10859	9695	8422
	95% Conf. Int	6982-7358	7216-7528	8409-8892	8221-8693	10446-11272	9261-10130	
MOE_{edge} (MPa)	Mean	5204	5041	5948	5873	7153	6358	5755
	95% Conf. Int	5026-5381	4872-5209	5698-6199	5668-6078	6733-7574	5883-6834	
	n	124	112	134	106	58	33	586
MOR (MPa)	5th Percentile	15.77	15.58	14.70	13.11	22.04	15.16	15.03
	Mean	27.58	24.84	30.16	27.86	41.44	30.79	29.52
	95% Conf. Int	26.0-29.1	23.5-26.2	28.2-32.1	26.0-29.7	38.0-44.9	26.9-34.6	
	n	124	112	134	106	58	33	588
Tensile strength (MPa)	5th Percentile	6.65	6.57	7.12	7.05	7.93	6.54	6.90
	Mean	9.15	8.80	11.63	11.22	16.40	14.57	11.40
	95% Conf. Int	8.7-9.6	8.5-9.4	10.9-12.3	10.5-12.0	15.2-17.6	12.7-16.5	
	n	108	91	119	95	59	29	524
R^2 value: MOE_{dyn} vs MOR (linear regression, all significant at 0.05 level)		0.41	0.34	0.62	0.33	0.59	0.29	0.56
		0.36		0.51		0.54		
		All bottom log boards: 0.64						
		All top log boards: 0.36						

Table 2 Measured data per board position. Data for the few board 3 and 4 positions were not included individually but included in the "All boards" column.

Modulus of elasticity

Stiffness was measured statically on the board's edge (MOE_{edge}) as well as with an acoustic method (MOE_{dyn}). The MOE_{edge} measurement is the method generally used to determine the characteristic and design MOE values for timber. The mean MOE_{edge} of the sample was 5755 MPa (Table 2) which was far below the minimum of 7800 MPa required for South African structural grade sawn timber (SANS 10163-1, 2003). This result suggests that in general the mean MOE_{edge} or stiffness of *P. patula* grown in the forest area sampled is about 26% below the requirement for structural sawn timber, which should be of a major concern. The mean MOE_{edge} values increased sharply from the pith boards of the bottom log (5204 MPa) to the second boards (7153 MPa) of the bottom log. Studies by Malan et al. (1997) and Malan (2001) showed that the first 12 to 15 years of growth more or less represents the corewood zone (sometimes referred to as the juvenile wood zone) of this species in terms of wood density. The second boards had a mean year ring number of 8.1 and 7.9 for the bottom and top logs respectively and would thus still be in the juvenile region. The juvenile wood region is characterised by rapidly changing wood properties which stabilise as the wood approaches maturity (Zobel and van Buijtenen 1989). It can, therefore, be expected that boards from the mature region formed later should have higher MOE_{edge} values. In a different study it was found that the mean MOE_{edge} values from sawn timber from sawmills which use a resource consisting of mainly mature *P. patula* logs harvested at around 28 years were found to be in the region of 7800 MPa (Crafford and Wessels 2011).

Current specifications require sawn timber to conform to either visual or mechanical grading specifications in order to qualify as structural products. Actual mechanical testing is not required on a continuous basis in terms of current specifications (SANS 1783-1 2004 and SANS 10149 2011) which means that sawmills processing logs from locally grown pine are often unaware of the fact that the structural sawn timber they produce might not conform to the stiffness requirements of the respective grades.

The dynamic modulus of elasticity (MOE_{dyn}) is arguably a better indication of the mean stiffness of a piece of timber compared to the static modulus of elasticity determined when tested on the edge (MOE_{edge}), as the full volume of material influences MOE_{dyn} whereas MOE_{edge} is influenced more by the local stiffness of the material at the highly stressed areas of a specific test setup. As MOE_{dyn} was determined on all the available boards, contrary to $MOE_{edge,}$ which was determined only on boards earmarked for bending tests, it provided a better measure for quantifying the extent and patterns of variation in stiffness among individual logs, trees and compartments.

A three-way analysis of variation indicated that compartment, log position and board position significantly influenced mean $MOE_{dyn.}$ A significant interaction existed between log position and board position (Table 3, Figures 3 and 4). Some compartments with too few data points had to be omitted to make the three-way ANOVA possible. The percentage variation explained by each component is also listed in Table 3 and it is noticeable that board position was the most influential component explaining 26.5% of the variation in MOE_{dyn}. Compartment explained about 8.0% of the variation.

Source of variation	SS	Degrees of freedom	MS	F	p	Variance components (%)
Compartment	2.62E+08	12	2.18E+07	9.05	0.0000	8.0 %
Log position	2.56E+07	1	2.56E+07	10.61	0.0012	0.8 %
Board position	8.69E+08	2	4.35E+08	180.06	0.0000	26.5 %
Compartment*Log position	3.66E+07	12	3.05E+06	1.26	0.2359	1.1 %
Compartment*Board position	8.53E+07	24	3.56E+06	1.47	0.0675	2.6 %
Log position*Board position	3.87E+07	2	1.93E+07	8.01	0.0004	1.2 %
Compartment*Log position*Board position	7.34E+07	24	3.06E+06	1.27	0.1768	2.2 %
Error	1.89E+09	784	2.41E+06			57.6 %

Table 3 A three-way analysis of variance for MOE_{dyn} (MPa). Significant factors at the 5% level are shaded. The last column gives the percentage variation that is explained by each component.

Since compartment was not involved in any significant interactions, the main effect could be interpreted. The mean MOE_{dyn} values per compartment varied between about 7500 and 10000 MPa (Figure 3). It is interesting to note that the mean MOE_{dyn} values of compartments from the same estate and which were relatively close to each other often differed significantly i.e. compartments A, B, and C were from the same estate (Nelshoogte) as well as compartments D, E, F and G (Uitsoek).

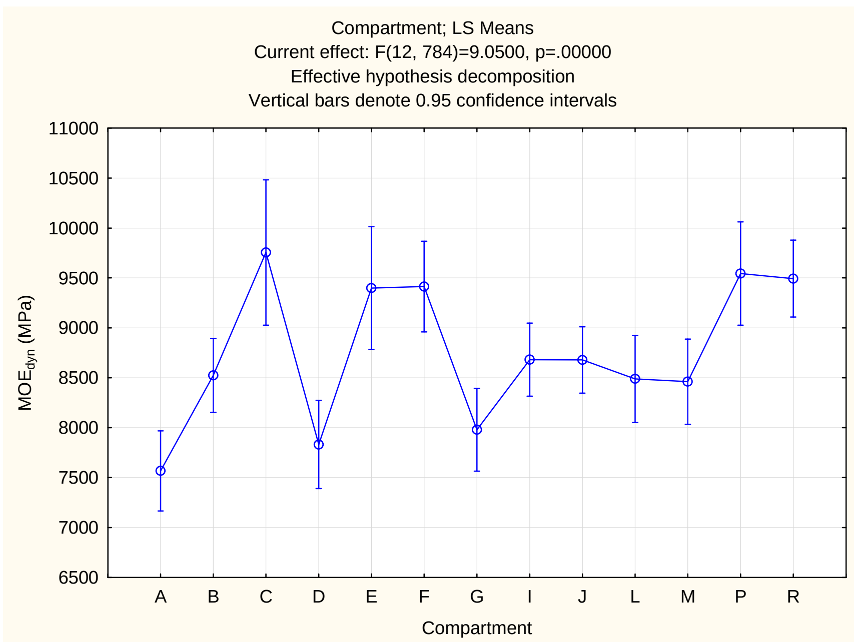

Fig. 3 The means and 95% confidence intervals of MOE_{dyn} for boards from different compartments

The influence of board position and log position on MOE_{dyn} can be seen in Figure 4. As expected MOE_{dyn} increased sharply from the pith boards to the second boards. The mean MOE_{dyn} of pith boards of the bottom logs did not differ significantly from the pith boards of the top logs. This was also the case for first boards. For second boards, however, the mean MOE_{dyn} was significantly higher for boards from the bottom log than from top log boards. This could probably be ascribed to the effect of pruning on 2^{nd} boards. All the compartments received pruning up to 3m at around 7 years and pruning to 5m height at around 9 years. The second boards of the bottom logs which had a mean cambial age (year ring number) of 8.1 would thus be partially knot free. This is supported by the fact that both the mean total knot area and the mean maximum knot area for second boards of the top logs was significantly different than for second boards of the bottom logs (Table 2).

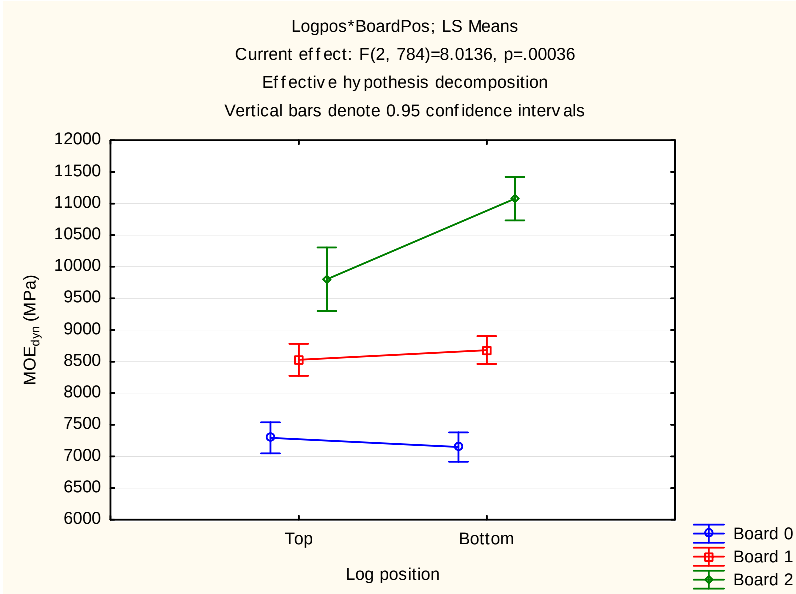

Fig. 4 The means and 95% confidence intervals of MOE_{dyn} of the different board positions from the top and bottom logs

A linear regression of the mean MOE_{dyn} values and the mean ring width of pith boards of each compartment showed a good relationship of $R^2 = 0.76$ (Figure 5). When a linear regression of the mean ring widths of the pith boards and mean MOE_{dyn} of **all** the boards per compartment was performed the R^2 value was still 0.50. The reason for this relationship is most probably that compartments with slow initial growth produce pith boards containing more and older year rings. Older year rings will have higher density and lower microfibril angles which is associated with higher stiffness. Additionally, these older year rings in the pith boards are usually also located at the edges of a board where their influence in terms of stiffness on edge of the full board will be maximised. These results suggest that the suppression of early growth might be one strategy to increase the mean MOE_{edge} and MOE_{dyn} of boards from the young *Pinus patula* resource. Also notice that faster growth at a later stage such as that experienced by compartment F did not seem to influence MOE_{dyn} negatively. This compartment had the slowest initial growth but at harvesting had an above average mean DBH and still had one of the highest mean MOE_{dyn} of all the compartments.

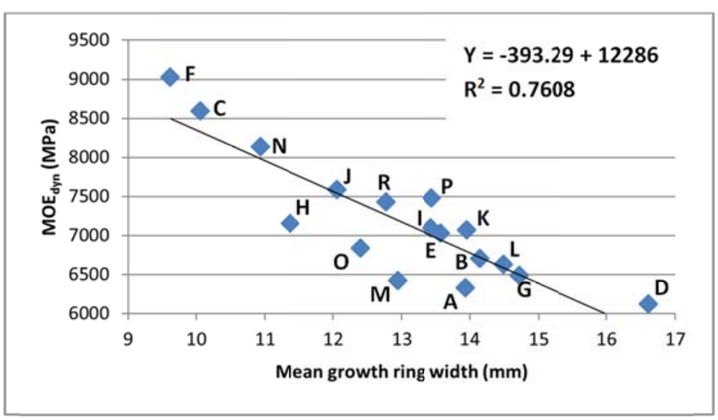

Fig. 5 A scatterplot and regression line of the mean MOE_{dyn} and mean growth ring widths of pith boards (board 0) of the bottom logs from different compartments. Individual compartments can be identified by the letter next to each plot

The MOE_{edge} of the young *Pinus patula* timber was lower than required for structural grades. If the South African sawmilling industry plans to use this resource for structural products it should focus on ways to improve this property. Recent research in North America (*P. taeda*) and New Zealand (*P. radiata*) showed that high initial planting density led to higher stiffness wood (Roth et al. 2007, Waghorn et al. 2007, Laserre et al. 2005, Laserre et al. 2009). Stiffness was shown, in these and other studies (i.e. Watt et al., 2006), to be related to tree slenderness which is a function of planting density. This might be one option worth investigating. High initial planting density is also associated with suppression of initial growth which was shown in this study to increase the mean MOE_{dyn} of boards. Take note that although individual tree growth might be suppressed by high planting density, the per hectare volume yields are often higher due to the higher stem counts.

Modulus of rupture (bending strength)

The absolute values of MOR for this young resource were surprisingly high. The value of most interest in terms of structural timber is the 5th percentile value or characteristic bending strength which is used for designing structures from a specific grade of wood. For all the boards tested in this study, the 5th percentile value as determined according to SANS 6122 (1994), was 15.03 MPa (see Table 2) which is well above the required 5th percentile value for the lowest and most commonly used structural grade in SA (S5, 11.5 MPa) and very close to the requirement for the next structural grade (S7, 15.8 MPa).

Contrary to expectation, the 5th percentile MOR values for the pith boards were higher than that of the first boards for both the bottom and top log (Table 2). The 5th percentile MOR value of the pith boards of the top logs was even higher than that of the second boards of the top log. This was an interesting result which did not conform to the expected trend of improved properties for boards further away from the pith. The mean MOR values, however, performed as expected where the mean MOR for second boards was higher than that of first boards which was again higher than that of pith boards. The 5th percentile value for 2nd boards improved dramatically for bottom log boards but remain fairly low for top log boards. This was most probably due to the fact that the second board of the bottom log already formed part of the pruned section where the effect of knots was removed.

Bending strength or MOR is usually related to the knot properties of boards. The mean maximum knot areas of pith boards and mean total knot areas were higher than for the first boards (Table 2). Other variables that are usually closely related to the bending strength of timber include density and MOE which were both lower in the pith boards than the first boards. A possible explanation for the high 5th percentile MOR values of pith boards might be that the maximum knot area measured by the X-ray scanning device for a pith board was often a combination of a few small knots from a single branch whorl resulting in a high maximum knot area measurement. Because these were mostly small knots, grain deviation around the knots, which is the actual cause of weakness in bending (see Walker, 1993), would not be very pronounced. For the first boards where single knots are usually bigger, a more pronounced grain deviation might result in very low bending values for a few boards – but only where the knot was situated close to a high stress area. This may explain why some boards further from the pith were characterised by higher mean MOR values but with lower 5th percentile MOR values. In other words, the weak tail section of the MOR histogram for 1st and 2nd boards were more pronounced than for pith boards even though the mean values were quite high.

When visual grading was performed on all the boards, and boards that did not make the structural grades were omitted from the sample, the same result was obtained. The 5th percentile value of the 1st boards was still lower than that of the pith boards. However, in this case the values were closer to one another than when no grading was performed. This means that visual grading was not completely successful in eliminating the cause of the lower 5th percentile bending strength values obtained in 1st boards.

There was not enough data for a three-way ANOVA and therefore successive two-way ANOVA's were done. The results showed that the mean MOR differed significantly between compartments, log position and board position. There was a significant interaction between board position and log position at the 0.05 level. For the pith and first boards the MOR did not differ significantly between the top and bottom logs (Figure 6). However, for the second board a large and significant difference between the mean MOR values of the top and bottom log was found. This was most likely due to the influence of pruning on the second boards of the bottom log.

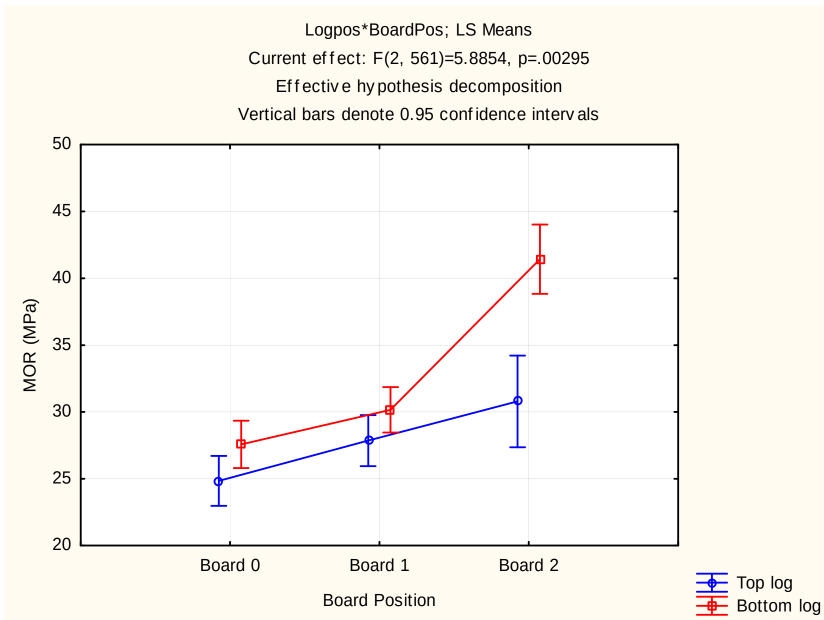

Fig. 6 The means and 95% confidence intervals of MOR of the different board positions from the top and bottom logs

Tensile strength

As with bending strength, the most important value determining the suitability of sawn timber for structural purposes is the 5th percentile tensile strength. The 5th percentile tensile strength for all the test boards combined was 6.9 MPa (see Table 2) which was slightly higher than the 5th percentile value of 6.7 MPa required for grade S5 timber. It should be taken into consideration that the tensile test setup was such that most pieces failed prematurely due to compression by the clamping effect at the grips. This problem influenced the stronger pieces more than weaker pieces – which usually failed at a knot - and had a bigger impact on the mean tensile strength than the 5th percentile value. Considering the young age of this resource as well as the problem with grip failures, the tensile strength seems to be acceptable.

Similar to the bending strength, the 5th percentile tensile strength values showed a different trend when compared to mean tensile strength values. The 5th percentile tensile values of the boards increased only moderately from the pith boards towards the 2nd boards whereas the mean values increased fairly sharply (Table 2). The 5th percentile tensile strength value of the 2nd board from the bottom log (7.93 MPa) was for instance only 19% higher than the value for the pith board of the same log whereas the mean value (16.40 MPa) was nearly 80% higher. The 5th percentile value of the top log's 2nd board was lower than that of the pith board. This was most probably due to the more severe grain deviation which was associated with the larger knots which characterised the weakest boards originating from the top logs. The 2nd boards of the bottom log had a much higher 5th percentile value. These boards originated from the pruned sections where the boards were less affected by the presence of knots. Analysis of variation indicated that the log position and board position significantly influenced the mean tensile strength and that there was a significant interaction between board position and compartment.

Warp (bow, spring, and twist)

The average bow and spring observed in all the boards examined were only 2.2 mm and 2.6 mm (Table 2) which was considerably less than the allowable limits for structural grade timber set by the SANS 1783-2 (2005) of 15 mm and 21 mm respectively. Bow and spring were clearly not a problem in this resource. The means of these properties for different board and log positions were very similar. The among-board variability in both properties decreased with distance from the pith.

Twist in the boards examined averaged 13.7 mm/m, with well over half the boards not passing the minimum requirement of 10 mm/m for 38x114x2100 mm size structural timber (SANS 1783-2, 2005). A three-way analysis of variance indicated that compartment and board position significantly influenced the level of twist (Table 4). Some compartments with too few data points had to be omitted to make the three-way ANOVA possible. The percentage variation explained by each component is also listed in Table 4 and board position was the most influential component explaining 18.5% of the variation in twist. Twist was significantly different between boards from different radial positions, with the most twist occurring in pith boards, followed by the 1st and and 2nd boards (Figure 7, Table 2). This was most likely due to the higher levels of spiral grain that usually characterises the centre core of this species (Gerischer and Kromhout 1964; Malan 2010).

	SS	**Degrees of freedom**	**MS**	**F**	**p**	**Variance components (%)**
Compartment	1302.6	12	108.5	2.208	0.0100	2.52
Log position	0.01	1	0.0	0.000	0.9914	0.00
Board position	9573.4	2	4786.7	97.371	0.0000	18.52
Compartment*Log position	459.5	12	38.3	0.779	0.6728	0.89
Compartment*Board position	1552.1	24	64.7	1.316	0.1431	3.00
Log position*Board position	206.2	2	103.1	2.097	0.1235	0.40
Compartment*Log position*Board position	1037.7	24	43.2	0.879	0.6316	2.01
Error	37557.8	764	49.2			72.66

Table 4. A three-way analysis of variance for twist (mm). Significant factors at the 5% level are shaded. The last column gives the percentage variation that is explained by each component.

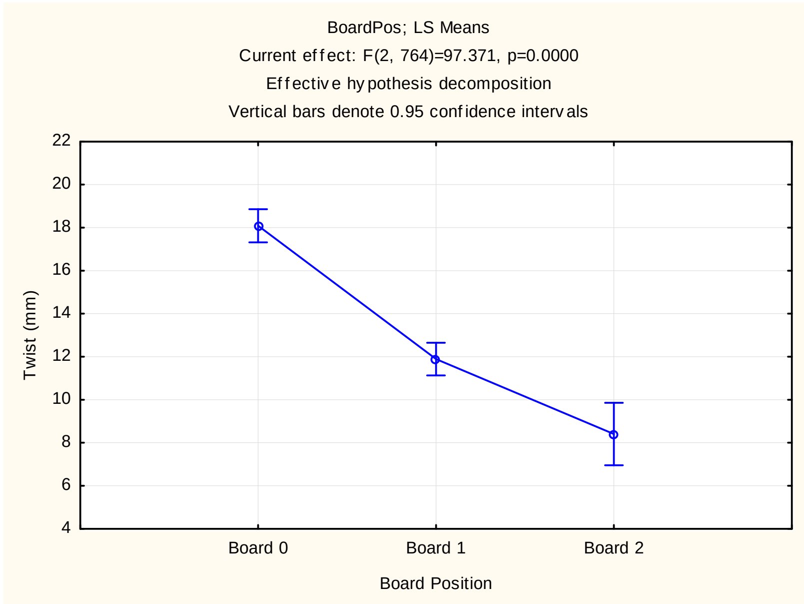

Fig. 7 The means and 95% confidence intervals of twist for boards from the different positions in a log

Density

Density as an individual property is less important for structural timber than strength and stiffness. However, density has a positive correlation with the different strength and stiffness characteristics which are of importance in structural timber and therefore most structural timber codes also require minimum density values for the various structural grades. Also, the withdrawal resistance of some structural joining methods, like nail plates, depends on the density of timber.

The density requirement for structural timber in South Africa is a minimum density of 360 kg/m^3 for grade S5 and 425 kg/m^3 for grade S7 at 12% moisture content (SANS 1783-2 2005). On average the density of the material was sufficient to meet the minimum requirement for S5-grade structural timber. Many boards originating from radial positions further away from the pith in fact met the minimum requirement for S7-grade structural timber.

A three-way analysis of variance indicated that compartment, log position and board position significantly influenced the density (Table 5). Some compartments with too few data points had to be omitted to make the three-way ANOVA possible. The percentage variation explained by each component is also listed in Table 5. Compartment was the most influential component explaining 10.5% of the variation in density. It was interesting to note that density was the only property where compartment was more influential than board position.

	SS	Degrees of freedom	MS	F	p	Variance components (%)
Compartment	118025	12	9835	9.11	0.000000	10.51
Log position	11452	1	11452	10.61	0.001171	1.02
Board position	78505	2	39253	36.38	0.000000	6.99
Compartment*Log position	18886	12	1574	1.46	0.134486	1.68
Compartment*Board position	21056	24	877	0.81	0.722443	1.88
Log position*Board position	1972	2	986	0.91	0.401388	0.18
Compartment*Log position*Board position	20598	24	858	0.80	0.745407	1.83
Error	852483	790	1079			75.91

Table 5. A three-way analysis of variance for density (kg/m^3). Significant factors at the 5% level are shaded. The last column gives the percentage variation that is explained by each component.

Coefficient of determination (R^2) between MOE_{dyn} and MOR

The coefficient of determination of boards from the top log was consistently much smaller than for boards from the bottom log (Table 2). The R^2 value for all the top log boards combined was 0.36 compared to an R^2 value of 0.64 for all the bottom log boards combined (Figure 8). What was very interesting was that the relationship remained weak for top log boards even when only the 1st or 2nd boards were considered individually (R^2 = 0.33 and 0.29). The difference in the MOE_{dyn} vs. MOR coefficient of determination between the 2nd boards of the bottom and top logs (R^2 = 0.59 and 0.29) can possibly be explained by the significant differences in the total knot area and maximum knot areas respectively of these two groups. The significantly larger knots in the top log 2nd boards possibly caused a less predictable MOR value. The reason for the difference in R^2 value for the 1st boards of the top and bottom logs (R^2 = 0.62 and 0.33) was less clear since the knot area values did not differ significantly for these boards.

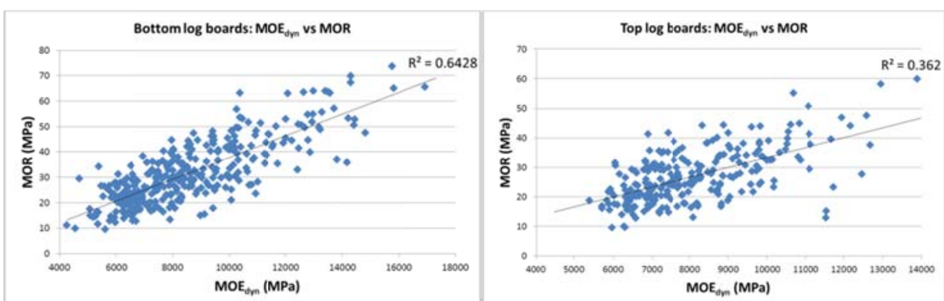

Fig. 8 Scatterplots with linear regression lines of the MOE_{dyn} vs. MOR relationship of boards from the bottom logs (left) and top logs (right)

The coefficient of determination of MOE_{dyn} vs. MOR for pith boards was smaller than for the other boards (R^2 = 0.34 to 0.41) but fell within the expected range (Glos 2004). This relationship was not nearly as poor as the MOE vs. MOR relationship reported by Gaunt (1999) for juvenile radiata pine from New Zealand.

The results indicated that the relationship between MOE_{dyn} and MOR for pith boards and top logs was fairly weak and in cases where these sections of a tree are processed separately, structural grading based on this relationship will be less efficient.

Radial, longitudinal and between-compartment variation in properties

As expected nearly all properties determining the suitability of sawn timber for structural purposes improved with increasing distance from the pith. The only notable exception was the 5th percentile value for MOR which was higher for the pith boards than for the 1st boards (Table 2). This was quite an interesting and unexpected result as even the mean MOR value for the 1st boards was significantly higher than the mean value for pith boards. Board position was by far the most influential component in explaining the variation in MOE_{dyn} and twist (Tables 3 and 4).

Log position had a significant effect on the MOE_{dyn}, MOR and twist although its influence was relatively small compared to board position (Tables 3 and 5). Differences between top and bottom log boards became more pronounced in the 2nd boards where pruning influenced some of the properties of the bottom log boards (Figure 4 and 6). The major difference in top and bottom log boards was the relationship between MOE_{dyn} and MOR. The R^2-values of boards from the top logs were much lower than that of boards from the bottom logs which will result in less efficient structural grading of top log boards (Table 2 and Figure 8).

Compartment had a significant influence on the important properties of MOE_{dyn}, MOR, twist and density. For all of these properties the board position was much more influential than the compartment except for density (Tables 3, 4, and 5) where compartment explained 10.5% of the variance.

Conclusions

Based on the results from this study, the following conclusions are made:

- The mean MOE_{edge} of this young *Pinus patula* resource was far below that required for structural grade timber in South Africa.
- The 5th percentile bending strength (MOR) was much higher and the 5th percentile tensile strength slightly higher than that required for the lowest SA structural grade.
- The mean twist of the sample was higher than allowed for structural timber in South Africa. The mean bow and spring were far below the maximum limit allowed.
- Most of the desirable properties for structural timber were improving for boards further removed from the pith. The only exception was the 5th percentile value for MOR which was higher for the pith boards than for the 1st boards. Board position was by far the most influential component in explaining the variation in MOE_{dyn} and twist.
- Log position had a significant effect on the MOE_{dyn}, MOR and twist. The R^2-value between MOE_{dyn} and MOR of boards from the top logs were much lower than that of boards from the bottom log making the non-destructive prediction of MOR using MOE_{dyn} less efficient for top log boards.
- A negative and significant correlation existed between the mean growth ring widths of the pith boards and the mean MOE_{dyn} values per compartment. In other words when the initial growth of a compartment was slow, the mean MOE_{dyn} value was high.

The results from this study can be used for various purposes but will be especially applicable for processing decision support in structural timber processing organisations. Further studies should focus on the methods available that could possibly improve the stiffness of the young *Pinus patula* resource such as higher planting densities, tree breeding selection strategies, and other silvicultural interventions. Methods to reduce twist in boards from this resource should also receive attention.

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Chapter 5.

Unpublished

The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees

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Abstract

Pinus patula is the most intensively planted conifer in the tropics and sub-tropics. In South Africa *Pinus patula* plantations are the main saw-log resource for structural lumber production. Improved intensive silvicultural practices and tree breeding have resulted in marked increases in the rate of growth. To reap the financial benefits of the faster growth, plantation managers are more and more inclined to reduce rotation ages, which inevitably results in the production of higher proportions of juvenile wood which often yield lumber which does not meet the minimum requirements in stiffness for structural lumber when harvested. The purpose of this study was to develop empirically based models for predicting the flexural properties of the wood produced from relatively young *Pinus patula* trees. Models were based on the properties of standing trees and their effectiveness was evaluated at board, tree and compartment levels. Models of this kind are becoming increasingly important to serve as tools in understanding and managing the effects of shorter rotation ages on the quality of the wood produced. Sample material was obtained from 170 *Pinus patula* trees (16-20 years old at the time of sampling) established in 17 compartments on the Mpumalanga escarpment of South Africa which represented a number of diverse site conditions. A large number of variables which could be obtained non-destructively from the trees while they were still standing were measured. The trees were subsequently felled and 340 logs (2 per tree) extracted from the trees and processed into 1402 boards for further measurements and destructive testing. Multiple regression models were developed which managed to explain 68%, 60% and 95% of the variation in the dynamic modulus of elasticity (MOE) on individual boards, trees and compartments levels respectively. The models developed for modulus of ruptured (MOR) explained 40% and 42% of variability at board and tree level respectively. At compartment level, 80% of the variation in the 5th percentile MOR value could be explained by the model. Sensitivity analyses showed that site index at base age of 10 years, acoustic time-of-flight, wood density and ring width were influential variables in the MOE models. The model developed for predicting MOR at compartment level included site index at base age 10 years, branch angle, branch spacing and ring width as influential variables. The

models indicated that tree slenderness during early growth seems to play a major role in determining the dynamic MOE and MOR of lumber. This is in agreement with Euler's buckling theory and the bending stress theory.

Keywords: modulus of elasticity, modulus of rupture, *Pinus patula,* lumber

1. Introduction

Planted forests are rapidly expanding on a global scale at about 5 million ha per year and currently account for about 7% of the total afforested area worldwide (FAO, 2013). In 1980 there were 18 million ha of planted forests, compared to 187 million ha in 1990 and 264 million ha in 2012 (Carle et al., 2002; FAO, 2013). Carle and Holmgren (2008) estimated that in 2005 globally about two thirds of the industrial timber originated from commercial plantations.

Pinus patula is the most intensively planted conifer in the tropics and sub-tropics. It is estimated that more than one million hectares are planted with this species; about half of that in Africa (Wright, 1994). *Pinus patula* is also planted in the Andean countries of South America with potential to increase the area under this species in the high altitude areas in Brazil (Hodge and Dvorak, 2012). In South Africa it is the most important commercial plantation softwood resource with a total of 338 923 ha planted with *Pinus patula* trees (DAFF, 2009). The Mpumalanga escarpment is the largest saw log growing area in South Africa with *Pinus patula* the main species being planted.

South Africa was one of the first countries to establish plantation forestry on a large scale, starting in the late nineteenth century. By 1960 the forestry area had increased to about 1 million ha (Owen and Van der Zel, 2000). Due to a shortage of suitable land available for afforestation, as well as competition from agriculture and water catchment, the area under forest plantations in South Africa has since stabilised. To meet the country's growing needs for wood this resulted in increased emphases in the forestry and wood processing industries on higher volume production per unit area through improved silvicultural practices and genetic improvement, as well as improved wood product yield and quality.

However, the increased size of the corewood zone, and the bigger proportion of corewood that results when rotation ages are shortened to reap the financial benefits of the faster growth, has become a wood quality factor of growing concern worldwide (Zobel and Sprague, 1998; Cown, 2006; Malan, 2010). Cown (2006) state that "researchers around the world have confirmed that aggressive silvicultural regimes have caused a significant reduction in mechanical properties" of plantation grown pines.

Studies in South Africa have shown sharp reductions in some of the mechanical properties of pine lumber processed from material harvested at a younger age, as trees reach merchantable size much earlier due to faster growth rates (Burdzik, 2004; Dowse and Wessels, 2013; Wessels et al., 2011a). Studies by Dowse and Wessels (2013) have shown that the mean modulus of elasticity (MOE) of plantation-grown softwood lumber harvested before the age of 20 years can be more than 25% below the requirement of the lowest structural lumber grade in South Africa, which will have a significant effect on revenue. While the financial importance of increased volume production of plantations is undisputed, it is increasingly important that forest managers and researchers take into consideration the adverse effects of their actions on end-product quality.

More than 70% of the solid sawn lumber produced in SA is sold as structural or building timber (Crickmay and Associates, 2011), a wood product category which has to comply to very strict strength and stiffness requirements Given the challenges caused by an increasing proportion of juvenile wood in the timber resource, there is a growing need for non-destructive methods, capable of accurately predicting the mechanical properties of the lumber from standing trees

Models to accurately predict mechanical properties can serve a useful role in managing the challenges of fast growing softwood plantations and shorter rotation ages. Tree-level predictions can assist tree breeders to screen and select for superior breeding material (Launay et al*.,* 2002; Lindström et al*.,* 2002; Ivković et al*.,* 2009), while at sawn board and compartment levels, predictions can be used to assist in decisions related to the allocation of trees to different processing facilities, especially where structural lumber is an option (Matheson et al., 2002; Cown, 2006; Wang et al., 2007). Models can also be used to assist in processing production planning (Uusitalo, 1997; Wessels et al., 2006) and to study the effects of site and silviculture factors on the mechanical properties of wood (Wang et al., 2000; Grabianowski et al., 2004; Wang et al., 2005).

The purpose of this study was to develop empirically based prediction models for the flexural lumber properties from standing *Pinus patula* selected from a number of diverse forestry sites on the Mpumalanga escarpment in South Africa. The intention was to evaluate various input variables in these models from data that could be obtained non-destructively from standing trees. This study is, to the authors' best knowledge, the first one of this nature performed on *Pinus patula* and the only one for any species where suitable compartment level models were developed to predict the MOE and MOR of its lumber*.*

2. Background

Structural engineers and other designers of timber constructions use six different strengths and a stiffness value in the design of a structure. Since a piece of lumber can only be destructively tested in one strength mode, the question arises, which of the strength properties are the most important in terms of end-use requirements. In a study by Peterson and Wessels (2011) it has been found that bending strength or modulus of rupture (MOR) and stiffness or modulus of elasticity (MOE) were the two most important design properties for residential roof truss construction in South Africa. Since more than half of all South Africa's sawn lumber is utilized in roof constructions (pers. comm. Roy Southey, Sawmilling South Africa, Feb 2013), the most appropriate evaluation method for lumber destined for structural use will therefore be the bending test from which both the MOE and MOR can be derived.

The characteristic strength and stiffness values used in designing timber structures are determined by testing large numbers of full-sized structural grade lumber members – a process referred to as in-grade testing. In the past these properties have been determined on small defect-free wood specimens but it has been shown that the fracture behaviour in clear wood compared to defect-containing lumber is very different (Madsen, 1992). Although clear-wood testing is more convenient with fewer sources of variation, it seldom gives a realistic indication of the strength and stiffness characteristics of full-sized, defect-containing lumber.

The MOE of wood is a well-researched topic and is known to depend on a number of basic wood properties. Evans and Ilic (2001) found that density alone accounted for 70% of the variation in the MOE of clear *Eucalyptus delegatensis* wood samples while microfibril angle alone accounted for 86% of the variation. The combined effect of these properties accounted for 96% of variation in MOE. Megraw et al*.* (1999) found that density and microfibril angle together explained 93% of variation of MOE in small clear wood samples of *Pinus taeda*. There is also a strong relationship between the acoustic velocity in the longitudinal direction and the microfibril angle of wood. Wang et al*.* (2007)

and Evans and Ilic (2001) reported coefficients of determination (R^2) of 0.855 and 0.86 respectively (for *P. radiata*). For full sized specimens the relationships were much weaker. Dowse (2010) found that the density of full-sized *Pinus patula* lumber explained 30% of the variation in MOE and when knot properties were added, the percentage increased to 36%. Acoustic or vibrational methods performed much better with the defect-containing lumber. For instance, Pellerin and Ross (2002) reported a number of studies where the MOE could be predicted with a coefficient of determination of more than 90%.

The bending strength or MOR of lumber, as with MOE, depends on several wood properties. The results of a number of studies on full-sized lumber have been summarised from Johansson (2003) and Glos (2004) in Table 1. From the fairly low R^2 values it is clear that MOR is a complex property that cannot be predicted easily. Although failures are almost always associated with grain distortion caused by knots, the measurable knot properties such as knot size and distribution did not explain variation in MOR very well. MOE has been found to be the best single property for explaining the variation in MOR. A combination of acoustic, density and knot properties explained up to 80% of the variation in MOR.

Table 1. The range of coefficient of determination values between MOR and other lumber properties on individual boards from various studies (compiled from Johansson, 2003, and Glos, 2004).

Properties	**Coefficient of determination range (R^2)**
Density	0.16 – 0.40
Knot properties	0.15 – 0.35
Annual ring width	0.20 – 0.44
MOE	0.40 – 0.72
Acoustic or vibrational properties	0.30 – 0.55
Knots and density combined	0.38 – 0.60
MOE and knots combined	0.58 – 0.73
Acoustic, knots and density combined	0.55 – 0.80

Many methods have been developed in the past to determine some of the properties listed above from standing trees using non-destructive methods. These methods have been extensively reviewed by Wessels et al. (2011b).

An important aspect to keep in mind when trying to predict the mechanical properties of structural lumber is that the characteristic strength of a grade is determined by the 5th percentile strength value (Figure 1), in other words by results representing the weak portion of the strength distribution curve (Madsen, 1992). It is therefore essential that any property and method used in a predictive study has to be an accurate predictor of the weak portion of the strength distribution curve. For stiffness, however, design codes often use the mean MOE values, necessitating predictions of the full stiffness distribution (i.e. SANS 10163-1, 2003 and CSA O86-01, 2001).

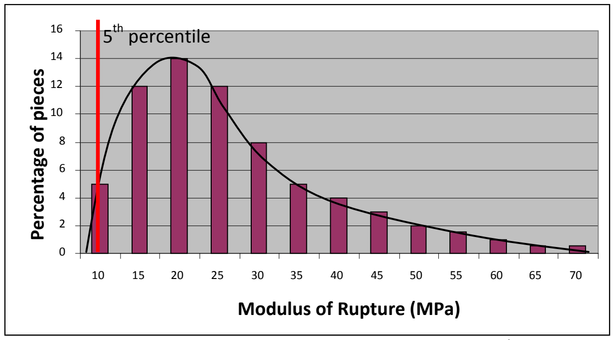

Figure 1. A typical histogram of the MOR of lumber with the 5th percentile value indicated

In South Africa the mean rotation age of pine plantations grown for sawlog production has reduced from 14.1 years in 1983 to 11.3 years in 2003 (Crickmay and Associates, 2004). This suggests a reduction in mean harvesting age from about 28 years in 1983 to about 23 years in 2003 resulting in increased proportions of juvenile wood (or corewood) when harvested.

3. Materials and methods

3.1 Description of the study area and sample compartments

The study area is located along the Mpumalanga escarpment, South Africa, stretching from 23°48'S to 25°49'S and from 30°02'E to 30°59'E. The area is geologically complex with large variation in soil characteristics, altitude, precipitation and temperature. A total of 17 sample compartments were selected across the area. The sample compartments varied in age from 16 to 20 years, situated at altitudes varying from 810 m to 1930 m above sea level, mean annual precipitations varying from 840 mm to 1299 mm and mean annual temperatures which ranged from 13.7 °C to 19.4 °C. Site indices at base age 10 years (SI10) ranged from 9.6 to 19.6 (Table 2). The compartments received the normal commercial management treatments of weeding, thinning and pruning.

The work described in this paper is one of several studies performed on the same experimental material. Previous studies include those reported by Louw and Scholes (2002, 2003 and 2006) on the influence of site factors on nitrogen mineralization in forest soils of the Mpumalanga escarpment area, the development of a method to predict the knotty defect core (Munalula, 2010) and a study which evaluated the structural grading parameters for this particular resource (Dowse and Wessels, 2013). Some results from the mentioned studies were used as inputs in the research described in this paper. A comprehensive description of the environmental variables, geology, soil and productivity of the sites can be viewed in Louw and Scholes (2002, 2003 and 2006).

A total of 126 environmental, soil, leaf analysis, and productivity variables were measured or calculated for each compartment. These variables were also considered for the development of predictive models described in this study. For brevity's sake only variables that were found to contribute significantly to the models are described in the Results section.

Table 2. General data for each sample compartment, the mean diameter at breast height (DBH) and the mean height of the ten sample trees.

Sample compartment	Plantation	Age (yrs)	Mean DBH (cm)	Mean height (m)	Site Index at age 10 (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
A (E66)	Nelshoogte	17	36	20.9	14.3	1061	16.0
B (E28a)	Nelshoogte	19	33.8	21.8	14.5	1036	16.1
C (G21)	Nelshoogte	16	26.2	18.4	15.5	1057	16.1
D (D1)	Uitsoek	17	32.7	22.3	15.7	944	17.4
E (D88)	Uitsoek	17	30.2	18.4	15.3	942	17.3
F (E55a)	Uitsoek	20	32.3	20.1	14.6	1151	13.7
G (E36c)	Uitsoek	19	31.9	23.0	16.8	902	14.0
H (E22)	Uitsoek	17	27.6	20.8	16.5	840	14.2
I (E5)	Berlin	19	36.5	23.8	16.7	1284	16.1
J (E15)	Berlin	19	37.4	23.8	17.6	1082	15.9
K (E35)	Berlin	16	29.1	18.0	16.5	1006	17.2
L (C22)	Blyde	20	34	27.0	18.5	1156	16.1
M (E3)	Morgenzon	17	31.4	20.6	13.5	1015	14.3
N (D74)	Morgenzon	19	26.9	16.4	9.6	997	16.2
O (A1a)	Morgenzon	16	27.8	19.0	13.6	862	15.1
P (D11)	Wilgeboom	18	29.4	22.8	19.6	1242	19.4
R (J20)	Wilgeboom	19	33.4	24.0	16.8	1299	18.5
Mean		**18**	**31.6**	**21.2**	**15.6**	**1052**	**16.1**

3.2 Tree measurements

In each of the 17 sample compartments, a stratified sampling procedure based on tree diameter was followed so that the sample trees represented the productive timber volume available from each compartment. One tree was randomly selected in each compartment from the first quartile (small diameter), two trees from the second quartile, three trees from the third quartile and four trees from the fourth quartile (large diameters), giving a total of ten sample trees per plot, thus 170 trees for the entire investigation.

The Fakopp TreeSonic® microsecond timer was used to calculate the speed of an acoustic longitudinal stress wave at breast height of each of the standing sample trees. This device measured the time-of-flight of a stress wave induced by a hammer tap between two probes, hammered into the outer 10 to 15 mm of the stem one meter apart around breast height. Sound velocity is often used in studies as an indirect indicator of the stiffness of the outer wood in trees. The use of acoustic technology in wood studies has been extensively reviewed by Wang and Ross (2002).

After felling, the height of each tree and the height to the first branch whorl were measured. As all trees had been pruned, branches generally only started at a height of 7m above ground. The number of branch whorls, maximum branch diameter and the branch angle of one randomly selected branch were measured for every two-meter section of the trunk up to a height of 19 meters (Figure 2).

A disc was removed from the stem at the breast height location and later used to perform ring width measurements on the cross-section in order to determine the annual growth rate of each tree (Munalula, 2010). Available pruning records were used to determine the maximum knotty or defect core size of all the logs originating from the pruned section of each tree (Figure 2). For comparative purposes the maximum defect core size of each log was expressed as a percentage of the log diameter.

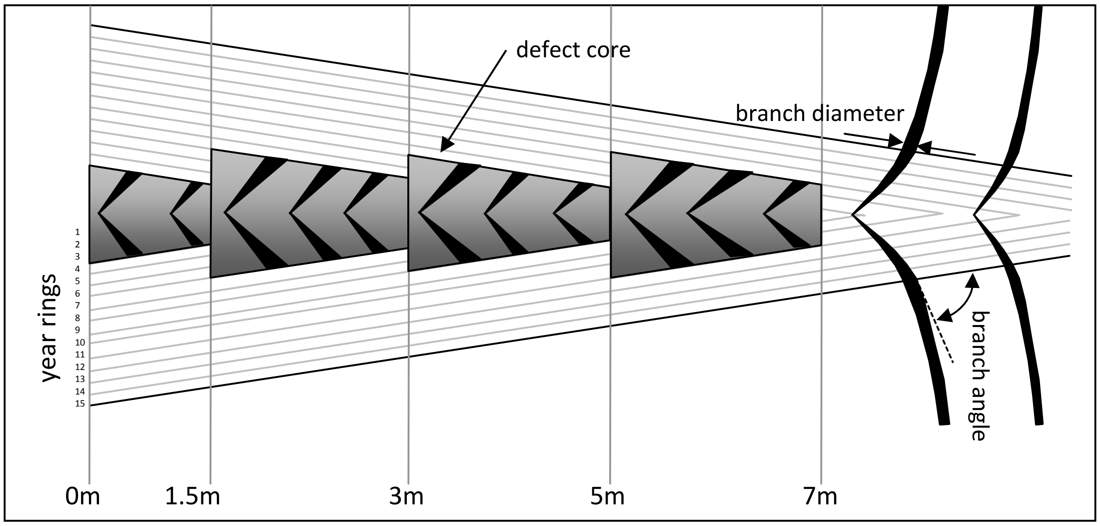

Figure 2. Defect core reconstruction using ring width data and pruning records. Branch properties measured are also shown (adapted from Munalula, 2010).

Two 2.1m long logs were removed from each tree; one from the pruned section of the stem at 2.3m height and one from the unpruned section at 7m height (Figure 3), which yielded 340 sawlogs.

3.3 Board measurements

The logs were processed at a local sawmill into boards of cross-sectional dimensions of 40 x 120 mm, using frame-saws and a cant sawing pattern (Figure 3). Only boards processed from the cant were used for this study since these boards represented the full diameter of each log. As the secondary breakdown saw was fitted with a curve-sawing device, the grain direction of the boards was predominantly parallel to the longitudinal axis of the log. A total of 1402 boards were produced. The boards were kiln dried to a target moisture content of 12%
using a medium temperature schedule.

Boards were numbered based on their position from the pith. Boards containing pith tissue were marked 0, the two boards on the outer side of the pith boards were numbered 1, the next two boards were numbered 2, and so on. Sometimes there was only one pith-containing board in a log and sometimes two pith-containing boards (Figure 3).

After drying board densities were calculated from the mass and dimensional data of each board and corrected for moisture content when necessary. Moisture content was measured with a resistance moisture meter.

The ends of the boards were sanded to improve the visibility of the annual rings. The number of annual rings on each board was counted and numbered from the pith outwards. This data was used to estimate the cambial ages (mean, maximum and minimum) of the wood which comprised each board. The cambial age was based on ring counts from the pith.

Ring widths were measured perpendicularly to the growth ring boundaries from the pith to the bark, using a digital calliper. Measurements were rounded to the nearest 0.1 mm. For each board the minimum, maximum and mean ring widths were calculated.

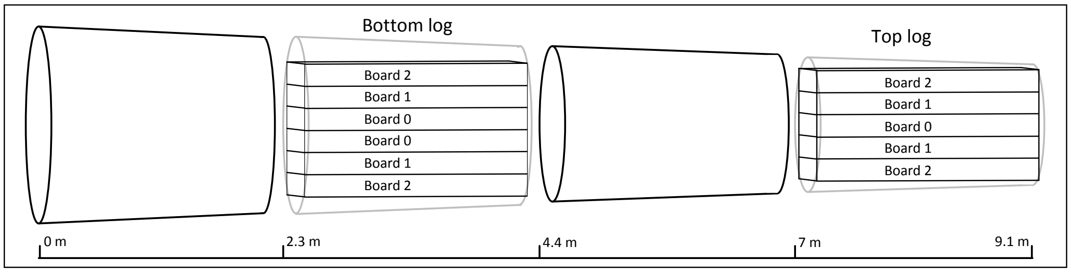

Figure 3. Position of logs and the numbering of boards processed from the cants.

The acoustic resonance frequency of each board was measured using the A-Grader Portable software from Falcon Engineering (http://www.falconengineering.co.nz). The dynamic MOE was determined from the frequency and the density using the following relationship:

$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)2$ ……………………………………………………………………………………………Equation 1

where:

MOE_{dyn}	=	Dynamic modulus of elasticity (MPa),
P	=	Density (kg/m^3),
l	=	Length of the test specimen (m),
f	=	Frequency of the test specimen (Hz).

The sample material was divided into two groups based on board position and a random allocation function. The random function was used to allocate the boards from the same position in a log (i.e. the two number 1 boards) into the two different groups. One group was tested in bending and the other in tension. Tension test results will not be discussed in this paper as most boards failed at the grips which might cause unreliable results. A total of 57 boards had to be discarded due to breakages which occurred during processing as well as due to numbering errors, which reduced the number of boards available for destructive strength testing to 1345.

Bending tests were performed in compliance with South African Bureau of Standards specification SANS 6122 (2008). Of the 699 boards that were subjected to bending tests 674 yielded useful results. Sixteen could not be tested successfully due to excessive warp, while the test results of nine boards had to be discarded due to numbering errors. The MOR and MOE for each board were calculated from the bending tests. The stiffness calculated from this test is referred to as the MOE_{static} as opposed to MOE_{dyn}, which was determined from acoustic measurements.

MOE_{dyn} was taken as the dependent variable in developing predictive models for wood stiffness rather than the static MOE_{static}. MOE_{dyn} was expected to give a better measure of the mean stiffness of a piece of lumber as it reflects the stiffness of the entire board mass, whereas MOE_{static} at best gives a measurement of the local stiffness of the material at the highly stressed areas of a specific test setup. Contrary to $MOE_{static,}$, which was determined on a sub-sample of boards, MOE_{dyn} assessments were performed on all available boards, which made it possible to study the extent and patterns of variation in stiffness among logs, trees and compartments in far more detail.

It should be noted that a number of properties were measured on both boards and/or from discs from the trees. In this study it was deemed preferable to remove the log processing step as a source of error and rather use, where possible, measurements conducted on the boards. For instance, tree ring widths were measured on both discs from trees and on the individual boards after sawmill processing. In this case the tree ring widths measured on the boards were used in developing predictive models. In practice, to obtain the tree ring widths of a standing tree an increment core will have to be obtained, ring widths measured, and individual tree rings will have to be related to boards from different positions in the stem. By using measurables from boards, inaccuracies in relating tree properties at specific positions to board properties are avoided. (Note: In this paper the extraction of increment cores from trees were considered non-destructive although, strictly speaking, it is a minimal invasive method).

3.4 Statistical analysis

Three different sample levels were used in this study viz. individual boards (n=1345), trees (n=170), and compartments (n=17). Some variables were measured on boards, some on trees and some for compartments. Where variables were measured on individual boards, the mean value of a specific variable for all the boards from a tree was used as the tree-level value. Similarly, the mean value of a variable for all the trees in a compartment was used as the compartment-level value.

Simple Pearson correlations were performed between all 143 variables. Most of the variables considered were environmental, soil, leaf analysis, and productivity variables as described in Louw and Scholes (2002, 2003, and 2006). To reduce the number of variables to consider in the multiple regression analysis, a factor analysis was performed and together with the results of the correlation analysis, some variables were removed from the dataset used in the regression analysis. Multiple regression analysis was performed using the best subsets in Statistica (www.statsoft.com) to develop predictive models. Mallow's Cp value was used as the criterion for choosing the best subset of predictor effects. This measure of the quality of fit addresses the issue of overfitting. It tends to be less dependent than the R^2 value on the number of effects in the model, and hence, it tends to find the best subset that includes only the important predictors of the respective dependent variable and thus helps establishing parsimonious models. Ordinary multiple regression was preferred above other methods such as mixed models due to the techniques available to select independent variables from a large number of possibilities. Predictive models were developed for the MOE_{dyn} and MOR of individual boards, trees and compartments. For individual boards the MOE_{dyn} and MOR were used as dependent variables. For trees the mean MOE_{dyn} and mean MOR value of the boards from a tree were used as the dependent variables. For compartments the mean MOE_{dyn} and the 5th percentile MOR value (MOR_{5perc}) of the boards from a compartment were used as the dependent variables.

Sensitivity analyses were performed on the models to determine the influence of varying independent variables, one at a time, on the dependent variables (Pannel, 1997).

4. Results

4.1 Correlation analyses

The variables that appear in the correlation matrix and in some of the predictive models developed shown later on can be seen in Table 3.

Results of Pearson correlation analyses for selected variables are shown in Table 4. Only variables which entered the regression models were included in the table. Correlation coefficients with regard to all three sampling levels, where applicable, are presented in each cell. The values in the first row are the correlation coefficients where boards were the statistical (experimental) unit, the correlation coefficients in the second row are based on tree values and those in the last row are based on compartments. For variables measured at the board level, the mean value for all the boards from a tree was used for tree-level correlations and models. Similarly, for variables measured at the tree level, the mean value for all the trees from a compartment was used for compartment-level correlations and models.

Table 3. Measured and derived variables used in predictive models.

Level	**Variable**	**Unit**	**Description**
Board	MOE_{dyn}	MPa	the dynamic modulus of elasticity for a board
	MOR	MPa	the modulus of rupture for a board
	MOR_{5perc}	MPa	the 5th percentile MOR value for all boards from a compartment
	LogPos	m	the midpoint log height in the tree from which a board was processed
	BoardPos		the radial position of a board with 0 being a pith board (see Figure 3)
	RingWidth	mm	the mean tree ring width in a board
	Density	kg/m^3	the density of a board at 12% moisture content
Tree	*DBH*	cm	the diameter at 1.3m height of a tree
	TOF	µs	the acoustic Fakopp time-of-flight reading for a tree between two probes 1m apart
	BranchDia	mm	the maximum branch diameter in the bottom two meters of the unpruned section of the stem of a tree
	BranchAngle	degrees	the angle between the branch and stem of a randomly selected branch in the bottom two meters of the unpruned section of the stem of a tree
	BranchSpacing		the number of branch whorls in the bottom two meters of the unpruned part of the stem of a tree
	DefCor		the ratio of the maximum defect core diameter to log diameter for a tree
Compartment	*Topheight*	m	the mean height of the four largest diameter trees sampled per compartment
	Age	years	the age of trees in a compartment
	SI10	m	the site index or dominant height at index age 10 of a compartment
	MAP	mm	the mean annual precipitation for a compartment
	MayP	mm	the mean precipitation during May for a compartment
	MAT	degrees C	the mean annual temperature for a compartment
	JulMinT	degrees C	the minimum temperature during July for a compartment
	NK		the ratio of N:K for a compartment determined from a leaf analysis 8 years prior to felling for this study

Table 4. Pearson correlation coefficients between selected board, tree, and compartment variables. The top value in each cell is the board correlation value, the second value tree correlations, and the bottom value compartment correlations. Statistically significant correlations at 0.1, 0.05 and 0.01 probability levels are indicated by the symbols *, ** and *** respectively.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. MOE_{dyn}	1 1 1																				
2. MOR	,76*** ,68*** ,89***	1 1 1																			
3. MOR_{5perc} (comp)	,74***	,77***	1																		
4. LogPos (board)	,13***	,21***		1																	
5. BoardPos (board)	,55***	,37***		,13***	1																
6. RingWidth	-,62*** -,42*** -,71***	-,43*** -,39*** -,57**	 -,70***		-,47***	1 1 1															
7. Density	,67*** ,65*** ,87***	,48*** ,36*** ,80***	 ,55**	,14***	,30***	-,46*** -,40*** -,56**	1 1 1														
8. Topheight		 ,16*		-,06*	,08**	,11*** ,23*** ,52**	-,09***	1 1 1													
9. Age	,11*** ,24***	,11** ,28***			,10***		,09***	,59*** ,52*** ,54**	1 1 1												
10. SI10		,13*** ,24***				,08** ,17*		,70*** ,72*** ,71***	,22*** ,15*	1 1 1											
11. DBH		-,08* -,16*			,30***	,23*** ,49*** ,49**	-,09*** -,15*	,35*** ,32*** ,62***	,29*** ,21** ,45*	,19*** ,20**	1 1 1										
12. TOF	-,18*** -,32*** -,52**	-,20*** -,24*** -,49**					-,19*** -,27*** -,45*	-,19*** -,22** -,47*	-,12***	-,16*** -,19**	,28*** ,30***	1 1 1									
13. BranchSpacing						-,08*** -,17** -,51**		-,40*** -,40*** -,76***	-,16***	-,32*** -,31*** -,54**	-,21*** -,19** -,43*		1 1 1								
14. BranchDia	-,09*** -,19**	-,18*** -,38***			,09***			-,23*** -,25*** -,47*	-,14*** -,16*	-,23*** -,23*** -,43*	,24*** ,24***	,20*** ,22*** ,45*	,06* ,42*	1 1 1							
15. BranchAngle	,06* ,14*				,07**		,11*** ,15*	,18*** ,17** ,46*	,25*** ,24*** ,48**		,21*** ,23***	-,16***		-,25*** -,23*** -,63***	1 1 1						
16. DefCor	-,07**				-,12***	-,08**		-,22*** -,18**	-,19*** -,15*	,06*	-,37*** -,31***	-,11***	,30*** ,34*** ,46*	-,11***		1 1 1					
17. MAP	,14*** ,28*** ,49**	,16*** ,27*** ,55**			,08**		,22*** ,28*** ,63***	,43*** ,41*** ,41*	,53*** ,52*** ,52**	,41*** ,40***	,31*** ,26*** ,46*	-,17*** -,15*	-,22*** -,21**		,06*	-,49*** -,47*** -,47*	1 1 1				
18. MayP	,15*** ,30*** ,53**	,17*** ,28*** ,56**			,07**		,23*** ,30*** ,61***	,41*** ,38***	,56*** ,56*** ,58**	,38*** ,35***	,23*** ,18**	-,19*** -,17**	-,26*** -,25*** -,42*			-,51*** -,49*** -,50**	,95*** ,94*** ,95***	1 1 1			
19. MAT		,08*				,12*** ,23***	,09***	,09***	-,07**	,38*** ,34***		-,23*** -,26*** -,45*		,09***	-,18*** -,18**	-,09***	,50*** ,49*** ,47*	,42*** ,40***	1 1 1		
20. JulMinT	,06*	,09**				,11*** ,19**	,12*** ,15*		-,1***	,29*** ,24***		-,19*** -,18**	-,06*			-,20*** -,19**	,57*** ,55*** ,55**	,43*** ,40*** ,42*	,84*** ,85*** ,84***	1 1 1	
21. NK	,19*** ,30*** ,62***	,14*** ,23*** ,45*	 ,57**			-,20*** -,42*** -,79***	,20*** ,26***	-,38*** -,45***	,336*** ,351***	-,36*** -,45*** -,42*	-,14*** -,17**		,21*** ,25*** ,42*	-,14***	,18*** ,16*	,19*** ,20**		,06*	-,31*** -,29***	-,11***	1 1 1

4.2 Predictive models for MOE_{dyn} and MOR

Multiple regression models were developed to predict the MOE_{dyn} and MOR for individual boards, trees and compartments. The number of input variables was very large and by inspecting the Pearson correlation coefficients and doing a factor analysis, variables which were considered less influential were excluded from the regression analyses.

As mentioned previously, the 5th percentile MOR value of a board grade is used in the design of structures. Since there were not enough boards from individual trees to determine a 5th percentile value the mean MOR value for each tree was used instead. Trees that yielded fewer than 5 boards in total, or fewer than 2 boards per log suitable for testing, were discarded. As a result the data of only 142 trees out of 170 trees could be considered for the tree level analysis.

For each compartment the mean MOE_{dyn} values for all the boards from that compartment were calculated and used as the dependent variable in the predictive model. The 5th percentile MOR value of all the boards from a compartment was used as the other dependent variable (MOR_{5perc}). Due to the limited number of compartments (n=17) a maximum of five independent variables were allowed for the compartment level models to avoid over-parameterisation.

The coefficient of determination (R^2) and the parameters for the models developed are presented in Table 5. Figures 4 to 7 show the predicted vs. observed values for the MOE_{dyn} and MOR_{5perc} models.

Table 5. Parameters and coefficients of determination (R^2) of the predictive models developed for MOE_{dyn} and MOR on individual board, tree and compartment levels. All models were significant at the 0.001 probability level. Parameters marked with *, **, *** were significant at the 0.1, 0.05 and 0.001 probability levels, respectively.

	Board		Tree		Compartment	
	MOE_{dyn}	***MOR***	***MOE_{dyn}***	***MOR***	***MOE_{dyn}***	***MOR_{5perc}***
Coefficient of determination (R^2)	0.682	0.402	0.600	0.421	0.952	0.798
Parameters:						
Intercept	1870.6	5.08	-290.9	8.16	6296.0*	
LogPos		0.72***				
BoardPos	803.4***	2.83***				
RingWidth	-152.4***	-0.69***	-90.2**	-1.04**	-315.4***	-1.69***
Density	24.4***	0.08***	21.4***	0.05**	18.2***	
SI10	145.3***	1.89***	150.3***	1.03***	43.2*	0.64**
TOF	-11.5***	-0.07**	-11.0**		-18.3**	
BranchDia	-12.6***	-0.13***	-11.5**	0.15***		
BranchAngle	-15.1***					0.28***
BranchSpacing						0.90**
DefCor	-2679.5***	-13.26**	-3544.7***	-9.09**		
MayP	-104.8***	-0.49**	-91.5**			
MAT	77.0**		282.2**			
JulMinT			-249.5**			
NK	734.2***		895.1***	2.98**		
Topheight (m)		-1.34***				
Age (years)		1.66**			81.2**	

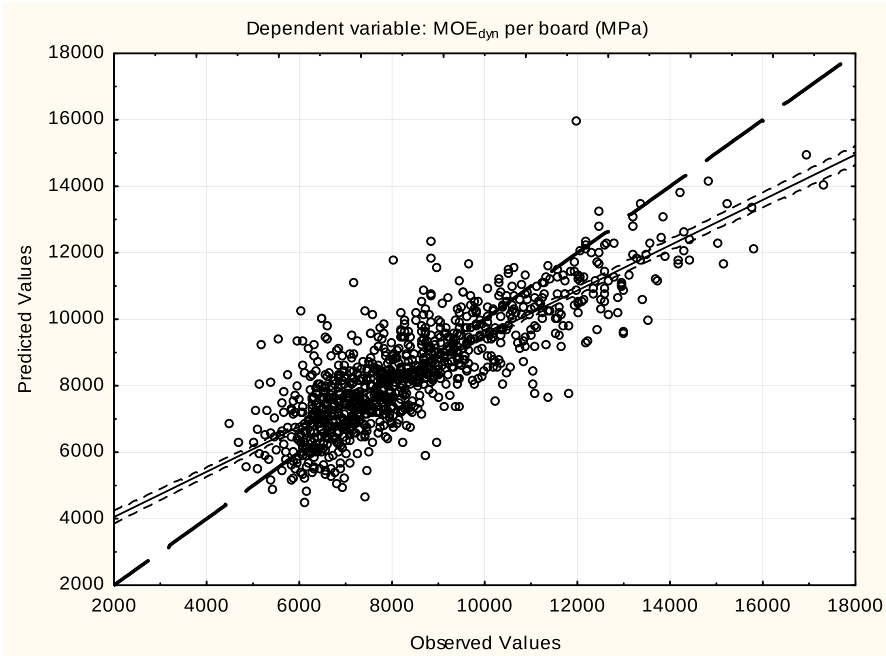

Figure 4. The predicted vs. observed values for the board-level MOE_{dyn} and 95% confidence limits (see model parameters in Table 5). The broken line indicates the 1:1 relationship.

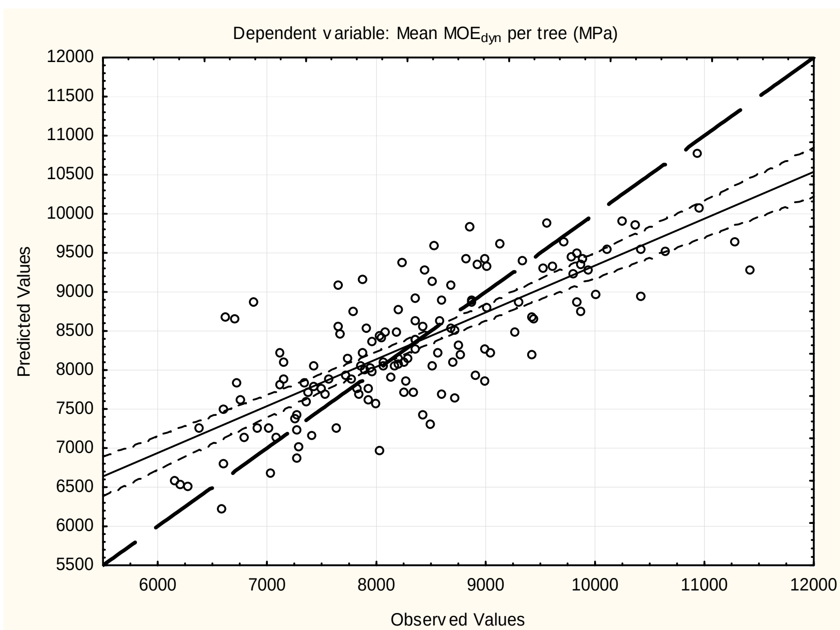

Figure 5. The predicted vs. observed values for the tree-level MOE_{dyn} model and 95% confidence limits (see model parameters in Table 5). The broken line indicates the 1:1 relationship.

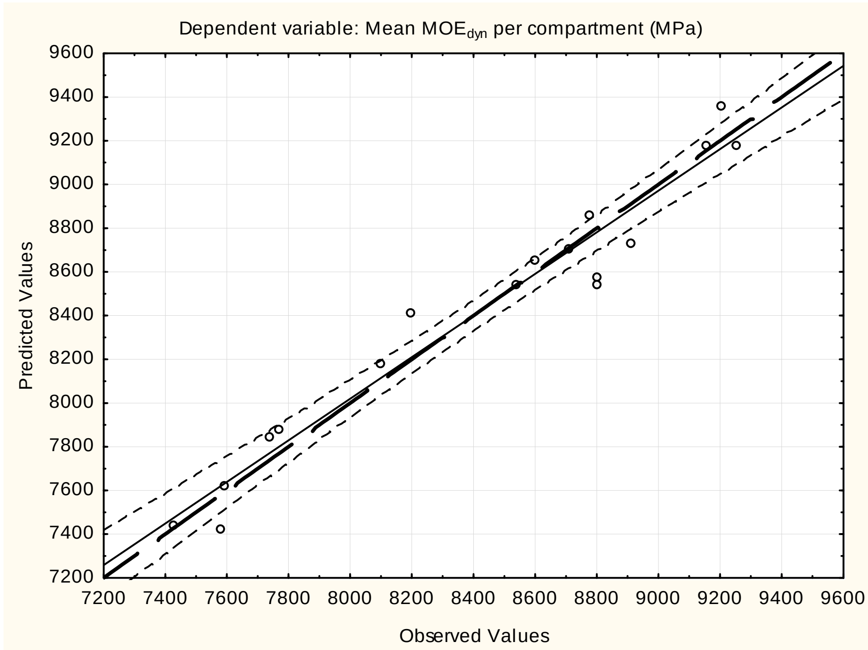

Figure 6. The predicted vs. observed values for the compartment-level MOE_{dyn} and 95% confidence limits (see model parameters in Table 5). The broken line indicates the 1:1 relationship.

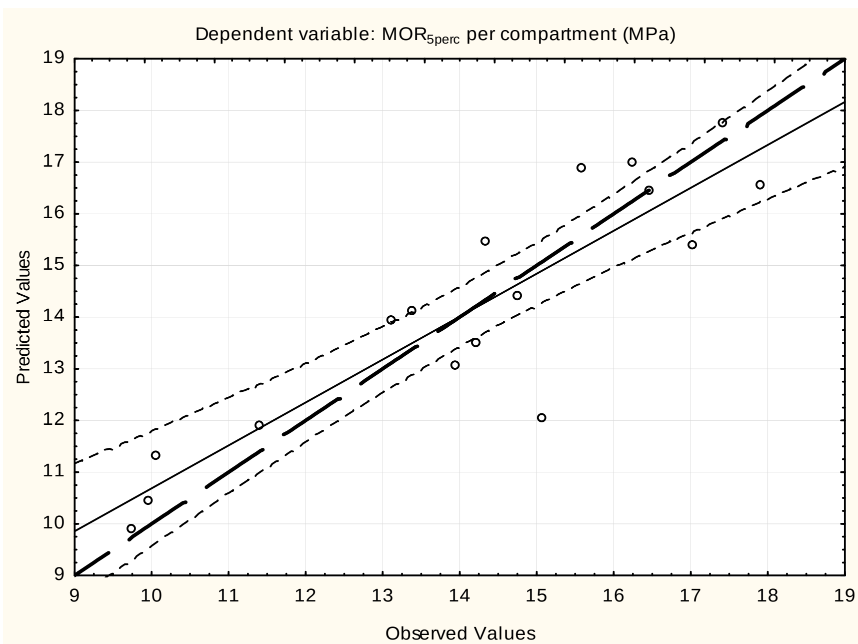

Figure 7. The predicted vs. observed values for the compartment-level MOR_{5perc} model and 95% confidence limits (see model parameters in Table 5). The broken line indicates the 1:1 relationship.

4.3 Sensitivity analyses

Table 6 shows the results of sensitivity analyses performed on the models developed for MOE_{dyn} and *MOR*. For the board and tree-level models each independent variable in the models was varied from the 5th percentile observed value to the 95th percentile observed value. For the compartment-level models the independent variables were varied from the minimum value to the maximum value. The effect of these changes on the dependent variable was expressed as the independent variable's influence (%). The influence is the relative effect that the change in the individual variable has, compared to the total range in MOE_{dyn} and *MOR* values. For example, when *RingWidth* in the board level MOE_{dyn} model was changed from the 5^{th} percentile observed value to the 95^{th} percentile observed value, and all the other parameters were kept constant at their mean observed values, the change in MOE_{dyn} was 13.7% of the total change in MOE_{dyn} possible (Table 6).

Table 6. Results of sensitivity analyses on the predictive models from Table 5. Independent variables of tree and board level models were changed from the 5^{th} to the 95^{th} percentile observed value and for compartment-level models it was changed from the minimum to maximum observed values. The influence (%) is the relative effect that the change in the individual variable has compared to the range in MOE_{dyn} and MOR.

Independent variables	**Influence (%)**					
	Board		**Tree**		**Compartment**	
	MOE_{dyn}	*MOR*	MOE_{dyn}	*MOR*	MOE_{dyn}	MOR_{5perc}
LogPos		4.3%				
BoardPos	12.4%	7.1%				
RingWidth	13.7%	10.2%	4.5%	20.2%	32.2%	28.2%
Density	22.0%	12.2%	15.0%	14.5%	30.0%	
SI10	6.8%	14.5%	12.3%	32.7%	12.5%	30.6%
TOF	4.4%	4.6%	4.6%		15.9%	
BranchDia	4.2%	7.1%	4.1%	21.5%		
BranchAngle	4.1%					20.2%
BranchSpacing						20.9%
DefCor	8.6%	7.0%	12.3%	12.2%		
MayP	8.7%	6.6%	8.0%			
MAT	3.4%		13.0%			
JulMinT			11.2%			
NK	11.7%		14.8%	19.1%		
Topheight		18.1%				
Age		8.4%			9.4%	

5. Discussion

The predictive models developed for MOE_{dyn} had moderate coefficients of determination at sawn board as well as tree level (R^2 = 0.682 and R^2 =0.600 respectively, see Table 5) but a high coefficient of determination at compartment level (R^2 =0.952). Compared to other studies where the modulus of elasticity of lumber at board-level was predicted from standing trees, the R^2–value found in this study was relatively high. For instance, Ikeda and Arima (2000) found an R^2-value of 0.410 in the case of mature Sugi trees, Wagner et al (2003) and Chestnut (2009) found R^2-values of 0.591 and 0.174 respectively in studies on Douglas fir trees and Bier (1985) found an R^2-value of 0.480 on radiata pine trees (all these were board-level predictions).

Tree-level models for predicting MOE and MOR developed by Liu et al. (2007) for 90-100 year-old black spruce trees, using both stand and tree characteristics as inputs, showed R^2-values of 0.65 and

0.68 for MOE and MOR respectively. Huang (2000) developed a tree-level model for loblolly pine and obtained an R^2-value of 0.51 and Launay et al. (2000) found an R^2-value of 0.29 for Douglas fir and larch trees. Most of the studies on lumber did not consider the MOR of the lumber. Bier (1985) obtained R^2-values of between 0.30 and 0.37 predicting the mean and minimum MOR of lumber from *P. radiata* trees. The authors are not aware of studies where an MOE model for lumber was developed at a compartment level.

The high coefficient of determination for the compartment level model for MOE_{dyn} (R^2 = 0.952) was surprising when compared to the board- and tree level models of this and other studies, where the R^2-values were generally lower than 0.7. As this was the first compartment level study of this type of which we are aware of, we cannot compare it with other results. The high R^2-value was probably due to the within-tree and within-compartment variability in properties that get averaged for all the boards from a compartment. Similarly, individual processing decisions which influenced, for instance, the position of knots within a board will also largely be cancelled at a compartment level due to this averaging effect.

Although a significant correlation exists between the values of both the board and tree level MOE_{dyn} models, it deviates substantially from the 1:1 relationship (Figures 4 and 5). This is an indication of a strong tendency to over-predict and under-predict at low and high MOE_{dyn} values respectively.

In the multiple regression models for MOE_{dyn}, the independent variables *Density*, *RingWidth*, *SI10*, and *TOF* appear in the models at all three sampling levels (Table 5). *Density* was the best single independent variable for predicting MOE_{dyn} with a Pearson correlation of r = 0.67 for boards, r = 0.65 for trees and r = 0.87 for compartments (Table 4). For boards, the correlation value corresponds roughly to those found in various structural grading studies reviewed extensively by Johansson (2003). The sensitivity analysis of the MOE_{dyn} models showed that *Density* was the most influential parameter at board -and tree level and the second most influential at the compartment level (Table 6).

Density has long been considered as one of the most important wood properties, if not the most important, in terms of its effect on the quality of solid wood products. For instance, in their extensive review Zobel and Van Buijtenen (1989) concluded “therefore, specific gravity largely determines the value and utility of wood and overshadows the importance of other wood properties”. This view has later been challenged by many authors i.e. Cherry et al. (2008) who questioned whether tree breeders should select solely for wood density because (i) the time-of-flight or acoustic velocity is a better predictor of stiffness than density, (ii) wood density has a negative correlation with growth, and (iii) density is expensive to measure on increment cores. Cave and Walker (1994) argued that only microfibril angle, and not density, can explain the large increase of stiffness over the first 30 years of growth of fast-grown plantation softwoods. Since microfibril angle was not measured in this study it was not possible to assess its influence on wood stiffness (or MOE) relative to that of density.

In the case of all three model levels, acoustic assessments (*TOF*) carried out on the outerwood of the standing trees were much less influential than *Density*. This is largely due to the fact that velocity assessments on standing trees only serve as a measure of the outerwood stiffness of the tree stem. The lesser influence of *TOF* was confirmed by the results of the sensitivity analyses on the MOE_{dyn} models, which showed that the influence of *TOF* was very small at the board and tree level (<5%) and only moderately influential at compartment level (Table 6).

RingWidth showed an inverse relationship with MOE_{dyn} with correlations of -0.62 at board level, 0.42 at tree level and -0.71 at compartment level (Table 4), suggesting that MOE_{dyn} decreases with increasing growth rate. At compartment level *RingWidth* was the most influential variable (Table 6), followed by *Density*. At tree level the influence of *RingWidth* in the model was noticeably lower. As with *Density, RingWidth* can be measured on increment cores from standing trees. It is correlated to the *DBH* of trees, although it was slightly surprising to see the moderate to low correlation of 0.49 between *RingWidth* and *DBH* at a tree level. The sum of all tree ring widths at a particular height level in a stem will in fact be the underbark diameter of the stem at that point. The poor correlation might be due to the fact that some tree rings occur in up to in as many as three boards from a log while others, such as the outer rings, might not be present in any of the boards. *RingWidth* will thus be weighted towards the younger year rings present in several boards. Other causes for the weak correlation might include the fact that the compartments were of slightly different ages and also that boards were recovered from logs from two different heights in a tree.

There were moderate and significant negative correlations between *Density* and *RingWidth* at all three levels (Table 4). In conifers large ring widths are often associated with smaller latewood percentage and subsequently a lower density. However, since *RingWidth* and *Density* both appear in the models it clearly suggests that the effect of ring width on MOE_{dyn} is not purely due to its effect on density.

It also needs to be emphasized that smaller ring widths ensure that older, more mature rings will be present in boards cut at or close to the pith. Since microfibril angles usually decreases sharply from the pith outwards, and density increases, such boards will be characterised by smaller microfibril angles and higher density (Cave and Walker, 1994) and boards will thus tend to be stiffer. The ring width was also related to tree shape, which may affect mechanical properties. The role of tree shape is discussed later.

The site index at year 10 (*SI10*) consistently appears in all the models for both MOE_{dyn} and MOR. This suggests an indirect effect of tree height on MOE and MOR, which can be explained in terms of the resistance of trees to buckling and bending failure, as illustrated in Figure 8.

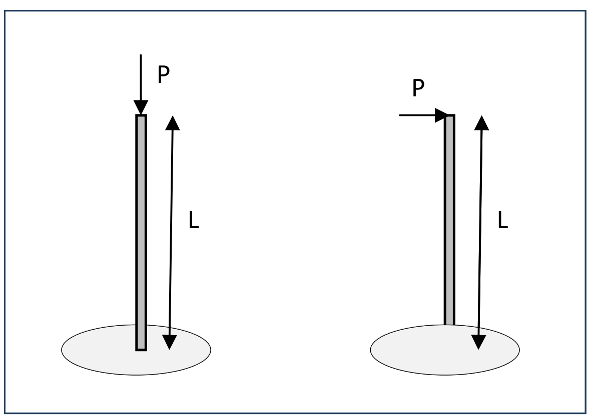

Figure 8. Basic models for a tree loaded by self-weight (left) and wind-load (right).

A tree loaded by its own mass behaves in a similar way as a rod, fixed at one end, under compressive loading (Figure 8). Using the Euler formula for buckling of a rod fixed at one end, the MOE required to withstand buckling failure yields Equation 2 (derived from Euler formula, Hibbeler, 2005):

$$MOE = \frac{16L^2P}{\pi^3r^4} \quad \text{.......Equation 2}$$

where *L* is the length of the rod (m), *P* is the compressive load on the rod (N), and *r* is the radius of the rod (m).

A tree under wind loading can be modelled as a cantilevered rod subjected to a point load (Figure 8). Basic statics theory using the bending stress formula shows that the rod requires the following bending strength or MOR to avoid a bending failure (derived from bending stress formula, Hibbeler, 2005):

$$MOR = \frac{4PL}{\pi r^3}$$ ………………………………………………………………………………………….….Equation 3

From the Euler formula it is clear that the ratio L^2/r^4 determines the MOE required for buckling resistance. The bending stress formula shows that the L/r^3-ratio determines the MOR required to withstand wind load. Trees with increased slenderness (i.e. trees that are tall in relation to their diameter) therefore require wood that's higher in MOE and MOR in order to increase their resistance to buckling under its own weight or breakage due to excessive wind loads. The radius or diameter, which is to the power four and three respectively in the two formulas, is also relatively more influential than the height of the tree. A positive correlation between tree slenderness and MOE has been found in several studies on other species (i.e. Lasserre et al., 2005; Watt et al., 2006; Roth et al., 2007; Lasserre et al. 2009).

In this study stem slenderness at felling age was very weakly correlated with MOE_{dyn}, and was therefore not included in any of the models. However, both *RingWidth*, which is related to the diameter of a tree and *SI10*, which is related to tree height, appear in all the models for MOE_{dyn} and MOR. In fact, these variables appear in all models, stressing the important influence they both have on wood strength and stiffness. As *RingWidth* has a negative parameter value in the models and *SI10* positive parameters, these two variables will (combined) function similar to a slenderness ratio in the models. The big difference with the slenderness ratio at felling age is the fact that *SI10* was the dominant height at age 10, while *RingWidth* is weighted towards growth during the earlier years. It appears as if the inclusion and influence of *RingWidth* and *SI10* in the models for MOE_{dyn} and MOR might, at least partially, due to its effect on stem form or slenderness during earlier growth in the trees. As one would expect from the Euler formula and the bending stress formula, *RingWidth*, which is related to radius, was more influential in the models than *SI10*, which is related to length (Table 6).

Johansson (2003) has found in destructive bending and tension tests, that failure was almost exclusively caused by knots. In this study failure was also usually initiated around knots. In spite of the marked influence of knots on MOR, the correlations between MOR and MOR_{5perc} with branching variables such as *BranchDia, BranchAngle, BranchSpacing* and *DefCor* were either not statistically significant or weakly significant (Table 4). However, branch variables nevertheless appeared in a number of models. *DefCor* was present in all the board and tree-level models. *BranchAngle* and *BranchSpacing* were present in the compartment level MOR_{5perc} model where the sensitivity study shows that together it accounts for about 41% influence in the model (Table 6). It was somewhat surprising that *BranchDia* was not included in the latter model as it appeared in all the other MOR models and will obviously be related to knot size. At a compartment level it means that the visible branch diameters at the bottom 2m of the crown did not add to the MOR_{5perc} model where *BranchAngle* and *BranchSpacing* were already included.

There are a number of possible reasons why branch characteristics were less prominent in the board and tree-level models than expected. In the first place the influence of a knot on the bending strength of a board is strongly dependent on the location of the knot. For instance, the effect of knots situated at or near high-stressed areas, such as at the bottom edge and close to the centre (lengthwise) of a board, is known to be far more pronounced on the bending strength of a board than knots situated elsewhere in the board. As knot location was a random variable it might dilute the effect of the measured branch characteristics. Since the bottom sections of the trees were pruned, measurement of branching characteristics could only be performed on the second logs which represented the 7-9m height section of the trees. The branching characteristics of the bottom log were therefore not directly reflected by any of the variables except for *DefCor*.

As expected, branching characteristics were not very influential in the MOE_{dyn} models where knots play a relatively less important role.

The ratio of nitrogen to potassium (NK), which was determined for each stand by leaf analysis eight years prior to sampling for this study, appears in a number of models, and has a moderate influence on MOE_{dyn} and MOR as suggested by the outcome of the sensitivity analysis. This variable was also found to correlate positively with MOE_{dyn} and MOR at board, tree and compartment levels (Table 4).

Nitrogen is required for tree growth as it is a constituent of proteins, nucleic acids and several other important substances, while potassium is essential for cell division and development. It is very mobile and soluble, principally being used in young tissues (Ache et al., 2010; Barrelet et al., 2006). The fact that the *NK* parameter was positive in all the models may suggest that trees grown in compartments characterised by a combination of high nitrogen and low potassium levels tend to produce wood which has higher MOE_{dyn} and MOR.

Louw and Scholes (2003), in a study using the same foliar data, concluded that too little N might be a growth limiting nutrient on these sites and age classes for *Pinus patula.* They observed large variation in the different foliar element concentrations between seasons. Higher concentrations of N were found in the needles during the active growth season, while higher concentrations of K were observed during the dormant season.

Barrelet et al. (2006), analysing seasonal profiles of K in Norway spruce wood, found that K seems to accumulate mainly in the latewood, in other words, mainly during dormant seasonal growth. Ache et al. (2010), in a review of the effect of potassium on wood formation in poplar, concluded that potassium peaks in the cambial region during the active growth period of trees where it is essential for cell division and elongation.

In this study, it can be argued that if the effect of *NK* on wood formation was purely a function of the rate of growth, it would not have added to the MOE_{dyn} and MOR models where *RingWidth* was already included. Due to the strong seasonal variation that exists for especially K in different parts of trees, it can be hypothesized, that the *NK* ratio might be related to the earlywood to latewood formation switch in the wood. This effect possibly explains why both *NK* and *RingWidth* significantly contributed to the models.

Earlywood and latewood were not assessed quantitatively in this study but a visual inspection/assessment and comparison of discs from the compartment with the highest *NK* ratio versus the compartment with the lowest *NK* ratio was done. The annual rings of the discs taken from the compartment characterised by a high *NK* ratio (compartment F) clearly exhibited larger latewood percentages than those from the low *NK* compartment (compartment L). Given that latewood has higher stiffness than earlywood (Watt et al. 2006), the effect would be a higher overall stiffness of the wood, which would support our hypothesis. A more detailed study would be required to thoroughly test this hypothesis.

Apart from the insight gained by developing models for the flexural properties of *Pinus patula* grown in South Africa, the models itself have practical significance. The tree-level models might be useful in tree improvement programmes for selecting trees with improved strength and stiffness. Experience in industry, supported by recent studies by Dowse and Wessels (2013), have shown that low MOE of sawn lumber is becoming more and more problematic in South African structural timber. The high predictive power shown by the compartment level model, which explained 95% of variability in MOE_{dyn}, proved that this model could be extremely useful in practice, as it would enable the identification of compartments that are expected to yield a significant proportion of structural grade lumber in their outputs prior to harvesting. Compartments that do not fall into this category can be earmarked either for other purposes, such as industrial or appearance grade lumber, where strength and stiffness are of less importance, or the decision can be made to allow the compartments to grow older in order to increase the proportion of lumber suitable for structural purposes at final harvest.

The relatively strong influence of tree slenderness during early growth might provide an ideal opportunity to improve wood stiffness during juvenile growth through silviculture of our current genetically advanced pines. For instance, planting at closer spacing will result in the development of more slender and less exposed trees, producing wood that might be of higher stiffness. This tendency has already been confirmed by studies on other species (Lasserre et al., 2005; Watt et al., 2006; Roth et al., 2007; Lasserre et al. 2009).

Further studies involving samples taken from suitable spacing trials, are therefore strongly recommended, as positive results will provide a relatively simple, easy-to-apply, silvicultural technique, capable of enhancing the formation of corewood with increased stiffness. Finding a short-term solution towards increased corewood stiffness is of utmost importance, as selective breeding for increased corewood stiffness in saw-timber, which is currently actively pursued in many breeding programmes in South Africa, has quite a more long-term horizon.

6. Conclusions

It was possible to develop multiple regression models to predict MOE_{dyn} and MOR of defect-containing lumber at a board, tree and compartment level for plantation-grown *Pinus patula* from the Mpumalanga escarpment, South Africa. The models developed were capable of explaining 68%, 60% and 95% of the variability in MOE_{dyn} at individual board, tree and compartment level respectively. The best models developed explained 40% and 42% of variability in MOR at a board and tree level respectively. At compartment level the best model explained 80% of the variability in MOR_{5perc}.

Results of sensitivity analyses showed that site index at base age of 10 years, acoustic time-of-flight, wood density and ring width were influential variables in the MOE_{dyn} models. In the MOR_{5perc} model at compartment level site index at base age 10 years, branch angle, branch spacing and ring width were influential variables.

The models developed also suggest that tree slenderness during early growth may play an important role in determining the MOE_{dyn} and MOR of boards originating from the corewood zone, which is consistent with the Euler buckling and the bending stress theories.

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Chapter 6.

Unpublished

The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber

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Abstract
Reduction in the rotation ages of softwood saw log plantations in South Africa is causing increased proportions of low stiffness sawn lumber at final harvest. It has been shown for some species that the microfibril angle (MFA) of the S2 layer of tracheids is strongly related to the modulus of elasticity (MOE) of wood, even more so than wood density, especially in wood formed during juvenile growth. The objectives of this study were to describe the variation in MFA in young *Pinus patula* trees and to determine the relationship between MFA and the dynamic MOE of sawn *Pinus patula* lumber. Thirty 16-20 year old trees from six compartments from the Mpumalanga escarpment were processed into discs and lumber. MFA, density and ring width were measured at two height levels using Silviscan 3. The average annual ring MFA varied between 7^{o} and 29^{o}; the pattern of variation depending mainly on height level and the ring number from the pith. The MFA in *P. patula* followed the same within-tree variation trends as in New Zealand-grown *Pinus radiata* but the average MFA was lower in absolute terms and differences between height levels were less pronounced. MFA and density exhibited highly significant Pearson correlations of 0.73 and 0.70 respectively with board dynamic MOE. A multiple regression model, which included MFA, density and ring width, explained 71% of the variation in the dynamic MOE of boards. A sensitivity analysis on the model showed that MFA and density had approximately similar influences on predicting the dynamic MOE of *Pinus patula* boards.

Introduction
Approximately 70% of the sawn timber produced in South Africa is sold as building or structural grade lumber (Crickmay and Associates 2011) and is mainly used in roof truss manufacture. For softwood sawmill processors it is therefore important that a high percentage of the lumber produced conforms to the structural grade requirements. Stiffness and bending strength are the two most important mechanical properties in lumber used for residential roof truss constructions in South Africa (Petersen and Wessels, 2011). Stiffness or the modulus of elasticity (MOE) determine

the resistance to deflection when subjected to bending stress as well as the compressive load that slender members can withstand.

As a result of accelerated growth due to the effects of tree breeding and improved silvicultural practices, the mean harvesting age of trees for sawlog production in South African dropped from 14.1 years in 1983 to 11.3 years in 2003 (Crickmay and Associates, 2004). This suggests a mean harvesting age reduction from about 28 years in 1983 to about 23 years in 2003. The younger harvesting ages resulted in increased proportions of juvenile wood and, as a result, a significant reduction in average MOE of structural lumber, as well as increased proportions of lumber not conforming to the minimum strength and stiffness requirements for structural lumber (Burdzik, 2004; Wessels et al. 2011; Dowse and Wessels, 2013).

In South Africa *Pinus patula* is the most important commercial plantation softwood resource with a total of 338 923 ha planted with this species (DAFF, 2009). The Mpumalanga escarpment is the largest saw log growing area in South Africa with *Pinus patula* the main species being planted. Studies by Dowse and Wessels (2013) and Wessels et al (In press) showed that the mean lumber stiffness of 16-20 year-old *Pinus patula* from the Mpumalanga escarpment was about 25% lower than required for the lowest SANS structural grade.

Many studies emphasized the influence of microfibril angle (MFA) of the S2 layer of tracheids on the MOE of wood (i.e. Cave 1968 and 1969; Cave and Walker, 1994; Megraw et al 1999; Evans and Ilic, 2001; Downes et al, 2002; Evans and Kibblewhite 2002). Cave and Walker (1994) argued that microfibril angle is the only property that can explain the large variation in MOE in *Pinus radiata* from the pith outwards and that MFA "is a principal predictor of timber quality, with density behaving as an auxiliary variable". Most studies were performed on small clear wood specimens but only a few of these studies attempted to relate average MFA to the stiffness of sawn lumber (i.e. Downes et al, 2002; Vikram et al, 2011).

In species such as *Pinus radiata* and *Pinus taeda* the variation in MFA has been studied extensively and is well understood (Donaldson 1992 and 1996; Cown et al, 1999; Megraw et al, 1999; Xu and Walker 2004; Burdon et al, 2004; Isik et al, 2008). In *Pinus radiata* the general trend of variation in MFA is a rapid decrease from the pith up to ring 10, followed by a transition phase, and then little change after ring 20 (Figure 1). MFA decreases from the base to the upper parts of the stem. Similar trends were found in *Pinus taeda* (Burdon et al, 2004; Megraw 1985; Megraw et al 1998 and 1999).

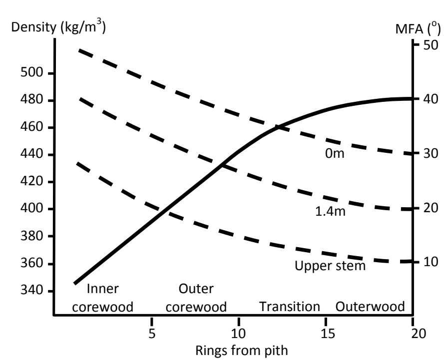

Figure 1. Typical variation of density and microfibril angle in *Pinus radiata* (adapted from Burdon et al, 2004). The broken lines indicate MFA and the solid line density.

Despite the importance of MOE, and its known close relationship with MFA, very little attention has been given to the within and between-tree differences in this property in the South African softwood industry. The only study conducted to date in South Africa involved the use of near infrared spectroscopy technology (Zbonak and Bush, 2006). In this study calibration models were developed to predict the MFA at breast-height in 14-year old *Pinus patula* trees from KwaZulu-Natal, but no attempt was made to describe the variability along the radius or along the longitudinal axis of the tree, or to relate MFA to the MOE of the wood.

The purpose of this study was twofold: Firstly, to examine the variation in MFA in different *Pinus patula* growth sites radially at different heights and secondly, to determine the relationship between MFA and the MOE of sawn *Pinus patula* lumber.

Materials and methods

Sample trees were selected from six compartments along the Mpumalanga escarpment, South Africa. Details of the sites sampled are given in Table 1. The plots received the normal commercial management treatments of weeding, thinning and pruning.

A stratified sampling procedure in terms of tree diameters was followed so that the sample trees represented the productive timber volume available from the compartments. Ten trees were selected from each compartment. One tree was randomly selected from the first quartile (small diameter), two trees from the second quartile, three trees from the third quartile and four trees from the fourth quartile (large diameters). These sample trees were also used by other researchers for previous studies related to strength and stiffness variation, structural grading and pulping properties (Kipuputwa et al, 2010; Dowse and Wessels, 2013; Wessels et al, In press).
Five of the ten trees were randomly selected for the purposes of this study.

Table 1. Sample sites details and site means.

Sample plot identification	Plantation	Age (yrs)	Mean DBH (cm)	Mean height (m)	Site Index at age 10 (m)	Mean annual precipitation (mm)	Mean annual temperature (°C)
A (E66)	Nelshoogte	17	36.0	20.5	14.3	1061	16.0
F (E55a)	Uitsoek	20	34.8	20.9	14.6	1151	13.7
G (E36c)	Uitsoek	19	32.0	23.1	16.8	902	14.0
K (E35)	Berlin	16	30.2	18.0	16.5	1006	17.2
N (D74)	Morgenzon	19	24.6	16.6	9.6	997	16.2
R (J20)	Wilgeboom	19	33.4	23.7	16.8	1299	18.5

From each tree sample discs were removed at breast height (1.3m) and at 6m height levels (Figure 2). A saw log of 2.2m in length was removed between the two discs. All saw logs were processed into boards of 40x120mm (green dimensions) and kiln dried to a target moisture content of 12%.

The static MOE on the flat side of each board (MOE_{flat}) was determined according to SANS 10149 (2002). The acoustic resonance frequency of each board was measured using the A-Grader Portable software from Falcon Engineering. This value was used to calculate the dynamic MOE (MOE_{dyn}) for each board:

$$MOE_{dyn} = \rho \cdot (2 \cdot l \cdot f)2$$

where:

- MOE_{dyn} Dynamic modulus of elasticity, in MPa;
- ρ Density of the test specimen at the moisture content at the time of testing, in kg/m^3;
- l Length of the test specimen in meters to the closest mm; and
- f Resonance frequency of the test specimen, in Hertz.

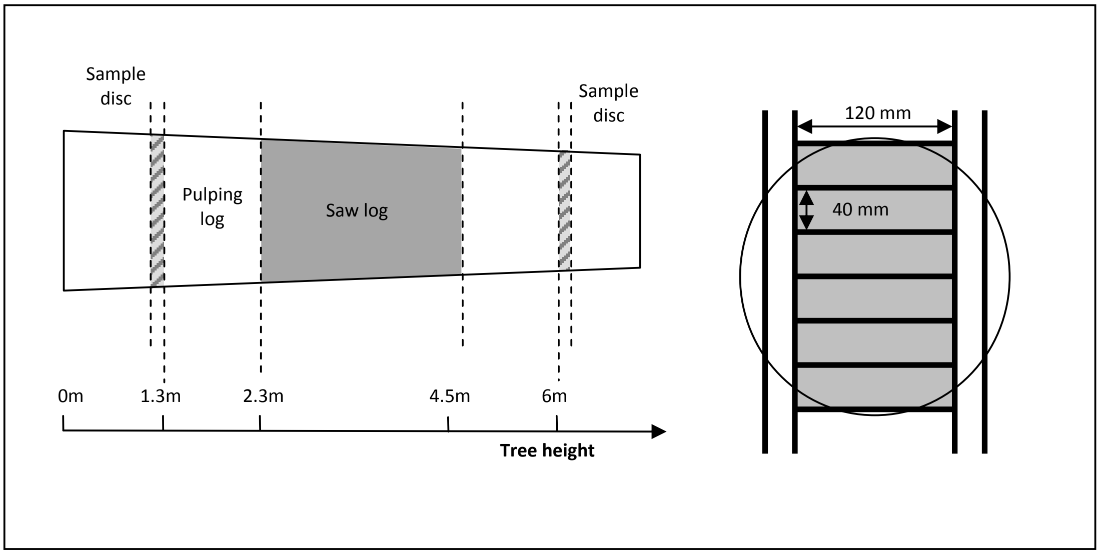

Figure 2. Sample discs, saw log position and the sawing pattern used.

MFA and wood density measurements were conducted on radial strips taken from both the breast-height and 6m discs, using Silviscan 3 (Evans et al, 1999), at resolutions of 2mm and 0.025mm respectively. The MFA and density values were recorded on an annual ring basis using the radial density profile to demarcate different year rings.

Year rings on both ends of each of the boards were dated by reconstructing individual logs and counting the rings from the outside where the barkside surface layer was still visible on the boards. If the stem surface was not visible the ring width patterns from the Silviscan output was used to date individual rings on board ends.

The MFA and density of specific rings were determined as the mean from the two discs. For every board a mean density ($Density_{SS}$) and mean MFA was calculated based on the year rings present in the board. A mean ring width ($RingWidth_{SS}$) was calculated for each board from the Silviscan ring width data of both heights. Mean ring age per board (RingAge) was calculated based on the age of tree rings on both ends of each board. The ring age started at one for the outer ring next to the bark and increased towards the pith.

A mixed model repeated measures ANOVA was performed using Statistica software (www.statsoft.com) to test the statistical significance of the effect of compartment, ring-age and height as main factors, and their interactions, on MFA and density. Multiple regression models were developed to predict individual board MOE_{dyn} from the MFA, wood density and ring width. Stepwise forward, backward and best subsets selection criteria were used to identify those factors that contributed significantly to the models. Sensitivity analyses were performed on the model to determine the relative influence of varying the independent variables, one at a time, on MOE_{dyn} (Pannel, 1997).

Results

In the mixed model repeated measures ANOVA, trees were used as a random effect and the other factors as fixed effects. Results for the ANOVA on MFA showed that there was a significant three-way interaction between compartment, height and rings from the pith (Table 2). Due to the complexity involved only the two-way interactions were interpreted. There was a highly significant interaction between rings and height and a moderately significant interaction between compartment and rings from the pith. The variation in MFA per year ring from the pith and for each height level is illustrated in Figure 3. Take note that only rings 0 to 11 were considered in the ANOVA as some disks at 6m height had 11 year rings only.

Density per year ring was significantly influenced by all the two-way interactions (Table 2). Figure 4 shows the variation in density as a function of year rings and height.

Table 2. ANOVA table for MFA and density of the year rings with compartment, height and rings from pith as factors.

Source of variation			**MFA**		**Density**	
	Numerator DF	Denominator DF	F	p	F	p
Compartment	5	24	1.9079	0.130341	4.24746	0.006586
Height	1	24	19.8627	0.000165	28.86990	0.000016
Rings from pith	11	264	249.4173	0.000000	81.70313	0.000000
Compartment*Height	5	24	0.1922	0.962580	3.26880	0.021636
Compartment*Rings from pith	55	264	1.5550	0.012291	5.27747	0.000000
Height*Rings from pith	11	258	5.0686	0.000000	2.36930	0.008361
Compartment*Height*Rings from pith	55	258	1.6693	0.004488	1.28312	0.103536

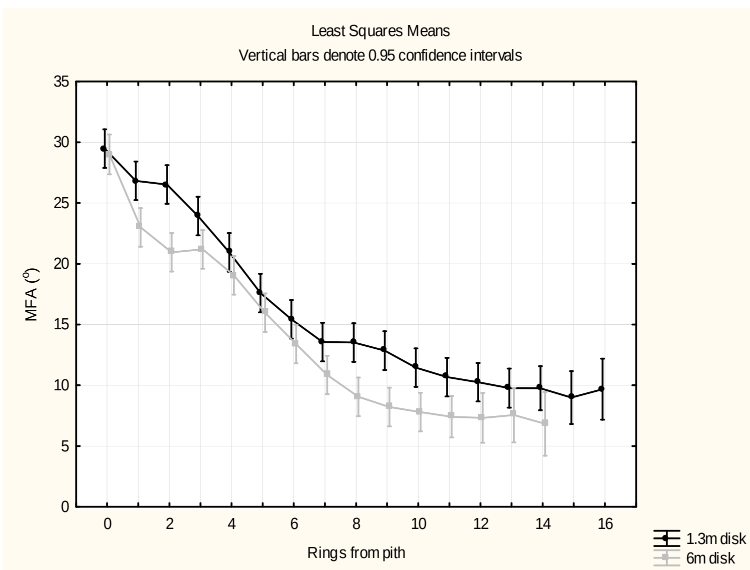

Figure 3. Variation in MFA at different heights and rings from the pith.

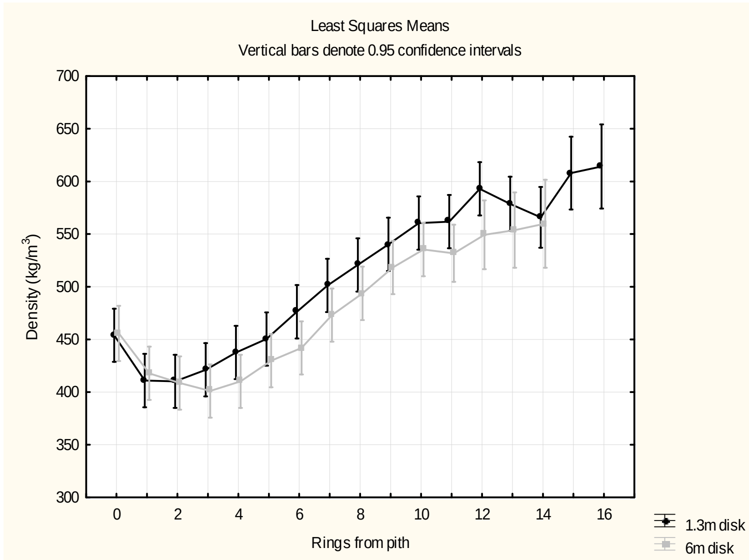

Figure 4. Variation in density at different heights and rings from the pith.

Pearson correlations between the various properties measured and calculated for individual boards are presented in Table 3. A multiple regression model was developed for MOE_{dyn} using the calculated board properties from Silviscan measurements as inputs. MFA and $Density_{SS}$ were highly significant ($p<0.001$) and $RingWidth_{SS}$ was a significant parameter ($p<0.05$) – see Table 4. The model could explain 71% of variation in MOE_{dyn}. A graph showing the observed vs. predicted values is shown in Figure 5. The model slightly under-predicts for high MOE_{dyn} values and over-predicts for low MOE_{dyn} values.

A sensitivity analysis was performed on the regression model (Table 4). The mean, 5^{th} percentile and 95^{th} percentile was determined from the observed values for each of MFA, $Density_{SS}$ and $RingWidth_{SS}$. In the model a specific variable was changed from its 5^{th} percentile value to the 95^{th} percentile value while the other variables were kept constant at their mean observed values. The change in MOE_{dyn} from the model as a result was expressed in absolute terms (ΔMOE_{dyn}) and as a percentage influence (Influence) of each variable in the model (Table 4). For example, by changing MFA from its 5^{th} percentile observed value of 10.1^{o} to its 95^{th} percentile observed value of 24.2^{o} in the regression model the predicted MOE_{dyn} decreased by 2884 MPa.

Table 3. Pearson correlations between various properties measured or calculated for individual boards (*, **, *** significant at 0.05, 0.01, and 0.001 probability levels, respectively).

	MOE_{dyn}	MOE_{flat}	$Density_{SS}$	MFA	RingAge	$RingWidth_{SS}$	$Density_{board}$
MOE_{dyn}	1.0000	.90***	.70***	-.73***	-.49***	-.71***	.69***
MOE_{flat}		1.0000	.68***	-.64***	-.50***	-.59***	.68***
$Density_{SS}$			1.0000	-.47***	-.36***	-.58***	.90***
MFA				1.0000	.61***	.69***	-.39***
RingAge					1.0000	.63***	-.23*
$RingWidth_{SS}$						1.0000	-.51***
$Density_{board}$							1.0000

Table 4. A multiple regression model for the MOE_{dyn} of *Pinus patula* lumber (R^2 = 0.71). Sensitivity analysis results show the relative influence of each independent variable in the model. Parameters marked with *, **, *** were significant at the 0.05, 0.01 and 0.001 probability levels, respectively.

Regression model		Sensitivity analysis				
	Parameters	Mean	5^{th} percentile	95^{th} percentile	ΔMOE_{dyn}	Influence (%)
Intercept	6404.8***					
$Density_{SS}$	16.3***	452	377 kg/m^3	553 kg/m^3	2868 MPa	39.9%
MFA	-203.8***	17.5	10.1^o	24.2^o	-2884 MPa	40.1%
$RingWidth_{SS}$	-151.2*	10.9	6.1 mm	15.6 mm	-1441 MPa	20.0%

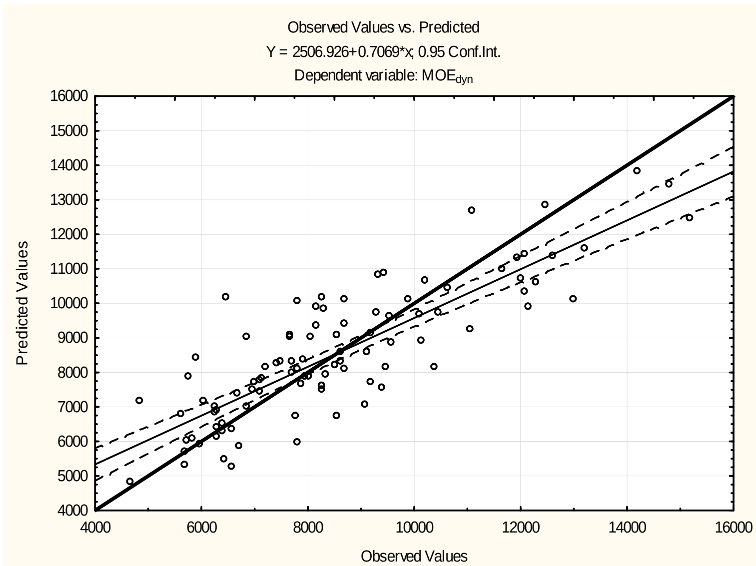

Figure 5. Predicted vs. observed values of a multiple regression model for MOE_{dyn} (Table 4). The model and 0.95 confidence intervals and the 1:1 line are indicated.

Discussion and Conclusions

The mean MFA per year ring in *Pinus patula* varied between 7^o and 29^o along the first 16 year rings from the pith. There were significant differences in MFA within the tree depending on the height in the tree and ring number from the pith (Figure 3). Average MFA varied from about 10^o at the 16th year ring at 1.3m height above ground level to nearly 30^o at the pith. (Figure 3). At 6m height above ground level the average MFA was about 2^o - 5^o lower than at breast height except at the pith where the average MFA was approximately the same at the two height levels.

Compared to New Zealand-grown *Pinus radiata* the MFA of *Pinus patula* at 1.3 m was roughly 10^o smaller at similar year rings from the pith (Figures 1 and 3). The differences at the different height levels were less pronounced compared to NZ *Pinus radiata*, showing differences in MFA of up to 10^o between breast height and upper stem compared to 2^o - 5^o for *Pinus patula*.

Density was significantly different at various rings, heights and compartments. It varied from just over 400 kg/m^3 per ring next to the pith to around 600 kg/m^3 at ring 16 (Figure 4). The trends are similar to that of *Pinus radiata* although in absolute terms *Pinus patula* density was roughly 100 kg/m^3 higher at similar ring positions (Figure 1).

The MOE_{dyn} measured on each board was closely related to MOE_{flat} (r=0.9), the most common method used for machine grading of lumber (Table 3). $Density_{SS}$, as calculated from Silviscan measurements also had a strong correlation with the density of the full board (r=0.9) despite the fact that no attempt was made to correct the $Density_{SS}$ calculation for the relative volume of each ring in a board. Due to pith eccentricity, logs that were not centered correctly in the primary and secondary breakdown saws, the taper of the log, and the curvature of rings, the actual volume of a ring in a board was too complex to determine. For this study the MFA and density of each year ring that appears in a board counted the same weight in terms of its contribution to the calculated mean MFA and density ($Density_{SS}$) of that board.

The board properties calculated from Silviscan measurements MFA, $Density_{SS}$ and $RingWidth_{SS}$ had similar and highly significant correlation coefficients with MOE_{dyn} of 0.73, 0.70 and 0.71 respectively (Table 3). The RingAge also had a significant correlation with MOE_{dyn} of 0.49.

The multiple regression model (Table 4) which included MFA, $Density_{SS}$ and $RingWidth_{SS}$ explained 71% of the variation in the MOE_{dyn} of the boards. Sensitivity analysis on the model showed that MFA was the most influential variable in the model (40.1%), followed by $Density_{SS}$ (39.9%) and $RingWidth_{SS}$ (20.0%). Both the Pearson correlations and the sensitivity analysis on the regression model thus suggest that microfibril angle and density are of roughly similar importance in explaining the MOE_{dyn} of the boards. When separating boards according to their distance from the pith, the Pearson correlation coefficients show that density and MOE_{dyn} were slightly better correlated for boards closer to the pith than MFA and MOE_{dyn} (not shown in Results section). This is contrary to results obtained from studies on small clear samples of *Pinus radiata* where MFA was found more influential in corewood (i.e Cave and Walker 1994; Walker and Butterfield 1996; Dickson and Walker 1997). It must be mentioned that the few results available from studies on full sized lumber seem to partially contradict those on small clear specimens. In a study on *Pinus radiata* Downes et al (2002) found that both density and MFA were correlated to board MOE for one of the sites considered. In the case of another site the effect of density on MOE was more dominant than the effect of MFA. Vikram et al (2011) found that density had a greater direct effect on the static MOE of Douglas-fir lumber than MFA.

The negative correlation of $RingWidth_{SS}$ with MOE_{dyn} (Table 3) and the fact that $RingWidth_{SS}$ also entered the multiple regression model as a negative parameter (Table 4) is noteworthy. The sensitivity analysis suggests that $RingWidth_{SS}$ is about half as influential as $Density_{SS}$ and MFA in determining MOE_{dyn}. This was most probably partly as a result of the effect of $RingWidth_{SS}$ on the slenderness of trees. Several studies found a strong relationship between tree slenderness and the stiffness of its wood (i.e. Lasserre et al., 2005; Watt et al., 2006; Roth et al., 2007; Lasserre et al. 2009).

Results to date suggest that the establishment of trees at higher planting densities with the objective to encourage the development of more slender trees, might be a useful practical plantation management tool to increase the production of stiffer and stronger wood, especially of the wood produced during juvenile growth. Higher planting densities also result in less exposure to wind – it has been shown that wind exposure results in less stiff wood (Bascuñán et al., 2006). While this approach will most certainly impair diameter growth, the financial gains that will result from the improved quality of the wood produced might surpass the negative effects (if any) caused by the reduced growth rate.

Higher planting density and the resultant reduction in growth rate may not necessarily have an adverse effect on volume production per unit area and may even increase it, depending on species and site conditions (Van Laar, 1978).

Microfibril angle, together with density, are clearly important properties in terms of their influence on the stiffness of sawn lumber from young *Pinus patula.* The potential use of MFA data by tree growers and processors depends on the application. Some authors suggested that tree breeders refrain from measuring and selecting for MFA due to the cost and that much cheaper acoustic stress wave methods, and density rather be used because of their excellent ability to predict MOE (Vikram et al 2011). However, in another study by the author on the same sample material it was found that acoustic velocity assessments performed on standing trees explained considerably less of the variation in MOE_{dyn} than MFA (Wessels et al, In preparation).

Measurement of MFA for *Pinus patula* can be particularly useful in studies where the effect of time-dependent treatments such as thinning or fertilising on wood properties needs to be evaluated. Since MFA can be measured on individual year rings, the effect of a treatment on MFA can be evaluated very effectively over a growth period.

Given the problems associated with reduced rotation ages on the stiffness of plantation grown *Pinus patula* in South Africa, the use of MFA information of this species in both research and industrial studies can be beneficial in managing these problems.

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Chapter 7. Summary of research results

The main findings of the full investigation as reported in the papers (Chapters 2 to 6) are summarised below.

- The sawn lumber from the 16-20 year-old *Pinus patula* trees had low stiffness and the mean MOE_{edge} of the visual and mechanical structural grades did not comply with the SANS 10163-1 (2003) requirements. This indicates that the relationship between various indicating properties for grading for this resource is very different to what it was when the characteristic values for South African pine was determined three decades ago. As a consequence grading rules and methods will have to be adapted for this resource.
- The 5^{th} percentile bending strength for this resource was much higher and the 5^{th} percentile tensile strength slightly higher than that required for the lowest SA structural grade.
- Most of the desirable properties for structural timber improved with distance from the pith. The only exception was the 5^{th} percentile value for MOR which was higher for the pith boards than for the 1^{st} boards.
- Log position or height above ground level had a significant effect on the MOE_{dyn}, MOR and twist in boards. The R^2-value for the relationship between MOE_{dyn} and MOR of boards from the top logs were much lower than that of boards from the bottom log, suggesting that the prediction of MOR from the non-destructive assessment of MOE_{dyn} would tend to be less efficient for log boards originating from higher up in the tree.
- Predictive multiple regression models for MOE_{dyn} and MOR of lumber were developed at a board, tree and compartment level. Models that were developed were capable of explaining 68%, 60% and 95% of the variability in MOE_{dyn} at individual board, tree and compartment level respectively. The best models developed explained 40% and 42% of variability in MOR at a board and tree level respectively. At compartment level the best model explained 80% of the variability in MOR_{5perc}.
- Results of sensitivity analyses showed that site index at base age 10, time-of-flight acoustic measurements, density and ring width were the most influential variables in the models developed for predicting MOE_{dyn}. In the model for predicting the MOR_{5perc} at compartment level site index at base age 10*,* the branch angle, branch spacing and ring width were the most influential variables.
- The models developed also suggest that tree slenderness during early growth might have played an important role in determining the MOE_{dyn} and MOR of boards originating from the corewood zone, which is consistent with the Euler buckling theory and the bending stress theory.
- Mean year ring microfibril angle (MFA) varied between 7^{o} and 29^{o} in the first 16 year rings from the pith. In general MFA decreased with distance from the pith and height above ground level. The microfibril angle of *Pinus patula* followed the same within-tree trends as *Pinus radiata* but was lower in absolute terms in the first species and differences between height levels were less pronounced.
- Microfibril angle and density had highly significant Pearson correlations of 0.73 and 0.70 respectively with board MOE_{dyn}. A multiple regression model which included microfibril angle, density and ring width explained 71% of the variation in the MOE_{dyn} of boards. Sensitivity analysis on the model showed that microfibril angle and density had roughly similar influences on the predicted MOE_{dyn} of *Pinus patula* boards.

The results from this study can be used by tree breeders, growers and processors of *Pinus patula* trees as well as researchers working on this species to help manage the problems associated with faster growth and lower rotation ages. The predictive models can assist with allocation of logs to processing facilities, decisions related to harvesting age, and selection of superior breeding material in tree improvement programs.

Outcomes of this study

Since the start of this study, several of the recommendations which resulted from the outcome of the studies described in Chapters 2 to 6 have been adopted by industry or have prompted further investigations. In-grade testing programs have been conducted at sawmills where both mature and predominantly young *Pinus patula* are processed (Crafford and Wessels, 2011; Wessels and Froneman, 2012). These results, combined with the results of the study outlined in Chapter 3 resulted in the development of a new South African National Standards (SANS) grading quality control code for the South African sawmilling industry. The first draft of the new grading quality control code has already been accepted by SawmillingSA and is currently in the process of being finalised by SANS.

This study also initiated a collaborative research project funded by industry with the objective to investigate new forest management regimes for specific South African pine species. This project will focus primarily on the effects of higher initial planting densities, adjusted thinning regimes and changes in rotation age. Planting at closer spacing will result in the development of more slender and less exposed trees, producing wood that might be of higher stiffness.

Results in this study suggested that a relationship might exist between the nitrogen to potassium ratio determined from leaf analysis, and the latewood percentage of wood. Since latewood has a higher stiffness than earlywood, the gross effect of an increased latewood proportion could be an increase in the stiffness of the wood in general. Unfortunately this aspect has not been considered in this study. Further studies are therefore strongly recommended. A better understanding of the factors that affect the transition from earlywood to latewood formation will be a valuable contribution.

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Appendix A: Declarations of candidate and co-authors

Declaration by the candidate (Chapter 2):

With regard to Chapter 2 of this thesis, the published paper "A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Reviewed literature - Conceptualised and wrote the paper	90%

The following co-authors have contributed to Chapter 2 of this thesis, "A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
FS Malan	fsmalan@gmail.com	Contributed to the writing of the paper	5%
T Rypstra	tr@sun.ac.za	Contributed to the writing of the paper	5%

Signature of candidate: ....

Date: 4/12/2013

Declaration by co-authors:

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 2 of this thesis, "A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber",

2. no other authors contributed to Chapter 2 of this thesis, "A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this thesis, "A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber" of this dissertation.

Signature	Institutional affiliation	Date
	Consultant: Wood Information Services	28/11/2013
	Stellenbosch University	4/12/2013

Declaration by the candidate (Chapter 3):
With regard to Chapter 3 of this thesis, the published paper "The structural grading of young South African grown *Pinus patula* sawn timber" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Conceptualised the study; - Provide study leadership as the main supervisor to the other author of this paper who was an MSc student at the time; - Performed some of the sampling and testing work; - Writing some parts of the paper which was based on the MSc thesis of the other author.	30%

The following co-authors have contributed to Chapter 3 of this thesis, "The structural grading of young South African grown Pinus patula sawn Timber":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
GP Dowse	georged@merensky.co.za	- Main author of the paper; - Performed most of the testing and analysis work	70%

Signature of candidate: ....

Date: 4/12/2013

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 2 of this thesis, "The structural grading of young South African grown Pinus patula sawn Timber",

2. no other authors contributed to Chapter 2 of this thesis, "The structural grading of young South African grown Pinus patula sawn Timber" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 2 of this thesis, "The structural grading of young South African grown Pinus patula sawn Timber" of this dissertation.

Signature	Institutional affiliation	Date
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Declaration by the candidate (Chapter 4):
With regard to Chapter 4 of this thesis, the published paper "Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Overall responsibility for project (sampling, testing, analysis) - Data analysis - Conceptualised and wrote the paper	88%

The following co-authors have contributed to Chapter 4 of this thesis, "Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
FS Malan	fsmalan@gmail.com	Contributed to the writing of the paper	5%
T Rypstra	tr@sun.ac.za	Contributed to the writing of the paper	5%
DG Nel	dgnel@sun.ac.za	Contributed to statistical analysis	2%

Signature of candidate: ....

Date: 4/12/2013

Declaration by co-authors:
The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 4 of this thesis, "Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*",

2. no other authors contributed to Chapter 4 of this thesis, "Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*" besides those specified above, and

3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 4 of this thesis, "Variation in strength, stiffness and related wood properties in young South African-grown *Pinus patula*" of this dissertation.

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Declaration by the candidate (Chapter 5):

With regard to Chapter 5 of this thesis, the published paper "The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Overall responsibility for project (sampling, testing, analysis) - Data analysis - Conceptualised and wrote the paper	86%

The following co-authors have contributed to Chapter 5 of this thesis, "The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
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T Seifert	seifert@sun.ac.za	Contributed to statistical analysis	2%
JH Louw	Josua.Louw@nmmu.ac.za	Compiled and analysed environmental data	2%

Signature of candidate: ....

Date: 4/12/2013

Declaration by co-authors:

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 5 of this thesis, "The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees",
2. no other authors contributed to Chapter 5 of this thesis, "The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees" besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 5 of this thesis, "The prediction of the flexural lumber properties from standing South African-grown *Pinus patula* trees" of this dissertation.

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	Stellenbosch University	5/12/2013
	NMMU	19 November 2013

Declaration by the candidate (Chapter 6):

With regard to Chapter 6 of this thesis, the published paper "The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber" the nature and scope of my contribution were as follows:

Nature of contribution	Extent of contribution (%)
- Overall responsibility for project (sampling, testing, analysis) - Data analysis - Conceptualised and wrote the paper	88%

The following co-authors have contributed to Chapter 5 of this thesis, "The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber":

Name	e-mail address	Nature of contribution	Extent of contribution (%)
FS Malan	fsmalan@gmail.com	Contributed to the writing of the paper	5%
T Rypstra	tr@sun.ac.za	Contributed to the writing of the paper	5%
M Kidd	mkidd@sun.ac.za	Contributed to statistical analysis	2%

Signature of candidate: ....

Date: 4/12/2013

Declaration by co-authors:

The undersigned hereby confirm that

1. the declaration above accurately reflects the nature and extent of the contributions of the candidate and the co-authors to Chapter 6 of this thesis, "The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber",
2. no other authors contributed to Chapter 6 of this thesis, "The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber" besides those specified above, and
3. potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material in Chapter 6 of this thesis, "The variation of microfibril angle in South African grown *Pinus patula* and its influence on the stiffness of structural lumber" of this dissertation.

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