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Mechanised Pine Thinning Harvesting Simulation: Productivity and Cost Improvements as a Result of Changes in Planting Geometry

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Abstract

Traditionally, the removal of entire rows at regular intervals through thinning compartments has been applied to facilitate access to mechanised timber harvesting operations in South Africa. These row thinnings have essentially involved the removal of every 7th row in a standard 2.7×2.7 m planting regime, resulting in a machine trail width of 5.4 m and a theoretical distance to the furthest tree of 8.1 m.

A simulation study, based on alternative planting geometries, investigated the effect on harvesting in terms of harvesting productivity, system costs and impact on stand structure. Compartments of different planting geometries ranging from 2.7×2.7 m to 2.5×2.9 m, 2.4×3 m and 2.3×3.1 m at two thinning reference ages were simulator generated. These compartments were then simulator thinned and harvested in the simulation.

Results showed that the boom reach of the harvester is optimised by extending row removal from the 7th to the 9th row. At the same time, machine trail length per hectare was reduced by 20%. This creates more productive area for tree growth, potentially reduced residual stand impacts, and increases the proportion of selectively harvested trees per hectare. The increased distance between row thinning removals enhanced the potential volume harvested trail length (m^3/m) and in turn led up to a 8% increase in harvesting productivity, up to a 21% increase in forwarding productivity and a reduction in total costs of up to 7% when changing planting geometry from 2.7×2.7 m to 2.3×3.1 m and 2.4×3.0 m, for first and second thinning.

Keywords: harvesting, simulation, thinning, planting geometry, productivity, system costing, optimisation

1. Introduction

The advent of more advanced mechanised timber harvesting systems has identified the potential of possibly modifying planting geometries and thinning practices (Bredenkamp 1984). One of the alternatives considered is that of row thinnings where an entire row or rows are removed at predetermined intervals throughout the compartment. However, a balance needs to be achieved between improved harvesting efficiency and potential losses by eliminating a portion of the selective thinning process (Bredenkamp 1984).

It had been found that, if the execution of these two entirely different thinning systems were not well aligned (i.e. selective thinning is carried out first without identifying the trees to be removed in the rows removals), it results in an irregular stand structure along the removed rows (Ackerman et al. 2013). Suboptimal tree volume growth and tree form is a further consequence (Ackerman et al. 2013).

The study simulated both felling and subsequent timber extraction operations in virtually constructed stands, where both access rows had been removed and selective thinning applied between these rows. The proviso was that the simulation exercise had to maintain regular stand structure to satisfy optimal stand development.

The use of an aggregation index (*R*), as proposed by Clark and Evans (1954), was applied as a measure of irregularity in the stands and, as an indicator of stand occupation efficiency, appears to have not been applied in South Africa forestry before. Similarly the application of computer simulation, now widely used in forest operations research worldwide (Asikainen 1995, 2001, 2010), was used to test different planting geometries on thinning harvesting productivity and cost. Simulation offers effective systems evaluation potential as alternatives (harvesting systems and management regimes) can be tested virtually without actual implementation of the said systems in the field (Talbot et al. 2003, Hogg et al. 2010, Pretzsch et al. 2002a).

2. Objective

The objective of the study was to quantify the consequences of alternative planting geometries to the conventional 2.7×2.7 m on mechanised cut-to-length CTL) harvesting. The study questioned whether the modification of planting geometry:

⇒ reduced machine trail length per hectare still maintaining suitable access for the harvesting machines;

⇒ maintained compartment tree spacing regularity when simulated thinnings are done;

⇒ increased harvesting productivity with reduced harvesting system costs.

3. Materials and methods

In South African forestry research, information on tree characteristics in compartments (individual tree models for *DBH* and height based on competition) and time consumption models for harvesting (time study data) is scarce. For this reason and for the sake of generating simulated stands and time consumptions, species growth models and harvesting system time models were sourced from worldwide research. These models were assumed to be representative to the work done for the area of operation in this paper.

The procedure followed by the investigation into changing planting geometries and simulation is summarised as a flow chart in Fig. 1.

The study was based on simulated compartments that were generated based on real data to mimic a realistic tree size distribution. Spatial adjustments of virtually generated compartments were done through a computer simulator and were based on existing silvicultural prescriptions for saw-timber production (Table 1). Various alternative initial planting geometries returning the same final stems per hectare (*SPHA*) as prescribed were tested during the simulation. The simulated planting geometries took into account the physical characteristics and limitations of both the harvester and forwarder that were to be used in the study for the harvesting simulation of both first and second thinnings.

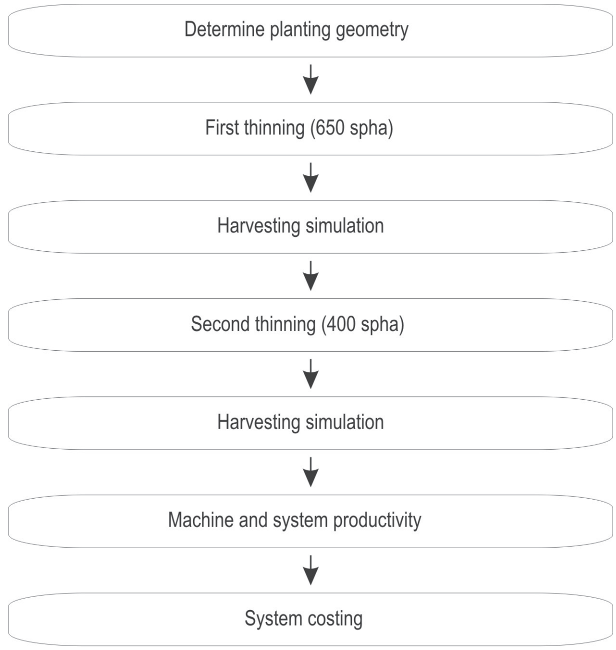


Fig. 1 Flow chart of the procedure followed for thinning and harvesting of compartments to maintain stand regularity

3.1 Determining tree characteristics to develop computer simulated compartments

The first step in the process to determine new planting geometries involved using pre-thinning enu-

Table 1 Standard establishment and thinning prescriptions in South Africa

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

meration tree data for compartments at thinning ages 8 and 13 years. This would establish the tree characteristics for each thinning age. The data set contained information for compartments of the same Site Index (SI_{20}) of 20. This data was used to develop *DBH* and height data representative of trees at the two particular thinning reference ages in a compartment.

However, applying this tree data randomly to a grid position does not sufficiently mimic the reaction of trees to growing space, nor to genetic variations. The reason is that compartment structure is not a purely random process. Competition between trees leads to a distinct tree dimension (Seifert 2003), relating to spatial pattern and compartment structure (Pretzsch 1997), where larger trees suppress their smaller neighbours. These spatial structures, resulting from competitive processes, had to be taken into account.

The structure generator, developed by Pretzsch et al. (2002b), was used for creating realistic diameter distributions and spatial distributions of trees. The results where validated with data from the existing trial plots. Tree diameters and heights were manually increased in proportion to the mean *DBH* and height based on pre-thinning enumeration data between first and second thinning. As a standard in South African growth and yield modelling, natural mortality is not taken into account in heavily thinned stands (Kotze et al. 2012), as evident between first and second thinning. This approach was applied to all the various alternative planting geometries investigated.

3.2 Determining optimal tree spacing and planting geometry

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

By adjusting the distances of trees within and between the rows, the alternative planting geometries in Table 2 were proposed. Distance between machine trials, width of the machine trails and length of machine trail per hectare were used as criteria for selecting the spacing geometry to be used in the study.

Table 2 Breakdown of various planting spacings tested

Spacing *x – y*	Rows to be removed
2.7×2.7 m	7^{th} and 8^{th}
2.5×2.9 m	7^{th}, 8^{th} and 9^{th}
2.4×3.1 m	7^{th}, 8^{th} and 9^{th}
2.3×3.0 m	7^{th}, 8^{th} and 9^{th}

3.2.1 Machine limitations used to determine minimum planting spacing

A Tigercat harvester and forwarder *CTL* system was selected for this study (Table 3), since these machines were already in operation on the plantation where the data was collected. A trail width of 1 m wider than the machine was considered a feasible criterion for the different planting geometries to prevent damage to stems and to limit tree root disturbances (Table 3).

3.2.2 Planting geometries used in thinning and harvesting simulations

Using the machine limitations (Table 3), a selection system was developed to test the feasibility of various planting geometries from Table 2. The aim of the evaluation was to increase the distance between machine trails as much as possible (> 7^{th} row), thus reducing the machine trail length per hectare and ensuring the distance between machine trail was equal to or less than 20 m so that the harvester boom could reach trees from the machine trail (10 m to the middle of the inter-row). Matching these criteria would limit stand impact and maximise the harvester boom reach.

Even row (8^{th}) spacing was excluded from the simulations due to the centre point between two machine

Table 3 Machine limitations based on boom reach and machine track width for Tigercat harvesters and forwarders (Tigercat 2011)

Machine	Machine type	Boom reach, max	Boom reach, telescopic	Machine width	Payload
Tigercat H822c	Tracked harvester	8.91 m	11.07 m	3.43 m	–
Tigercat 1075B	Forwarder	7.83 m	N/A	3.30 m (bunk)	14,000 kg

trails possibly falling exactly on the same tree row. This would lead to sub-optimal harvesting, as the machine would essentially have to harvest four rows from one machine trail and only three from the other, thus not utilising absolute boom reach on one side.

3.3 Stand simulations

Following the process of matching machine specifications to various planting geometries, spatial tree lists containing x-and y-coordinates, *DBH* and height information of a 1.5 ha compartment were created in Excel. This was done for each of the planting geometries selected for the study. As a standard, the x-value always indicates the planting spacing used where a row of trees are removed for a machine trail. These were used as input into a specially designed simulation programme for thinning and harvesting, which was coded in the statistical language *R* (*R* Core Team 2012). A thinning from below was simulated for each stand. In this process trees that were marked as thinned were harvested by a harvesting simulator.

3.3.1 Thinning

Thinning from below generally concentrates on the removal of trees that are smaller in relation to the neighbours in the same growing area, thus relieving competition (Murray and von Gadow 1991, Kassier 1993, Pukkala and Miina 1998, Pretzsch 2009). The thinning was simulated with a rule based algorithm without stochastic components, as this would have created an additional source of variance. As a consequence of this deterministic approach, a repeated application of the algorithm to the same stand would have resulted in the removal of the same trees. Input for the programme was the targeted final stem number per hectare as related to the size of the plantation area to be thinned (N_{target}). The programme would evaluate neighbouring trees in relation to a particular tree to determine the growing area and the growth status of the centre tree. Within the programme, a defined local search radius for tree neighbours around a target tree from the N_{target} was calculated by estimating the average growing area per tree (Eq. 1).

$$A_{grow} = \frac{10,000}{N_{\text{target}}} \quad m^2 \tag{1}$$

The local search radius for neighbouring trees was determined as 2.5 times the radius of a circle with the same area as A_{grow} (Eq. 2).

$$r_{\text{grow}} = \sqrt{(A_{\text{grow}} / 0)} \tag{2}$$

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

Lastly, the values calculated were summed up to determine a potential for a tree to be removed in the thinning process. The summed values were then ranked, and the trees with the highest potential to be thinned to the target *SPHA* were marked »to be removed« (*TBR*) and the rest were marked »not to be removed« (*NTBR*) as flags in the output. To limit the effect of stand edges on thinning, a subset of 1 ha subset was taken from the middle of the stand.

A measure of aggregation (*R*) (Clark and Evans 1954) was used to determine the uniformity of the spacing in the stand after thinning. This measure of aggregation provided a test to evaluate the efficacy of the thinning algorithm. The particular data preparation and outputs for first and second thinnings are described below.

3.3.2 Simulated marking for thinning

Before the first thinning simulation, the rows that were thinned for the extraction trails (7$^{\text{th}}$ or 9$^{\text{th}}$ row) were removed from the dataset as this would be done in practice. The full data set, with these row trees removed, was then thinned and trees TBR to the desired stand density (including removed row trees) and *NTBR* trees were marked. The row trees were then reintroduced as *TBR* for further analysis. The resulting dataset with the marked trees (row thinned and selectively) was then used as input for the spatial harvesting simulation.

The second thinning simulation followed the same procedure, based on the stem numbers resulting from the first thinning operation except for the fact that no further row-thinnings were applied.

3.3.3 Harvesting

In the harvesting simulation process, the spatial reach of a harvester moving along a skid trail was simulated. Based on x-and y-coordinates of trees and the flag for *TBR* or *NTBR* trees, individual tree harvesting was conducted. Each individual skid trail location (defined by start and end) was used as an input to the simulator.

The output identified all the trees around the machine trail that could be reached by a 10 m boom, flagging them as accessible. If trees were attributed as ac-

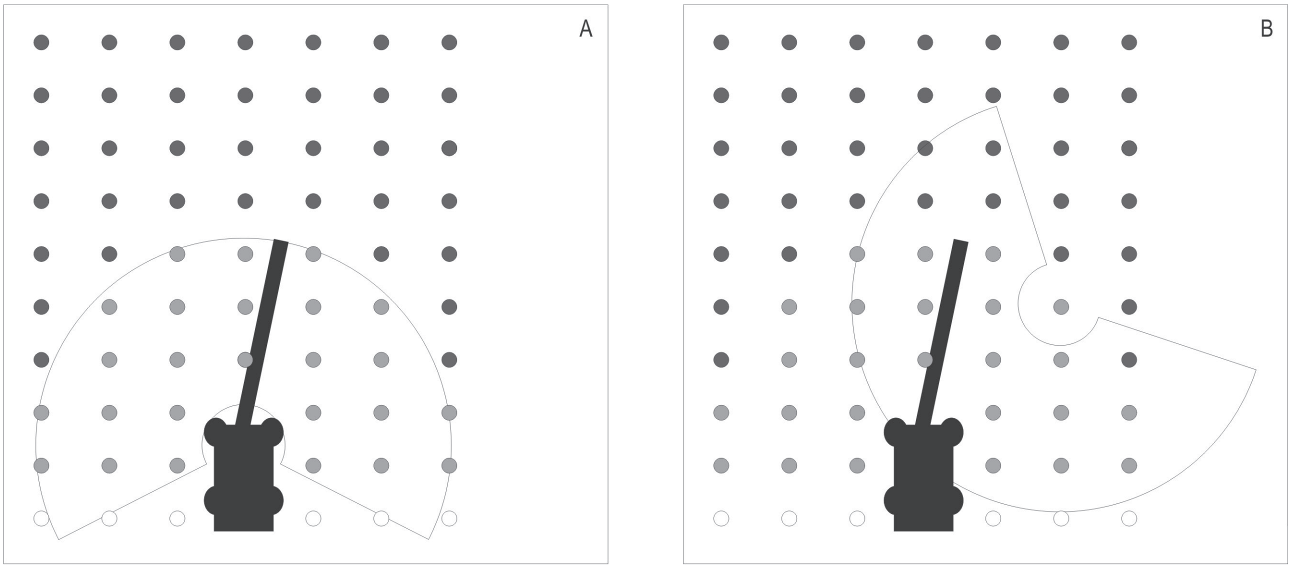


Fig. 2 a) harvester boom swath area and b) tree reach polygon

cessible and marked, *TBR* would be flagged as harvested for a particular harvesting stop. These stops were determined and calculated using a harvesting simulator.

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

The simulation was based on pure geometry using only the tree positions and the line on which the harvester moved on the machine trail. The reach of the boom and the tree coordinates were used to identify the optimal point from which most trees could be harvested, (Fig. 2a and b). From a start position, the harvester moved forward on the machine trail to the first optimal point at which most trees could be reached. From this first stop, once all the harvestable trees had been virtually harvested, the next optimal point was selected and the harvester moved forward to that point.

It was assumed that all trees in the polygon of Fig. 2a could be reached by the harvester head from the harvester position, the boom swath area. This, in reality may not be the case.

The next step was to define the area from which a specific tree could be reached by the harvester, the tree reach polygon (Fig. 2b). The tree reach polygon can be derived by calculating all possible harvester positions from which the harvester boom can reach the targeted harvestable tree. Geometrically this equals the inversion of the boom swath area in Fig. 2a. By intersecting the tree reach polygon with the machine trail, a new harvester stop line segment was created (Fig. 2). If the harvester was on this line segment, the boom could reach a particular tree.

The procedure followed a sequence to find the optimal position to harvest most trees from a position, without reversing, assuming that this would match the strategy of a real harvesting operator. Selection of the nearest trees to harvest and the line selection for each stop are shown in Fig. 3. The intersection of the tree reach polygon (Fig. 2b) with the machine trail line defines the line of the segment where trees will be harvested for that stop. All tree polygons (Fig. 3), which intersect the starting line segment, are added to the list of harvested trees. When no more trees intersect the segment, the maximum number of trees that can be harvested from that line segment has been found and the endpoint of this segment is used as the new harvester position.

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

A tree volume, based on the *DBH* and height values, was assigned to each harvested tree using the Schumacher and Hall function with parameters for *P. patula* (Bredenkamp 2012). The volume per harvesting

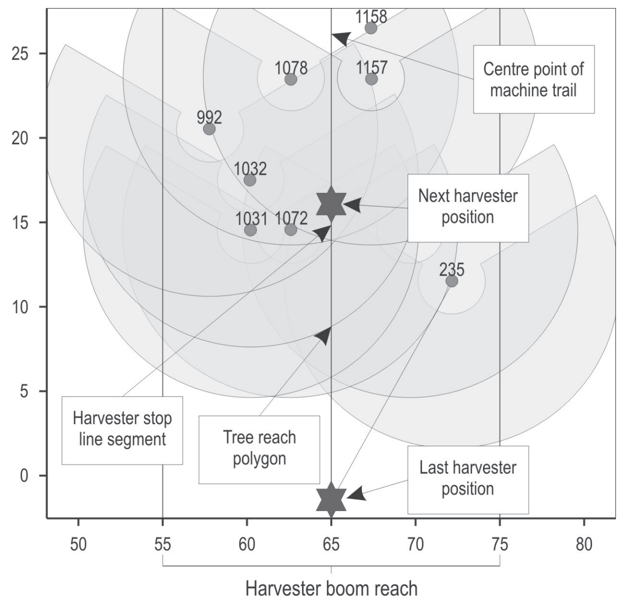


Fig. 3 Nearest tree to harvesting stop and tree selection polygons inverted and translated to the tree position

Table 4 Time element calculations used to determine time consumption in simulated operation

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

stop was totalled for each row with the distance between harvesting stops and accumulated distance travelled along the machine trail.

3.4 Harvester and forwarder productivity

Volumes harvested at each harvesting stop were calculated. In order to determine the productivity of the harvesting system, the time taken to harvest and forward the timber needed to be determined. Time consumption was determined using existing time study functions with the harvesting and forwarding time consumption broken up into time elements. Due to actual time studies not being within the scope of the project in South Africa, element times and machine speeds were taken from studies by Eliasson et al. (1999) and Nurminen et al. (2006), respectively, for Nordic countries (Table 4).

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

A harvester cycle starts at the base of the first machine trail and moves to the first harvesting stop as determined by the harvesting simulation. All the trees for that particular harvesting stop are assumed to be harvested and processed. Once the harvesting is complete, the next cycle starts with the machine moving north to the next harvesting stop (Fig. 4). At the end (highest x-and y-coordinate) of the machine trail, the machine moves to the base of the next machine trail and the simulation starts again.

As with the harvester (Fig. 4), the forwarder would move into the stand from the start of machine trail one. It would then travel empty along the trail to the first timber stack, load and travel partially loaded to the next stack and continue loading. This was repeated until the forwarder was fully loaded to its capacity of 20,000 kg or 18.86 m^3 (Table 3) for a Tigercat 1075B. This figure is based on a direct conversion of weight to volume of 1.06 tonnes to m^3 provided by Bredenkamp (2012).

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

Information gathered from the machine work methods and the time models was used to calculate

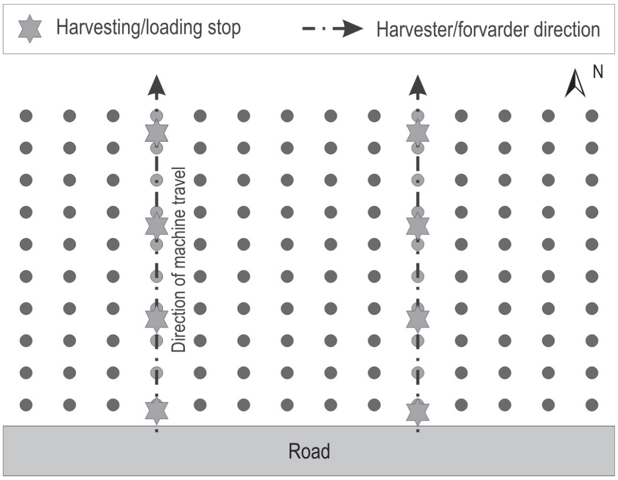


Fig. 4 Simulation steps for harvester and forwarder for harvesting and loading time allocation

the time taken to harvest 1 m^3 of timber for each scenario and it was then compared to the standard spacing (2.7×2.7 m). Inputs to fixed and variable costs were based on standard industry data and input from the machine dealers. Operator, licensing, insurance, other miscellaneous costs and delays were not taken into account. Based on this information (Table 5), machine costs were determined for each scenario using a standard machine costing model (Eliasson 2013).

3.5 Statistical analysis

A Levene-test for variance homogeneity was used to check for violations of the assumptions of homogenous variance between groups. Analysis of variance (ANOVA) was used to determine whether there were significant differences between the test criteria in planting geometries. In some cases, heteroscedasticity prohibited traditional *t*-tests and ANOVA. A non-parametric Welch's *t*-test was used in these cases; this test is more robust against homoscedasticity violations. Subsequently, to determine further differences between planting geometries, a Bonferroni multiple hypothesis test or a Tamhane *T2* test were applied, depending on homoscedastic or heteroscedasticity of variance respectively (Lyman Ott 1990).

4. Results

4.1 Harvesting thinnings from optimised stand structure

4.1.1 Determining the optimal tree geometry

The planting geometry selection process found that the following planting geometries 2.5×2.9 m, 2.3×3.1 m and 2.4×3.0 m (Table 6), were suitable alternatives for the conventional 2.7×2.7 m geometry; i.e. the control.

Table 5 Costs (South African Rand) and costing assumptions for machines and attachments used in system costings (G. Olsen pers. comm. 2012, J. van Heerden pers. comm. 2013)

Item	H822C Harvester	1075B Forwarder
Fixed cost inputs		
Machine cost	R4'056'754.00	R4'728'538.00
Harvesting attachment	R1'319'985.00	No attachment
Machine life	18,000 hrs	18,000 hrs
Harvesting attachment life	18,000 hrs	NA
Salvage cost machine, %	10	10
Salvage cost attachment, %	0	NA
Interest rate, %	9	9
Insurance, registration, set-up and garaging costs	R 0.00	R 0.00
Variable cost inputs		
Fuel costs	R 11.60 (Feb, 2013)	R 11.60 (Feb, 2013)
Fuel consumption	28 l/hr	12 l/hr
Oil cost of fuel cost	20%	10%
Maintenance cost machine, %	100	100
Maintenance cost attachment, %	100	NA
Number of tracks/tyres	2	8
Cost per track/tyre	R 155,000.00	R 42,000.00
Life of track/tyres	9000 hrs	8000 hrs
Cutter bar life	61.2 PMH	NA
Cutter bar cost	R 1500.00	NA
Chain life	38.25 PMH	NA
Chain cost	R 500.00	NA
Sprocket life	612 PMH	NA
Sprocket cost	R 1100.00	NA
Operator inputs	–	–
Operators per shift	1	1
No operator costs were taken into account		
Productivity inputs		
Working days per year	240	240
Shifts per day	2	2
Hours per shift	9	9
Productivity per hour	Based in time study information	Based in time study information
Machine utilisation	85%	85%

Table 6 Acceptable planting geometries based on rows removed, machine trail length and closest tree distance

Planting geometry m×m	Machine trail width m	Distance to furthest tree m	Row remove machine trail	Spacing between trails m*	Trail length ha^{-1} m	Number of rows removed ha^{-1}
2.7×2.7	5.4	9.45	7th	18.9	599.4	6
2.5×2.9	5.0	10.0	9th	22.5	500.0	5
2.3×3.1	4.6	9.2	9th	21.6	504.0	5
2.4×3.0	4.8	9.6	9th	20.7	506.0	5

*Measured from the mid-point of the machine trails

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

In order to test the efficiency of the thinning in maintaining an evenly distributed tree structure, a Clark and Evans aggregation (*R*) index was carried out on the tree distribution before and after thinning. The results of this analysis appear in Table 7.

Table 7 Clark and Evans (*R*) index for stands before and after thinning

Thinning	Planting geometry m×m	Clark and Evan aggregation index, *R*	
		Before thinning	After thinning
First	2.7×2.7	1.863	1.098
	2.5×2.9	1.760	1.132
	2.4×3.0	1.701	1.124
	2.3×3.1	1.641	1.156
Second	2.7×2.7	1.425	1.126
	2.5×2.9	1.398	1.100
	2.4×3.0	1.386	1.196
	2.3×3.1	1.641	1.156

4.1.2 Virtual harvesting of sample stands

Harvested volume data of the virtually thinned stands are shown in Table 8.

The results show the removed and remaining volume after each thinning, mean volume harvested at each harvesting stop and the mean distance between the harvesting stops. The mean differences between the different planting geometries (control vs potential scenarios) and the abovementioned criteria were compared.

4.1.2.1 Volume harvested per stop for each planting geometry

ANOVA analysis results for differences between the mean volumes harvested at each harvesting stop on machine trails for each planting geometry are shown in Fig. 5. Analysis of the data indicates that there were significant differences (p<0.05) between mean harvested volume at each harvesting stop for both first and second thinning.

A post hoc analysis using a Bonferroni multiple comparison test found that there were significant differences (p<0.05) between volume harvested at each stop for all of the geometries in the first thinning, except for the control and 2.4×3.0 m planting geometry. In the second thinning, there were no significant differences (p>0.05) between volume harvested at each stop for all of the geometries, except for a significant difference between 2.5×2.9 m and 2.3×3.1 m geometries.

4.1.2.2 Distance between harvesting stops for each planting geometry

A Welch *t*-test showed differences between the mean distances between harvesting stops on machine trails for each of the planting geometries (Fig. 6). The results of this test show that there were significant differences (p<0.05) between the distances between harvesting stops in both first and second thinning.

A Tamhane *T2* multiple comparison indicates significant differences between all the geometries except for the control and 2.4×3.0 m and the control and 2.3×3.1 m planting geometries in first thinning. In the second thinning, there were no significant differences between any of the combinations except for the control and 2.5×2.9 m planting geometry.

4.1.2.3 Harvesting time per harvesting stop for each planting geometry

ANOVA analysis was done on the first thinning data; it is, however, necessary to make a Welch *t*-test

Table 8 Harvested data before initial thinning and after first or second thinning

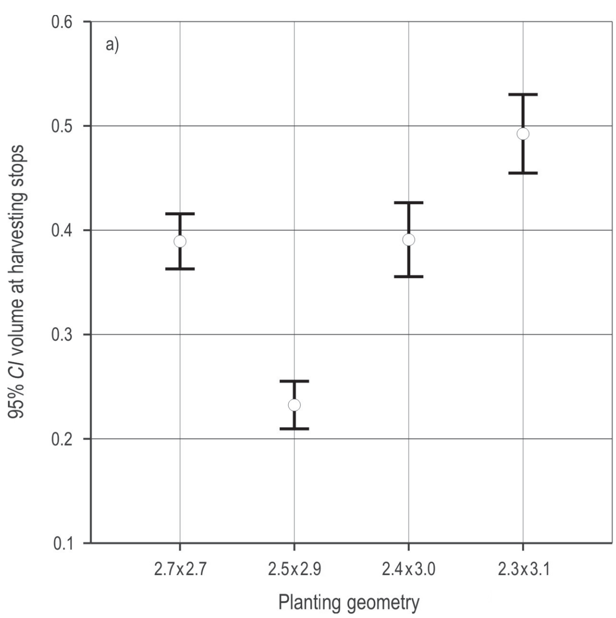
Thinning	Planting geometry m×m	Total volume, m^3/ha		Means per harvesting stop			
		Removed	Remaining	Volume, m^3	σ	Distance, m	σ
First	2.7×2.7	30.37	46.96	0.41	0.08	7.91	0.14
	2.5×2.9	27.66	48.13	0.26	0.03	5.19	1.02
	2.4×3.0	30.27	46.96	0.42	0.08	7.23	0.72
	2.3×3.1	28.56	47.46	0.51	0.05	9.05	0.43
Second	2.7×2.7	35.85	93.89	0.91	0.17	12.85	1.28
	2.5×2.9	35.31	90.87	0.76	0.20	10.38	1.39
	2.4×3.0	35.98	89.91	0.88	0.12	11.64	2.03
	2.3×3.1	39.02	90.57	1.00	0.12	11.86	1.12

on the second thinning data, too (Fig. 7). The results show that there were significant differences between the mean harvesting times at each harvesting stop. Significant differences were also found between all of the planting geometries in first thinning operations except for the control and the 2.4×3.0 m planting geometry (Bonferroni multiple comparison test). The second thinning showed no significant differences between the geometries, except between the 2.5×2.9 m and the 2.3×3.1 m geometries (Tamhane *T*2 multiple comparison test).

4.1.3 Time study and cycle times

Harvester cycles, volume and production achieved in the two thinning operations for each planting geometry are shown in Table 9. The number of cycles depended on the number of harvesting stops determined by the harvesting simulator.

In the first thinning, production was reduced between the control and the remaining planting geometries, while in the second thinning the opposite was true as an increase was evident. Forwarder cycles (Table 10) were limited by the load capacity of the



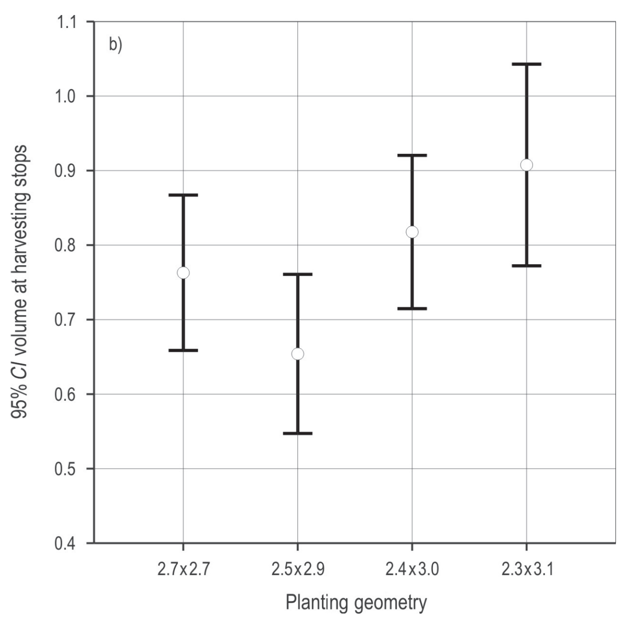


Fig. 5 Mean volume harvested for each stop (a) first thinning and (b) second thinning for each planting geometry

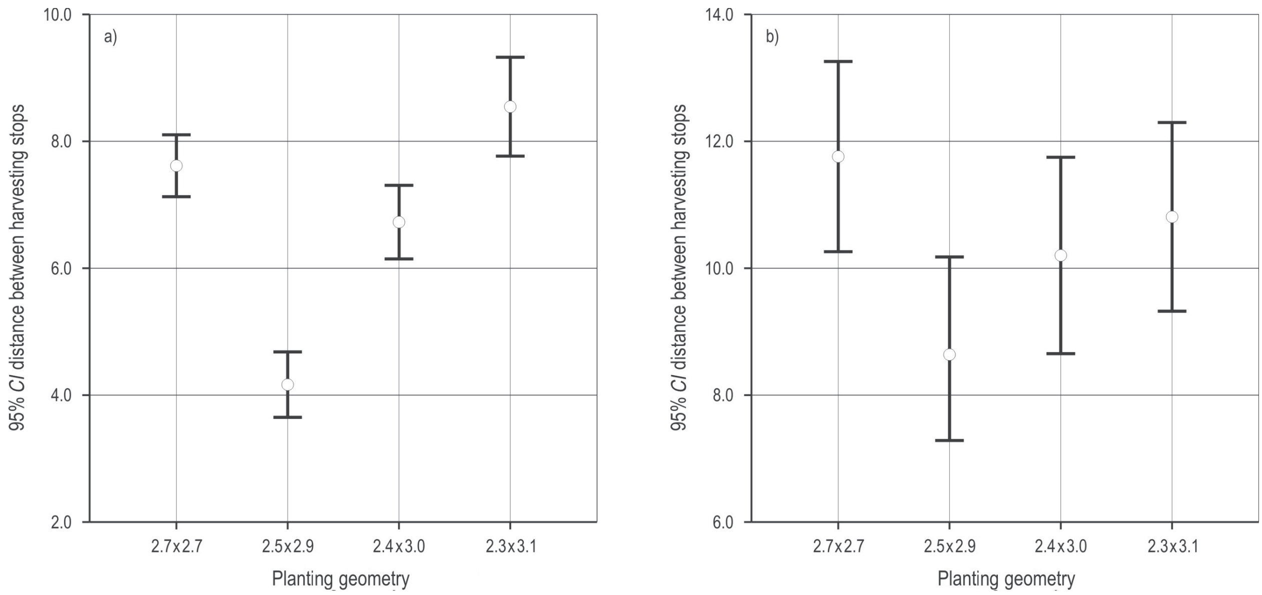


Fig. 6 Mean distance travelled between harvesting stops for (a) first thinning and (b) second thinning for each planting geometry

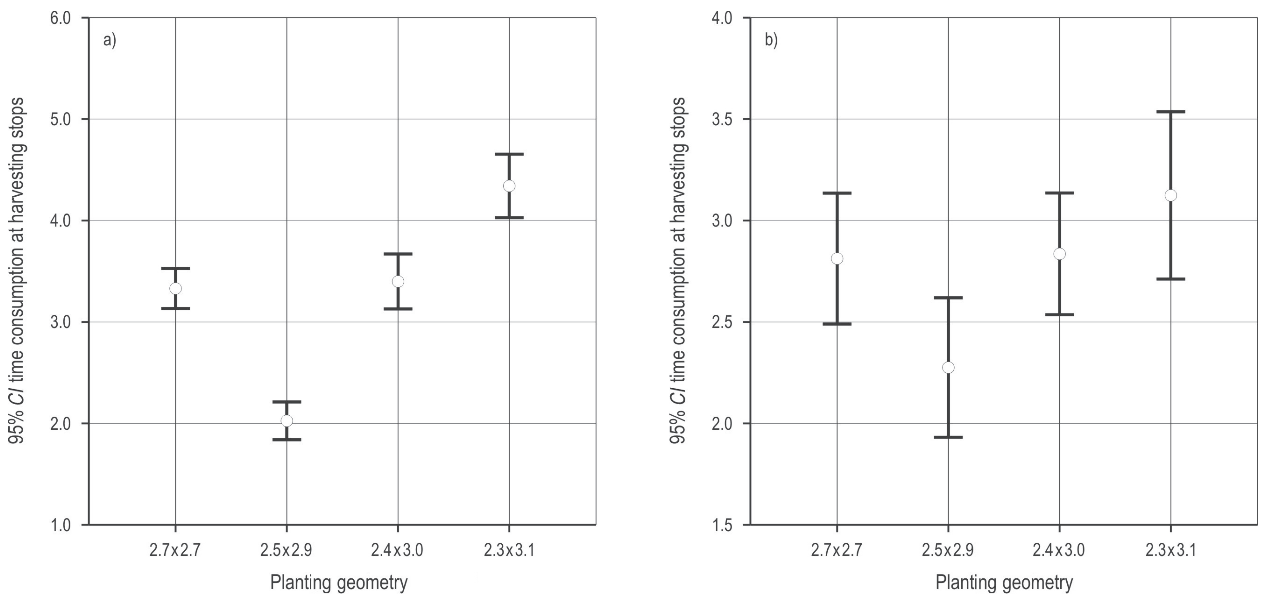


Fig. 7 Mean time consumption to harvest trees for each harvesting stop for first thinning (a) and second thinning (b) for each planting geometry

forwarder, and in most cases only one full load was possible (18.86 m^3) followed by a partial load. However, in the second thinning on the 2.3x3.1 m geometry, the additional volume to the machine trail led to two full loads and one partial third load being forwarded.

The lowest production was found in 2.5x2.9 m planting geometry; there was, however, a general increase in production from the control to the remaining planting geometries.

4.1.4 Machine and systems costing

The results of the machine costing and system costing are shown in Table 11.

In first and second thinning, the most expensive thinning operation (total costs) was for the 2.5x2.9 m planting geometry (*R* 306.76·m^{-3} and *R* 139.90·m^{-3}). In the first thinning, the cheapest system was that of the 2.3x3.1 m planting geometry (*R* 236.78·m^{-3}). The second thinning showed a reduction in cost between the control and the remaining planting geometries.

Table 9 Harvester total cycles, time taken, volume, productive machine hours (*PMH*) and volume per *PMH* for each geometry and thinning

Thinning	Planting geometry, mxm	Cycles	Time	Volume	*PMH*	m^3/PMH
First	2.7x2.7	78	259.66	30.75	4.33	7.11
	2.5x2.9	119	240.95	28.22	4.02	7.03
	2.4x3.0	72	244.74	28.50	4.08	6.99
	2.3x3.1	58	251.79	28.84	4.20	6.87
Second	2.7x2.7	47	132.2	35.70	2.20	16.20
	2.5x2.9	54	122.88	35.61	2.05	17.39
	2.4x3.0	44	124.78	36.20	2.08	17.41
	2.3x3.1	43	134.34	39.24	2.24	17.53

5. Discussion

5.1 Planting geometry changes

The alternative planting geometries that were compared in this simulation study (Table 6) indicated that a 20% reduction in machine trail length (from 599.4 m/ha to 500 m/ha) is possible when compared to the standard 2.7x2.7 m planting geometry (the control). A reduction in machine trail length has a number of advantages. Large gaps in the canopy, created by the cutting out of rows for machine trails in standard planting geometries, were reduced in size or limited. Furthermore, the likelihood of damage to residual trees during harvesting, purely because there are fewer trails, is also reduced (Hunt and Krueger 1960, Ohman 1970, Kromhout and Bosman 1982, Vasiliauskas 2001). However, in some cases, the distance between machine trails can cause the harvester head at full boom reach to lose control of the harvest tree. The resultant uncontrolled fall of the harvested tree can in some cases lead to residual tree damage (Fröding 1992 and Sirén 1992), if not monitored effectively.

It could be assumed, based on works of Warkotsch et al. (1994) and Bettinger et al. (1998), that fewer trails also resulted in reducing the potential of soil damage in terms of soil compaction and displacement. Similarly, the reduction in gaps in the canopy and irregular stand structure also reduce the negative effects on branchiness of the planted trees (Seifert 2003, Ackerman et al. 2013).

CTL harvesting, as applied in this study, generally shows reduced stand impact over tree-length and full-tree harvesting systems (Wang et al. 2005). This has great advantage over the traditional planting geometries.

5.2 Stand regularity after thinning

Alternative planting geometries and a thinning algorithm were developed to provide realistic thinning output while maintaining stand regularity. The aggregation index, (*R*) (Clark and Evans 1954) showed that the thinning algorithm was effective in terms of maintaining regular stand spacing.

The aim of the simulator was to avoid clustering of the trees and to maintain a (*R*) value higher than 1.0. All the aggregation index results were higher than this threshold (Table 7). This illustrates that the stands were thinned to a random distribution with no clustering.

5.3 Harvesting and forwarding productivity

5.3.1 Harvester

As expected, volumes per harvesting stop on machine trails increased with a reduction in machine trail length (Table 9). This was also closely associated with the distance between harvesting/loading stops and the time consumption for harvesting at each stop. In all cases, the 2.5x2.9 m planting geometry consumed less time than the control (2.7x2.7 m) and all other alternatives due to the lower volume per stop and shorter distances between stops. There were, however, many more stops per hectare than for the other geometries.

There was an overall increase in time consumed at each harvesting stop in the first as opposed to the second thinning. This was due to higher stem numbers (of lower piece volume) in the younger stand harvested. The individual tree volume in this simulation did not influence time consumption. The harvester boom movement related activities were the main driver of

Table 10 Forwarder cycle times and volumes per cycle for each thinning and geometry and total time and volume per hour

Thinning	Planting geometry, mxm	Cycle one		Cycle two		Cycle three		Total		*PMH*	m^3/PMH
		Time	Volume	Time	Volume	Time	Volume	Time	Volume		
First	2.7x2.7	144.78	18.86	101.02	11.89	NA	NA	245.80	30.75	4.1	7.51
	2.5x2.9	233.07	18.86	116.65	9.36	NA	NA	349.72	28.22	5.83	4.84
	2.4x3.0	137.5	18.86	88.97	9.64	NA	NA	226.47	28.5	3.77	7.55
	2.3x3.1	115.84	18.86	64.93	9.98	NA	NA	180.77	28.84	3.01	9.57
Second	2.7x2.7	85.11	18.86	107.22	16.84	NA	NA	192.33	35.7	3.21	11.14
	2.5x2.9	107.31	18.86	112.9	16.75	NA	NA	220.21	35.61	3.67	9.7
	2.4x3.0	97.94	18.86	81.67	17.34	NA	NA	179.61	36.2	2.99	12.09
	2.3x3.1	89.09	18.86	81.31	18.86	15.09	1.52	185.50	39.24	3.09	12.69

this. In other words, due to the individual tree volume being less in first thinnings, the multiple boom movements did not translate into a potentially higher volume harvested (Eliasson and Lageson 1999, Talbot et al. 2003). This phenomenon will potentially decrease productivity of the system in first thinnings (Belbo 2010).

Analysis of the scenario data revealed that the distance a harvester moved between harvesting stops and the volumes harvested at each stop influenced each other. In order to optimise machine working and movement time, a balance between these two factors would greatly increase the productivity. This is supported by results in other studies (Talbot et al. 2003).

When deciding on a feasible alternative to the control (2.5x2.9 m, 2.4x3.0 m and 2.3x3.1 m), the productivity results for the harvester were inconclusive in the first thinning mainly due to the great number of small trees. One would assume that the spacing geometries with the highest volume per harvesting stop, the shortest distance between stops and lowest total harvesting time consumption would appear to be the best alternative.

Harvester productivity decreased by between 1 and 3% in the first thinning and increased by between 7 and 8% in the second thinning. This was, however, a net increase in productivity over the two thinning operations. There was a general increase in productivity between geometries 2.4x3.0 m and 2.3x3.1 m when compared with the control. It is evident that these were the best suited alternatives to change planting geometry at this point.

5.3.2 Forwarder

Forwarder productivity depended on the distance travelled between loading points and the volume available at each stop in the scenario simulation (Table 11).

Table 11 Results of machine costing for first and second thinning for harvesting and forwarding operations (South African Rand)

Thinning	Planting geometry, mxm	Harvester cost, *R*/m^3	Forwarder cost, *R*/m^3	Total system cost, *R*/m^3
First	2.7x2.7	153.06	99.86	252.92
	2.5x2.9	154.81	154.95	306.76
	2.4x3.0	155.69	99.33	255.02
	2.3x3.1	158.41	78.37	236.78
Second	2.7x2.7	67.18	67.32	134.50
	2.5x2.9	62.58	77.32	139.90
	2.4x3.0	62.51	62.03	124.54
	2.3x3.1	62.08	59.10	121.18

The grapple size influences the number of times the boom had to be deployed. While boom movement influenced time consumed loading the forwarder, as with the harvester, travel time did not have a great effect on the productivity. The main influence of productivity, evident from this study, was the increase in forwarder productivity when volume per harvesting stop increased.

Similar travelling distances between harvesting stops were found in the simulation between the control, 2.4x3.0 m and 2.3x3.1 m, showing the importance of the volume per stop as a factor driving productivity increases. Overall productivity increases of between 21% (first thinning) and 12% (second thinning) could be achieved by using alternative planting geometries. Similar to that of the harvester, 2.4x3.0 m and 2.3x3.1 m were the most productive planting geometries for the forwarder.

5.4 Harvesting system cost

In general, there was a decrease in cost/m^3 between the control and the alternative planting geometries (Table 11). The planting geometries that led to the lowest costs were 2.4x3.0 m and 2.3x3.1 m in both first and second thinning operations. These two systems yielded an overall reduction in cost of 7% (*R* 16.14 m^{-3}) and 10% (*R* 13.32 m^{-3}) in first and second thinning, respectively. As discussed above, these two planting geometries did not significantly differ from each other in terms of volume per harvesting stop, distance between harvesting stop and time consumption per harvesting stop. However, a reduction of *R* 18.24 m^{-3} and *R* 3.66 m^{-3} could be achieved in first and second thinning operations, respectively, when choosing between 2.4x3.0 m and 2.3x3.1 m planting geometries; the latter having the lowest cost.

The results show evident financial benefit of adopting alternative planting geometries to the control one. However, by changing the planting geometry the potential cost reduction can make these thinnings more competitive for the current systems.

6. Conclusion

When optimising the planting geometries for mechanised thinning operations, it was found that the thinning simulator can effectively maintain stand regularity thus proving the efficacy of the method for the purpose of this study, and the overall system productivity could be increased by up to 8% and 21%, respectively, in harvester and forwarder productivity if the planting geometry was changed. This showed that rectangular geometries were superior to standard quadratic planting geometries, resulting in the possibility of achieving a cost reduction of up to 7% in first and 10% in second thinnings.

Adding to the understanding of stand characteristics, the development and application of a computer based harvesting simulation model has once again highlighted the power of simulation techniques in providing answers to these complex issues. Financial decisions to implement changes in stand management require the ability to test these scenarios without the associated risks involved by trial and error applications. This work has also attempted to change mindsets by exploring alternatives to standard, square planting geometries by showing that small adjustments can potentially improve overall harvesting productivity and costs and reduce damage to the stands.

The benefit of maintaining stand regularity in terms of tree growth characteristics and volume increment is evident. Furthermore, the objective of implementing other planting geometries, while maintaining stand regularity, has also shown to improve harvesting productivity and reduce overall harvesting system cost in a simulation environment.

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

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