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A Decision Support System for Selective Cleaning

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Cleaning (pre-commercial thinning) costs have increased relative to logging and regeneration costs, creating a desire for rationalisation. Cleaning with robots may be a solution, but automating stem selections requires a decision support system (DSS) capable of rendering acceptable results. The aims were to develop a DSS for automation of individual stem selections in practical cleaning, and to test, using simulations, if it renders acceptable results. Data on 17 young forest stands were used to develop a DSS that selects stems by species, position (including distance and density parameters), diameter, and damage. Six simulations were run, following the DSS, with different target settings for density, percentage of deciduous stems and minimum distance between stems. The results depend on the initial state of the stands, but generally met the requested targets in an acceptable way. On average, the density results deviated by –20% to +6% from the target values, the amount of deciduous stems shifted towards the target values, and the proportion of stems with defined damaged decreased from initially 14–90% to 4–13%. The mean diameter at breast height increased and the minimum allowed distance between stems was never violated. The simulation results indicate that the DSS is operational. However, for implementation in robotics a crucial problem is to automatically perceive the selected attributes, so additional simulations with erroneous data were run. Correct measurements of diameters are less crucial than to find the majority of the trees and the majority of trees with damages.

Keywords automation, forestry, practical cleaning, pre-commercial thinning
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List of Symbols

mdc = Mean diameter at breast height (dbh) of coniferous stems in the area (mm)
mdt = Mean dbh of all stems in the area (mm)
T1 = Threshold no. 1, regarding undamaged stems outside the preferred diameter range
T2 = Threshold no. 2, regarding damaged stems
T3 = Threshold no. 3, regarding the final selection of stems
P1 = The requested spacing between stems (m)
P2 = The minimum allowed distance between two stems, stem surface to stem surface (m)
P3 = The requested percentage of deciduous stems (%)
A = No. of stems retained in the "OK-Tree-list" at this point (cf. Fig. 4)
B = Total no. of selected stems at this point
C = No. of visited sections (including the current section)
D = No. of undamaged stems in the section's "Tree-list" (cf. Fig. 4)

1 Introduction

Cleaning (pre-commercial thinning) is currently applied, prior to commercial thinnings, to overdense young stands. In the Nordic countries this tending operation is made in stands of ca. three to five meters of height (Varmola and Salminen 2004). It is used e.g. to increase volume growth at the tree level and to decrease the likelihood of damage (cf. Berg et al. 1973, Röjning… 1999). The cleaned area in Sweden in 2002 amounted to 256 300 hectares (Statistical yearbook… 2004). The average cost for cleaning has increased during the last twenty years compared with logging and regeneration costs (Ligné et al. 2005). Furthermore, the number of remaining stems per hectare after cleaning has increased during this period (Pettersson and Bäcke 1998), although the cleaning instructions have remained similar (e.g. Brunberg 1990, Röjning… 1999).

Cleaning operations can be selective, geometrical, or a combination of both (Berg et al. 1973). In selective cleaning the remaining stems, i.e. the main-stems, are chosen individually depending on their position and characteristics. Reasons for making individual selections include a desire to improve stand quality and/or influence species composition (e.g. Berg et al. 1973). Selective cleaning, hereby referred to simply as cleaning, is predominant in e.g. Sweden and Finland, whereas non-selective cleaning, i.e. geometrical cleaning, is common e.g. in loblolly pine (*Pinus taeda* L.) stands in USA (Lloyd and Waldrop 1999). Herbicides are used in some 35% of the treated area in Canada (Ryans and St-Amour 1996, Compendium of Canadian… 2004).

Almost all of the cleanings in Sweden are currently done motor-manually with brush-saws, however, there are difficulties in finding cleaners and the work is laborious (Vestlund 2004). There are concerns in Canada too, that cleaners will become difficult to recruit, and that costs of cleaning will rise (Annual Report… 2001, St-Amour 2004). One way to solve these problems would be to mechanise the cleaning operation. Mechanised cleaning has been a subject for studies since the early 1970's in Sweden (cf. Berg et al. 1973). In practice, mechanised cleaning in Sweden had a peak in the early 1990's (Mattsson 1995). Poor cost effectiveness, together with high levels of damaged trees lead to a decrease, and by the year 2000, no such machines were in use in Sweden (cf. Glöde and Bergkvist 2003). For a more detailed description on the historical development of mechanised cleaning, see Ligné (2004). Currently new mechanised cleaning concepts have proven to clean with the same quality (damages and number of remaining trees) as motor-manual cleaners (Ligné 2004), but still with poor economy (cf. Ligné 2004, Kaila 2005). One way to solve the problem with expensive mechanised cleaning would be to automate the operation. "The results of cleaning performed by robots have to reach acceptable results and be done at a competitive cost. The robot has to find, select, and handle trees in the whole assigned area according to given instructions. Furthermore, it must be safe for humans, capable of moving safely within the forest environment, and be able to handle snow and other prevalent boreal weather conditions. The vehicle's size and mass are of importance, and bear on its ability to manoeuvre among remaining stems. Generally, the robot must be capable of operating independently and unattended for several hours in a dynamic and non-deterministic environment. Obstacle avoidance and target identification are identified as the most difficult problems" (Vestlund and Hellström in press). Automation of cleaning would require an appropriate decision support system (DSS) for selecting stems to remain. DSSs are computer-based systems designed to represent and process knowledge in order to support decision-making activities (cf. Holsapple and Whinston 1996). Such a system could also be used as a training-tool for less experienced cleaners to improve the quality of the work (Vestlund 2004).

Cleaners manage to perform cleanings, usually deemed acceptable by the assigners, in the dynamic and non-deterministic forest environment (cf. Vestlund 2004). Interviewed cleaners express clear preferences concerning the characteristics of preferable main-stems, but their implicit rules they follow in the selection process can only be partially clarified (ibid.). However, to attain acceptable results with a DSS there is a need for explicit rules. Today, acceptable cleaning results are usually assessed through the variables: number of stems per hectare, species composition, and percentage of stems with damage (Vestlund 2004). Furthermore, gaps between stems should be less than the double-spacing (Brunberg 1990), and there should be at least 0.5 m between two remaining stems (Vestlund 2004). Consequently, DSSs must include these variables and it is important to use attributes that are connected to them. There are two types of attributes that need to be analysed: single-tree attributes and relational attributes (Füldner et al. 1996, Daume and Robertson 2000a). Single-tree attributes are descriptors of a tree (e.g. species and diameter) and relational attributes describe a tree in comparison to other trees in the stand (e.g. position and relative diameter).

For a DSS to be useful, it must render sufficiently good decisions quickly. Therefore the attributes used must be available as inputs in a model, comprehensive, and measurable (Keeney and Raiffa 1993, Daume and Robertson 2000a, Daume and Robertson 2000b). Vestlund (2004) presented a semi-algorithm based on cleaning manuals and some of the desirable and undesirable attributes mentioned in interviews by cleaners. Given target restrictions regarding stand density and the minimum distance between remaining stems, the semi-algorithm initially suggested selection of stems fulfilling all "quality criteria". The suggested "quality criteria" for the main stems were, in order of importance, that they should be of a preferred species, within the preferred diameter range and undamaged. Other possible criteria were stem straightness, preferred height, branch diameter, straightness of branch-angles, and healthiness of the leading shoot. These five criteria were not presented in any specific order. To meet the density targets, acceptable stems (stems fulfilling some of the "quality criteria") were to be selected if no better alternatives existed and bad stems (stems not fulfilling any of the "quality criteria") were to be selected if only bad stems existed.

Previous programmes for selecting crop-trees in simulated thinnings have used attributes like diameter, position, height, crown length, stem quality, tree vitality, stem damage, species, "crown tension", and "competition index" (Söderbergh and Ledermann 2003). These models give general ideas about attributes and rules but in most cases they are not useful in practice as these models process data for whole stands, i.e. they are not made for operational use. However, a DSS for operational use in thinnings, presented by Daume and Robertson (2000a), works in areas that are within the scope of human observation, i.e. on a small-scale level. This DSS focuses on an "elite-tree" and the trees surrounding it. Practical selections of main-stems in cleaning must also rely on data concerning a small-scale area, since information beyond a certain distance is unobtainable. Vestlund (2004) found that cleaners usually manage to obtain and work with information gathered within a radius of some 5 m. The information acquisition range when using a DSS in practice would probably be similar.

The aims of this study were to develop a DSS for automation of individual stem selections in practical cleaning, and to test, using simulations, if it could render acceptable results.

2 Material and Methods

2.1 General

In order to develop a DSS for automatic selection of main-stems, a forest inventory was conducted and, at the same time, the semi-algorithm by Vestlund (2004) was extended and refined. Data from the inventory along with previously published data (Gustavsson 1974) were used when six cleaning scenarios were simulated with the proposed DSS. Four additional simulations were run with erroneous data.

2.2 Forest Stands

The field inventory (FI) was conducted in the summers of 2002 and 2003 at two areas near Enköping, two near Skutskär, and two near Jönköping (Fig. 1). The selected stands, four dominated by pine and two by spruce (Table 1), were in need of cleaning according to cleaning manuals (cf. Röjning… 1999) and the target was to leave approximately 2500 stems per hectare after cleaning. The studied area at each location was 160 m^2 (20 m × 8 m), except the Jönköping-Pine-area, where it was 224 m^2 (28 m × 8 m).

To increase the available data, an old field inventory (OFI) by Gustavsson (1974) with eleven areas (Fig. 1) was included. These stands were described as representative Swedish cleaning stands but varied regarding e.g. density, species composition, and height (Table 2). The utilised areas were 480 m^2 (20 m × 24 m) at each location.

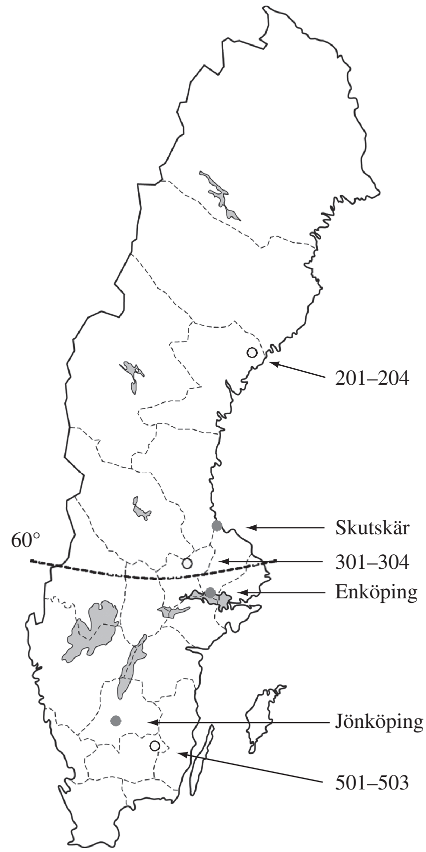

Fig. 1. Sweden, location of the field inventory areas (Skutskär, Enköping, and Jönköping) and the old field inventory areas (Gustavsson 1974) (201–204, 301–304, and 501–503). The position of the 60th parallel is roughly marked.

Retrieved attributes in the FI were: diameter, position, species, and damage; in accordance with the findings in Vestlund (2004). All stems over one cm in diameter at breast height (dbh) were callipered with mm precision (Fig. 2). The centre positions of the stems were measured in X and Y-plane at breast height with cm precision. The stems were categorised as; Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.), juniper (*Juniperus communis* L.), birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.; species not separated), or other deciduous. There are a number of damage types (cf. Brunberg 1990, Röjning… 1999, Vestlund 2004), and four

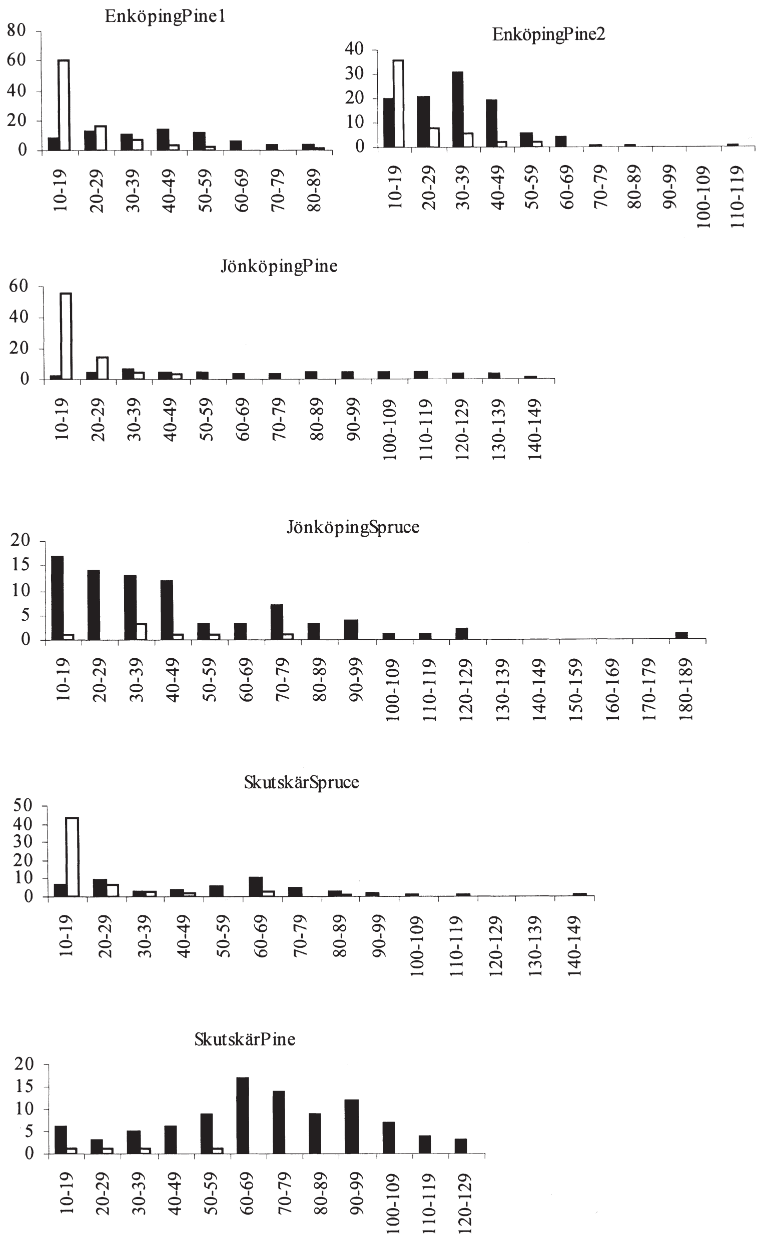

Fig. 2. Diameter distribution for coniferous and deciduous stems in the FI-areas. The Y-axis corresponds to number of stems, and the X-axis to diameters at breast height in mm.

Table 1. Stand data from the field inventory (cf. Fig. 1), all stems over 1 cm in diameter at breast height, dbh, were counted and measured.

Stand data	Location					
	Enköping Pine1	Enköping Pine2	Jönköping Pine	Jönköping Spruce	Skutskär Pine	Skutskär Spruce
Density (stems per ha)	10000	9875	5893	5500	6188	6938
Proportion of birch stems (%)	51.9	32.9	59.1	8.0	2.0	18.9
Proportion of "other deciduous" stems (%)	3.8	1.3	0.0	0.0	2.0	36.0
Proportion of stems with damage (%)	57.5	41.1	65.2	15.9	14.1	60.4
Proportion of stems with "undefined damage" (%)	4.4	0.6	7.6	6.8	5.1	4.5
Mean dbh, total (mm)	30	29	40	46	69	36
Mean dbh, coniferous (mm)	42	34	72	47	70	50
Mean dbh, deciduous (mm)	20	19	18	41	30	24
Age (years)	15	15	15	12	24	17
Site index	T 22	T 22	T 25	G 28	T 24	G 26

Table 2. Stand data from the old field inventory (cf. Fig. 1), all stems were counted and measured.

Stand data	Location										
	201	202	203	204	301	302	303	304	501	502	503
Density (stems per ha)	5542	8021	19021	9688	7125	4104	8604	13500	11250	8625	27146
Proportion of birch stems (%)	63.5	27.0	7.6	27.5	20.8	60.4	45.8	59.0	3.3	34.8	93.6
Proportion of "other deciduous" stems (%)	6.8	47.0	2.1	33.8	11.1	2.0	1.2	0.6	0.0	13.8	0.0
Proportion of stems with damage (%)	49.6	63.6	64.2	70.8	59.9	31.0	67.8	78.4	74.6	67.6	89.9
Mean dbh [a)], total (mm)	31	15	40	25	28	24	35	25	31	49	12
Mean dbh, coniferous (mm)	46	10	40	41	33	34	52	28	32	67	5
Mean dbh, deciduous (mm)	25	16	36	16	17	17	15	23	10	31	12
Age (years)	15	9	39	26	21	10	23	17	17	17	11
Site Index	T 26	T 22	T 20	G 20	G 32	T 32	T 28	T 28	T 28	G 32	G 30

[a)] Diameter at breast height. Stems below breast height were given the value zero.

types considered automatically measurable were chosen for defining damage (Fig. 3). Damage was noted according to these definitions. Damage of types other than those defined were observed and noted as "undefined damage" for 34 of the 748 measured stems. The average tree age for each area was provided by the landowners (Table 1).

Utilised attributes from the OFI were: diameter, position, species, and damage (Gustavsson 1974). In the OFI all stems were measured. The dbh was measured with mm precision; and stems shorter than breast height were given the value zero. The stems were categorised as: Scots pine, Norway spruce, birch, or other deciduous. The stems' positions were measured in X and Y-plane at breast height with dm precision. The stems were classified in seven quality levels, and the lowest level was used for defining damage in the cleaning simulations. The age of the trees in the areas was determined by counting growth rings in sample trees (Gustavsson 1974, Table 2). A thorough description of the OFI-areas, including e.g. diameter distributions, can be found in Gustavsson (1974).

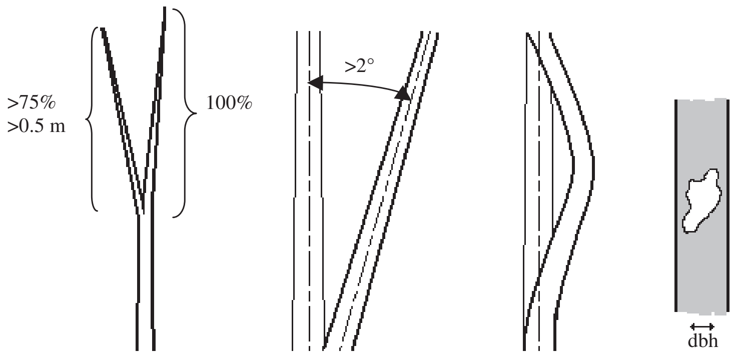

Fig. 3. The defined types of damage: 1) Double top, where the height of the shorter top was at least 0.5 m and at least 75% of the height of the taller top, 2) Leaning stems, i.e. stems having a mean inclination angle larger than 2° from root to top, 3) Stems with crooks, where it was not possible to join the centres of each end with a straight line without crossing the outer edges of the stem at any point, and 4) Stem damage with an area larger than the squared radius at breast height (r^2) of the stem.

2.3 The Decision Support System

Vestlund's (2004) semi-algorithm was used as a starting point for the development of the DSS described here. The restrictions and attributes included in the DSS were evaluated and improved in accordance with the variables used today for representing acceptable cleaning results, i.e. number of stems per hectare, species composition, and percentage of stems with damage (ibid.). Restrictions for minimum and maximum distances between stems were also included. One of the areas, EnköpingPine1, was used as a pilot-area.

The DSS, presented here as an algorithm (Fig. 4), uses three parameters, three thresholds and a "quality criteria" definition regarding stem attributes for selecting remaining main-stems. To fulfil the "quality criteria" stems had to be undamaged (Fig. 3), of preferred species, and within the preferred diameter range. Since the dbh for all stems in the areas were known from the inventory, the coniferous and total mean dbh values (mdc and mdt) were calculated and these values were used for selecting preferred diameter ranges (Eqs. 1–2). The constants used for the range-sizes were selected with the purpose to increase the mean dbh, but to reject stems with very large dbh.

$$(0.66 \times \text{mdc}) \le \text{coniferousdiameterrange} \le (1.66 \times \text{mdc}) \tag{1}$$

$$(0.66 \times \text{mdt}) \le \text{deciduousdiameterrange} \le (1.66 \times \text{mdt}) \tag{2}$$

The three user-defined parameters depend on the purpose of the cleaning. The first parameter is the requested spacing [P1], and concerns the density target and the maximum distance restriction. Each area was divided in smaller parts, here called sections (Fig. 5). The size of a section is the squared double-spacing and varies with the requested number of remaining stems. To reach the density target each section should have four remaining stems, on average, after cleaning. However, to prevent gaps and deal with the maximum distance restriction at least one stem should remain in each section, if possible. The second parameter is the minimum allowed distance between two stems [P2], stem surface to stem surface. This parameter causes the DSS to reject stems, regardless of their quality, if they are situated within this distance from an already selected stem. The last parameter is the requested percentage of deciduous stems [P3], and influences the final selection of remaining stems.

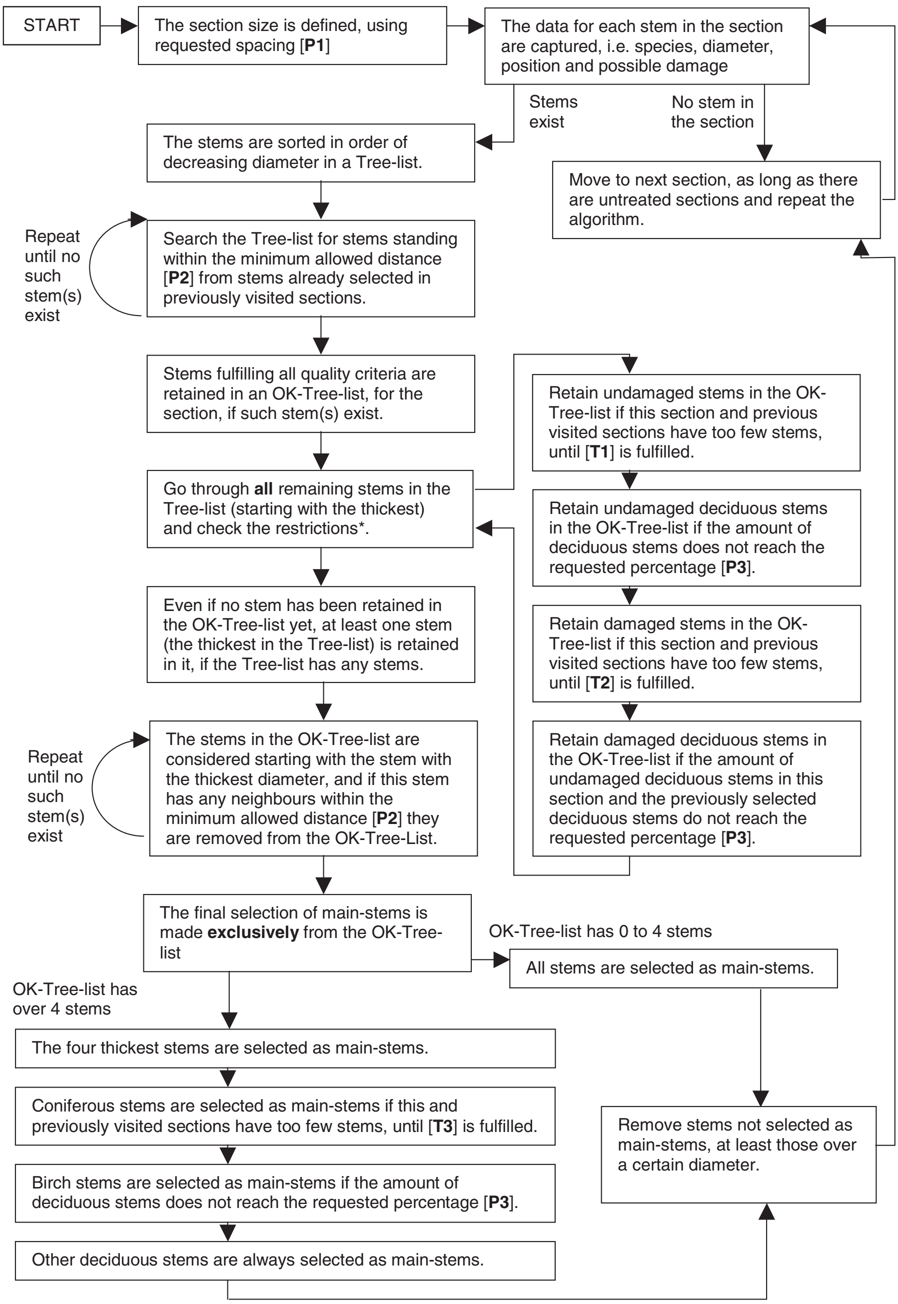

Fig. 4. The developed DSS for selective cleaning presented as an algorithm. The parameters [P1–3] depend on the purpose of the cleaning and the thresholds [T1–3] (Eqs. 3–5) influence the number of selectable and selected stems in each section. See also List of symbols. To fulfil all "quality criteria" stems must be undamaged, of preferred species, and within the preferred diameter range for the species (Eqs. 1–2). * = Each stem is compared with the restrictions, in the presented order, and if the stem fulfils a condition it is retained and the comparing-procedure starts over again with the next stem in the "Tree-list" if such stem(s) exist, as no stem is retained more than once.

In areas where there are too few stems that fulfil the "quality criteria" to reach the targeted density more stems can be selectable according to two thresholds. The first threshold [T1] sets how many undamaged stems outside the diameter range that can be retained in the "OK-Tree-list" with selectable stems (Eq. 3). The second threshold [T2] does likewise but for damaged stems (Eq. 4). The last threshold [T3] influences the final selection of remaining stems (Eq. 5).

$$\frac{(A+B)}{C} < \text{valueUndamaged}[\text{T1}] \quad (3)$$

where (A) is the number of stems retained in the "OK-Tree-list" at this point (cf. Fig. 4), (B) the total number of selected stems at this point, and (C) the number of visited sections (including current section).

$$\frac{(A+B+D)}{C} < \text{valueDamaged}[\text{T2}] \quad (4)$$

where (D) is the number of damaged stems in the section's "Tree-list" (cf. Fig. 4).

$$\frac{B}{C} < \text{valueDefinitive}[\text{T3}] \quad (5)$$

When these restrictions have been set, the selection process, which is made section by section (Fig. 5), can start. Within the diameter range thicker stems are preferred. When stems outside the diameter range must be selected, larger stems are preferred. If an "other deciduous" stem has been retained in the "OK-Tree-list" it is always selected. The DSS does not regard stems outside the marked off areas and it only uses the predefined damage. The design of the DSS was based on the intention that in practical use all unselected stems should be cut. The selections rest upon accessible inputs, i.e. data from the current and previous sections, and selections that have already been made are not changed. A decision to save a stem affects forthcoming decisions, especially in surrounding sections.

The DSS was written in C++. The programme is automatic and reads the inventory data from a text file, but needs the user-defined parameters [P1–3], which are situation-dependent, and the threshold values [T1–3]. The output is deterministic and Boolean, either a stem is saved or it is not. Note that Scots pine and Norway spruce are considered equal in the DSS.

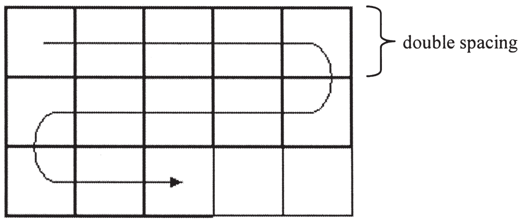

Fig. 5. General layout of the measured area and sections. The arrow displays how data for each section were added to each other.

2.4 Simulations with Different Cleaning Targets

Six cleaning simulations with different settings were run (Table 3). In accordance with general instructions to cleaners (Vestlund 2004) the "General" simulation had a density target of 2500 stems per hectare after cleaning, so the spacing was set to 2 m, i.e. each section was 4 m × 4 m. The minimum allowed distance between stems was 0.5 m, and as a target 10% of the remaining stems should be deciduous, "valueUndamaged" [T1] was set to 4, "valueDamaged" [T2] to 3, and "valueDefinitive" [T3] to 5.5 (Eqs. 3–5, Table 3). The "Reverse" simulation had the same settings as the "General" simulation but the "Reverse" simulation started in the opposite corner of the areas.

The "Changed thresholds" simulation increases the importance of reaching the targeted number of remaining stems. The "valueUndamaged" [T1] and "valueDamaged" [T2] were increased to 5 and 4, respectively, in order to have more stems to choose from. However, to reach the targeted number of remaining stems the "valueDefinitive" [T3] was decreased to 4.5.

In the "4000-stems" simulation, the spacing parameter [P1] was decreased as the targeted number of stems per hectare was increased to 4000. Other values were as in the "General"

Table 3. Target settings for the six simulations. P1 is spacing in m, P2 the minimum allowed distance in m between stems, and P3 the requested percentage of deciduous stems. The threshold values "valueUndamaged" [T1], "valueDamaged" [T2], and "valueDefinitive" [T3] are described in Eqs. 3–5.

Simulation	Settings					
	P1	P2	P3	T1	T2	T3
General	2	0.5	10	4	3	5.5
Reverse	2	0.5	10	4	3	5.5
Changed thresholds	2	0.5	10	5	4	4.5
4000-stems	1.58	0.5	10	4	3	5.5
Increased minimum distance	2	1.0	10	4	3	5.5
30%-deciduous	2	0.5	30	4	3	5.5

simulation. The simulation "Increased minimum distance" was used to analyse how the selection of stems in one section influences other sections. Here, the minimum allowed distance between stems [P2] was increased and other settings were as in the "General" simulation. In the "30%-deciduous" simulation the targeted percentage of deciduous stems [P3] was increased and other settings were as in the "General" simulation.

Means and 95% confidence intervals (CI_{95}) were calculated for the results of each simulation of the FI areas, OFI areas, and all areas together with respect to density, proportion of deciduous stems, and proportion of damaged stems. These values and the different simulations' effects on the diameter were searched for significant differences ($p<0.05$). When doing pair wise comparisons, Tukey's test was used to avoid mass significance. The 2-sided F-test was used to test for equal variance. When equal variance could be assumed pooled variances were used, and when two means of small samples with different variances were compared the statistics are referred to as the Behrens-Fisher problem (Everitt 2002).

2.5 Simulations with Erroneous Data

In an outdoor environment like the forest it can be difficult to collect fully correct data (cf. Vestlund and Hellström in press), instead it is likely that the precision will be lower than the data used here. Therefore, four simulations with erroneous data were run in order to further test the DSS and perceive its sensitivity to the precision of different attributes. Each attribute was varied individually to obtain more detailed indications of conditions in which the DSS might render unacceptable results. The target settings in these simulations were as in the "General" simulation (Table 3). The four simulations were:

- No damage were identified (No Damage)
- The diameter got a random error of ±25% (Diameter ±25%)
- All deciduous trees were treated as birches (All birches)
- Stems with dbh<2 cm were not considered (No dbh<2 cm)

Note that the calculated diameter ranges (Eqs. 1–2) always used correct data.

3 Results

The "General" cleaning simulation in the FI areas gave a range of 2009 to 3500 remaining stems per hectare, which should be compared to the density target of 2500. The proportion of deciduous stems was less than the target of one-tenth for the SkutskärPine-area, and the mean dbh of deciduous stems was greater than the mean dbh of coniferous stems for the SkutskärSpruce-area (Table 4).

The OFI areas had smaller variations in remaining stems after the "General" cleaning simulation than the FI areas, and only two areas (203 and

Table 4. Results of the "General" cleaning simulation in the field inventory areas.

Stand data	Location					
	Enköping Pine1	Enköping Pine2	Jönköping Pine	Jönköping Spruce	Skutskär Pine	Skutskär Spruce
Density (stems per ha)	2625	3063	2009	2563	3500	2500
Proportion of deciduous stems (%)	9.5	8.2	11.1	12.1	3.6	15.0
Proportion of stems with damage (%)	9.5	8.2	8.9	7.3	1.8	0.0
Mean dbh [a)], total (mm)	47	39	73	55	81	57
Mean dbh, coniferous (mm)	46	39	79	57	83	53
Mean dbh, deciduous (mm)	57	30	30	40	18	77

[a)] Diameter at breast height, stems over 1 cm.

Table 5. Results of the "General" cleaning simulation in the old field inventory areas.

Stand data	Location										
	201	202	203	204	301	302	303	304	501	502	503
Density (stems per ha)	2313	2229	2542	2396	2333	2063	2458	2354	2479	2604	2354
Proportion of deciduous stems (%)	40.5	27.1	13.1	12.2	13.4	34.3	11.9	23.9	6.7	10.4	47.8
Proportion of stems with damage (%)	2.7	0.0	2.4	1.7	3.6	1.0	0.0	0.0	6.7	9.6	0.0
Mean dbh [a)], total (mm)	50	13	63	51	46	32	71	43	46	78	11
Mean dbh, coniferous (mm)	50	11	61	51	48	36	77	44	48	81	6
Mean dbh, deciduous (mm)	39	20	73	46	32	23	30	40	13	52	17

[a)] Diameter at breast height, all stems measured.

502) had more stems than the targeted 2500. The proportion of deciduous stems exceeded the target of one-tenth for five out of eleven areas. For three areas (202, 203, and 503) the mean dbh of deciduous stems was larger than the mean dbh of coniferous stems (Table 5).

On average, the "General" and "Reverse" simulations gave almost the requested number of remaining stems per hectare (Table 6). With the "Changed thresholds" simulation the density was slightly above target, but the CI_{95} decreased compared to the "General" and "Reverse" simulations. The "30%-deciduous" simulation increased the number of remaining stems compared to the "General", "Reverse", and "Changed thresholds" simulations. However, these density differences were not statistically significant ($p > 0.05$) (Table 6). The density after the "Increased minimum distance" simulation was below target, but was not significantly different ($p > 0.05$) from the density achieved with the "General" simulation. In the "4000-stems" simulation the density target was increased to 4000 stems per hectare, and after the simulation stand density varied between 2360 and 4423 stems per hectare. The number of stems was above target in one area, however, the number of stems was significantly higher than in the other simulations ($p < 0.05$) (Table 6).

The percentage of deciduous stems was above target in 76 % of the cases, and within ±3% of the target in 39% of the cases. This percentage was in all six simulations below target for one FI area (SkutskärPine) and above target for three OFI areas (201, 302, and 503). The amount of deciduous stems was higher in the "30%-deciduous" simulation; but the differences were not statistically significant ($p > 0.05$) (Table 6). The number of "other deciduous" stems varied from 10 to 51 after the different simulations, i.e. from 0.7% to 3.2% of all remaining stems.

Table 6. Mean values and 95%-confidence intervals (CI_{95}) for the six simulations with different target settings (Table 3). Values within the same subheading and column followed by different letters (a, b, and c) are significantly different ($p<0.05$).

Simulation	FI [a)] mean	FI [a)] CI_{95}	OFI [b)] mean	OFI [b)] CI_{95}	Total mean	Total CI_{95}
			Density (stems/ha)			
General	2710	±538	2375	±100	2493ab	±181
Reverse	2680	±512	2439	±109	2524b	±166
Changed thresholds	2761	±140	2551	±126	2625b	±101
4000-stems	3602	±541	2969	±208	3193c	±252
Increased minimum distance	2331	±390	2146	±139	2211a	±144
30%-deciduous	2960	±522	2494	±200	2659b	±221
			Proportion of deciduous stems (%)			
General	9.9	±4.1	21.9	±9.3	17.7a	±6.5
Reverse	11.3	±5.4	21.6	±9.2	17.9a	±6.3
Changed thresholds	11.5	±5.3	21.7	±9.1	18.1a	±6.2
4000-stems	15.6	±12.5	25.9	±10.9	22.3a	±7.9
Increased minimum distance	8.5	±5.1	22.2	±9.8	17.4a	±7.0
30%-deciduous	21.7	±11.3	30.9	±6.6	27.7a	±5.6
			Proportion of remaining stems with damage (%)			
General	5.9	±4.2	2.5	±2.1	3.7a	±1.9
Reverse	7.6	±6.5	2.5	±1.8	4.3a	±2.5
Changed thresholds	10.8	±9.1	4.5	±1.9	6.7ab	±3.2
4000-stems	12.8	±10.9	11.9	±3.2	12.2b	±3.4
Increased minimum distance	8.1	±8.3	3.2	±2.4	4.9a	±3.0
30%-deciduous	16.9	±9.8	10.5	±6.0	12.8b	±4.8

[a)] FI = field inventory (cf. Table 1)
[b)] OFI = old field inventory (cf. Table 2)

In the "General" cleaning simulation 3.7% of the remaining stems had defined damage. In comparison, the number of damaged stems was higher in the "Reverse" and "Increased minimum distance" simulations and almost doubled in the "Changed thresholds" simulation. The "4000-stems" and "30%-deciduous" simulations had damage frequencies greater then 12%; significantly higher than the results of the "General", "Reverse" and "Increased minimum distance" simulations ($p<0.05$) (Table 6). Most of the stems with "undefined damage" (61.8–85.3%, i.e. 8.7–10.3% of all remaining stems) in the FI areas remained after the different cleaning simulations.

In the "General" simulation three damaged stems were selected as main-stems, which caused stems in other sections to be rejected. However, these stems were also damaged, i.e. no selection of a damaged stem forced the DSS to discard any undamaged stems in these 394 sections. In the "Increased minimum distance" simulation, damaged stems in eight sections influenced surrounding sections, causing the rejection of five undamaged stems and twelve damaged stems.

The increase of the total mean dbh was significant ($p<0.05$) and ranged from +40.1% (CI_{95} ±12.8) to +55.7% (CI_{95} ±16.7) for the different simulations. The total mean dbh increased with 22–34% for coniferous stems and with 42–78% for deciduous stems. However, the total mean dbh decreased in the 503-area in every simulation. The increases in total, coniferous, and deciduous dbh were not significantly different between the simulations ($p>0.05$).

The desire to have a maximum distance between stems less than the double spacing, expressed in

Table 7. Mean values and 95%-confidence intervals (CI_{95}) for the four simulations with erroneous data.

Simulation	FI [a]		OFI [b]		Total	
	mean	CI_{95}	mean	CI_{95}	mean	CI_{95}
			Density (stems/ha)			
No damage	2920	±487	2733	±303	2799	±232
Diameter ±25%	2689	±522	2377	±95	2487	±173
All birches	2706	±534	2373	±101	2490	±179
No dbh<2 cm	2695	±540	2078	±303	2296	±283
			Proportion of deciduous stems (%)			
No damage	16.7	±10.0	33.6	±18.3	27.6	±12.2
Diameter ±25%	10.4	±4.1	21.9	±9.2	17.8	±6.4
All birches	9.9	±4.1	21.9	±9.3	17.7	±6.5
No dbh<2 cm	9.7	±4.8	29.3	±19.7	22.4	±13.0
			Proportion of remaining stems with damage (%)			
No damage	24.9	±13.5	42.7	±15.5	36.4	±11.1
Diameter ±25%	6.4	±4.8	2.5	±2.0	4.0	±2.0
All birches	5.9	±4.2	2.5	±2.1	3.7	±1.9
No dbh<2 cm	6.4	±5.3	15.1	±17.5	12.0	±10.9

[a] FI = field inventory (cf. Table 1)
[b] OFI = old field inventory (cf. Table 2)

this model as at least one stem per section, was reached in all sections that initially had stems.

The four simulations with erroneous data had various results (Table 7). In the case where no damage were identified there was a considerable increase in the proportion of damaged stems. The density and proportion of deciduous stems also rose in general, but the variations were large especially in the OFI areas. In the cases where the diameter got a random error of ±25% and when all deciduous trees were treated as birches the results were less affected. However, in the case where stems with a dbh below 2 cm were not considered the density decreased and proportion of damaged and deciduous stems increased in general, but some areas, e.g. the FI areas, were hardly affected so the variation were large. The number of "other deciduous" stems varied from 9 to 78 after the different simulations, i.e. from 0.6% to 4.5% of all remaining stems. In the case when all stems were treated as birches 9 "other deciduous" stems remained in the areas, which should be compared with the results of the "General" simulation were 10 such stems remained.

4 Discussion

4.1 The Decision Support System

This cleaning DSS is analytical and is intended to select main stems, like human cleaners, but not necessarily in the same way (cf. Murphy 2000, Vestlund 2004). The activities are currently pre-programmed, i.e. the DSS-recommendations are deterministic in the sense that they always follow the given instructions/settings. Another approach would be to let the DSS learn which qualities are requested, and in future this approach might be tested. Such a design may be useful when several sensors can capture the input data instead of it being provided, as here, through a text file. DSS tools can also be synthetic, providing a large number of alternative courses of actions. Mendoza and Sprouse (1989) discuss this technique by which a wide variety of decision alternatives provide a wide range of choices. However, besides generating satisfactory alternative solutions, the generated alternatives must be examined, evaluated and synthesized by the decision maker. This calls for a prioritised set of alternatives, a measure of their relative importance, in order to make the selections (Mendoza and Sprouse 1989). Since the selections in this case must be made automatically and since the decision environment is complex, the priority of the alternatives would probably be set in similar terms to how the restrictions are set in the current DSS.

The attributes used in the DSS were selected since cleaners and cleaning manuals mention them (cf. Vestlund 2004) and because it should be possible to detect them automatically. A cleaning DSS should include as many attributes (and rules) as needed to give acceptable result, but as few as possible to make the system simple and fast (cf. Daume and Robertson 2000b). This DSS was developed to suit conventional Swedish cleanings, i.e. cleanings of stands at some three or four meters of height where Scots pine and Norway spruce are favoured species (cf. Brunberg 1990, Varmola and Salminen 2004, Vestlund 2004, Ligné et al. 2005). A usual request regarding company owned forests is to have 2500 stems per hectare after cleaning of which 10% deciduous (Vestlund 2004) and the FI-areas were selected accordingly. The OFI areas were included in order to test the DSS in a larger variety of forest types (cf. Tables 1 and 2).

The most challenging problem in developing a DSS for automatic cleaning are probably how the attributes should be sensed automatically in the forest environment. Machine vision, radar, and laser scanners, and combination of such sensors, appear to be promising solutions (Vestlund and Hellström in press). Erikson and Vestlund (2003) proved it possible to find trees with a dbh <0.05 m in images produced with data from a laser scanner. It seems that necessary sensors, algorithms, and methods to develop and demonstrate operationally viable outdoor autonomous vehicles already exist (cf. Durrant-Whyte 2001). However, what quality this kind of data holds is difficult to state at this moment of the development phase.

The attributes diameter, position, and straightness are attributes that should be possible to detect with machine vision and/or laser measurements (cf. Erikson and Vestlund 2003). It should also be possible to identify species and detect the other three defined damage types (cf. Fig. 3) with such approaches (cf. Mattsson 1996, Blackmore et al. 2002, Holmgren 2003). For instance, Holmgren (2003) has shown that computerised systems can discriminate the species of large trees, although these attributes (species/damage) require thorough and careful description in order to be determined automatically.

The constants in the presented diameter-range (Eqs. 1–2) were set with the purpose to increase the mean diameter but to reject stems with the largest diameter. With this range-size, the remaining stems should be more uniform in size. As long as there are undamaged stems of preferred species within the preferred diameter interval the number of potential "wolf-stems" and small stems will be reduced. However, if there are too few desirable stems in a section, larger or smaller stems will be selected, if possible. The reason for using mean dbh values in the range equation was to avoid making active decisions during the actual field inventory, and it was also an advantageous approach for the OFI material. Clearly, this procedure cannot be adopted in future practical cleanings, since the diameters of the stems in the stand will not be known in advance. The diameter range applied here was not advantageous for areas where the coniferous stems had smaller diameters than the deciduous stems. However, this problem will disappear when the user/operator provides preferable diameters, in accordance to the requests of the assigners, which will be used for calculating the preferred range-size. The values for the diameter ranges could also be adjusted as stems in the stand are measured. The constants could naturally also be altered, for example to broaden or narrow the range for different species.

The final number of selected stems is dependent on the density target, the three threshold values [T1–3], and the requested target for deciduous stems [P3]. The intention was that all other stems should be cut. In a practical cleaning, stems that are too small to compete with the main stems could be left uncut (cf. Brunberg 1990, Vestlund 2004). The reason for setting the "valueUndamaged" [T1] higher than the "valueDamaged" [T2] was to decrease the final number of damaged stems and to allow more undamaged stems to be selected in other sections. However, setting "valueDamaged" [T2] to 3 could lead to areas with 25% fewer stems than the requested target. The "valueDefinitive" [T3] sets the final number

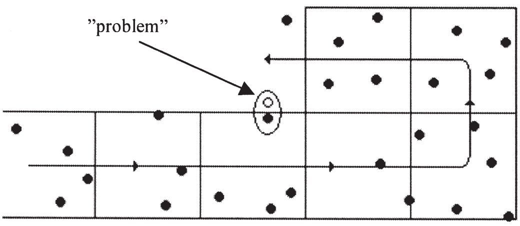

Fig. 6. The dots represent selected stems. The ring symbolises a stem of better quality than the already selected stem. The stem of better quality will be cut since it is within the minimum allowed distance to the already selected stem, i.e. the "problem".

of selected stems, along with the parameter regarding deciduous stems [P3], which can raise the number of deciduous stems in the "OK-Tree-list" and final selection to meet the requested target. When "valueDefinitive" [T3] is set to 5.5 the DSS is allowed to select up to 37.5% more stems than the density target, if there are more stems in the "OK-Tree-list". However, the number of stems is also dependent on previously visited sections. The reason for this design was to compensate for sections not yet visited which could have a lack of desirable stems, and stems of good quality should not be removed simply in order to create a uniform stand (cf. Brunberg 1990). In the future, threshold values could be set by the operator and modified in accordance with factors such as the amount of gaps in the stand. These values could then be automatically adjusted as the work proceeds. Setting all threshold values to 4 would increase the ability to meet the density target but could increase the proportion of damaged stems, or stems of undesirable species.

Selected main-stems in previously visited sections influence stems in other sections standing within the minimum allowed distance from the main-stems. A problem with this design is that a damaged stem can be selected as it is the best stem in one section, but the next section may contain an undamaged stem within the minimum allowed distance from it. The undamaged stem will then be cut immediately as it was too near the damaged stem that had already been selected (Fig. 6). This was not a problem in the simulations where the minimum allowed distance was 0.5 m. When the minimum distance was increased to 1.0 m between stems, the problem appeared, but only five undamaged stems were rejected in the 17 areas. However, a more complex design where the selection is changed and the damaged stem is removed and the "better" stem is selected instead would eliminate this problem. Another approach would be to obtain new information on surrounding stems when a damaged stem is about to be selected as a main-stem.

The DSS preferably selects undamaged stems and thus reduces the number of damaged stems if possible. Currently a stem is regarded as damaged if it has one or more of the defined damage types. However, it might be better to sometimes allow the selection of damaged stems. Deciduous stems of the preferred diameter with damage could, for instance, be selected instead of undamaged stems outside preferred diameter range. The species could also have separate definitions regarding damage types. Stems browsed by moose could possibly also remain, in the interest of wildlife, if they are not competing with main-stems (Röjning… 1999).

The stems with "undefined damage" usually remained in the areas, since they were regarded as undamaged by the DSS. All defined types of damage were treated in the same way whereas stems with very few living needles/leafs were accepted as undamaged, so this type of damage should be included in the pre-defined damage list. There will always be some unidentified types of damage in a DSS because they are undefined (rare). Damaged stems can also be unidentified because of a restricted view. Decisions can only be made in accordance with available instructions and information, and viewing obstructions can cause problems for cleaners too (cf. Vestlund 2004). Cleaners might be able to detect more types of damage, but technical instruments have other advantages, e.g. the ability to measure the inclination angel of a stem (Fig. 5). Damage types could be ranked, such that particular types of damage are preferred to others. The damage could also be graded, i.e. a leaning stem with 3° inclination could be preferred to a leaning stem with 5° inclination. However, to do this each damaged stem would have to be examined extensively to ensure that the degree of damage was correctly designated, and time spent on damaged stems might be wasted. Furthermore, grading damage is problematical since no real validation can be made of the relative seriousness of different types of damage.

This DSS includes, in order to be simple and operational, only a few attributes, which were considered to be assessed automatically. There could also be other interesting attributes indicating preferable stems. For instance, Persson (1976) showed that the thickest branch of a tree is a suitable indicator of the quality of sawn goods. Height is also an interesting attribute, especially in pine stands as pines, which are pioneers, are more susceptible to competition than spruces (Nilsson and Gemmel 1993). Height was not used as it is correlated with diameter (Kahn 1995) and since dbh seem to be easier to estimate correctly with automatic techniques than height as inclination angles can cause perspective problems (cf. Clark et al. 2000, Erikson and Vestlund 2003). Branch attributes were neither not measured in this study. However, with more research it should be possible to automatically make adequate estimations of height, as well as of branch-size and branch-angle. Living-crown-height seems to be a less useful indicator in these young stands, since most stems in the OFI areas had living branches all the way down to the root (cf. Gustavsson 1974). Attributes like quality and vitality can be assessed by a human, but are quite complex to define in ways that a computer could use. However, there are many promising sensing techniques for determining the vitality of seedlings and plants, e.g. infrared thermography, multi-spectral analyses, and chlorophyll measurements (Mattsson 1996, Blackmore et al. 2002),

Since the selected FI areas either were dominated by pine or spruce (regarding coniferous stems) these species were not separated in the current DSS. When assigners seek to preserve or change the mix of coniferous stems this condition must be added and can be handled as the birch are handled in the presented DSS. However, to separate pine and spruce automatically should be one of the easier tasks of species discrimination since these species appearance are different. Furthermore, this DSS does not deal with "fruit-bearing" species (e.g. mountain ash (*Sorbus aucuparia* L.), bird-cherry (*Prunus padus* L.), and juniper. These species should always remain (Röjning… 1999) and this should also be added to the DSS.

4.2 Simulations

On average the "General" cleaning simulation reached the density target, the amount of deciduous stems was somewhat above target, and 4% of the remaining stems had defined damage. The number of remaining stems per hectare varied more in the FI than in the OFI areas. The FI areas were about one third the size of the OFI areas, so each stem and each decision influenced the results more. The FI areas were more heterogeneous in the sense that the variation in number of undamaged stems was higher. The OFI areas had a larger initial variation in total number of stems per section (4 m × 4 m), i.e. 0 to 87 stems per section. The FI areas had initially 5 to 30 stems per section (4 m × 4 m). It should also be noted that the FI and OFI results are not completely comparable due to differences in the measurement procedures involved.

A number of areas had higher stem densities than targeted because they had a high number of stems fulfilling the quality criteria (undamaged stems of preferred species in the preferred diameter interval). In these cases the stand density was largely decided by T3. For example, SkutskärPine in the "General" simulation was only limited by T3 since many stems fulfilled the quality criteria and in the last section an extra deciduous stem was added, leading to a final density of 3500 stems per hectare. In stands with a high share of damaged stems T2 will limit the stand density, and as seen in the present study JönköpingPine had 20% fewer stems than targeted after the "General" simulation. However, to leave exactly 2500 stems and have more damaged stems might not be advantageous. To have fewer stems where there are many stems fulfilling the quality criteria might also be unwise. Nevertheless, the results can in both cases be adjusted by altering the threshold values [T1–3].

An inventory by Pettersson and Bäcke (1998) revealed that stands in Sweden had, on average, 4000 stems per hectare and some 30% deciduous stems after cleaning. In accordance the user-defined parameters were changed. When the requested density was increased to 4000 stems per hectare the target proved difficult to meet, mostly due to a lack of undamaged stems. Some of the areas (e.g. JönköpingPine, SkutskärPine, and 503) did not reach all targets. However, it is important to remember that the state of the initial stand affects the possibility to reach the targets, especially the requested species mix, as stems must be selected throughout the whole area and some parts of the stand can lack the desired species. The species mix must be individually selected in accordance with the state of the initial stand. An area like SkutskärPine that has few deciduous stems (4%) before cleaning is difficult and perhaps not even desirable to change into a stand with 10% deciduous stems. Similarly, aiming at 90% coniferous stems when the area before cleaning had over 90% deciduous stems (e.g. 503) may not be rational. Although "other deciduous" retrieved in the "OK-Tree-list", was to be left in order to have a diversified forest, just ten such stems were selected in the "General" setting, as most of them (98.3%) were damaged.

The first six simulations all decreased the percentage of stems defined as damaged substantially. When more stems were to be left or the share of deciduous stems were increased the amount of stems with damage increased, as inferior stems had to be selected when no better alternatives existed.

On average, the mean dbh increased, although there were exceptions. For example, the total mean dbh decreased in areas where coniferous stems initially had a smaller mean diameter than the deciduous stems. The respective means for coniferous and deciduous stems also decreased in some cases. This was because these areas initially had a low number of preferable coniferous and deciduous stems, respectively, and the undamaged stems proved to be smaller stems.

The four simulations with erroneous data clearly emphasize the need for the automatic sensors to be able to identify all trees and to identify damaged trees. If this is not possible there is no need to pursue the development of automatic selective cleaning, instead one option for automation of the operation would be to further investigate whether geometrical cleaning could be automated. The core of selective cleaning is the ability to select stems with certain attributes. Furthermore, if it is impossible to find small stems it is not possible for the robot to realise when the cleaning is done. The robot also needs to find trees in order to cut them or retain them in the stand. A further analysis of different sensors and their ability in forestry has been made by Vestlund and Hellström (in press).

4.3 Conclusions

This DSS was developed to suit stands with a predominance of coniferous stems remaining after cleaning, and the FI areas were selected accordingly. In general the DSS produced acceptable results, when the correct data was used. The state of the initial stand will influence the results of the cleaning operation, i.e. different stand types need separate cleaning instructions. Thus, the species mix, threshold values, and dbh ranges etc. must be individually selected in accordance with the state of the stand and the assigners' requests. However, the ability to change the restrictions in accordance with stand characteristics and preferred results seems to be acceptable, but could be improved. For example should stems with few needles/leafs be defined as damaged, furthermore should fruit-bearing stems be differentiated so they can be saved in the stands. Possibly also damaged deciduous stems should be possible to select as remaining stems.

The simulation results indicate that the DSS is operational. However, for implementation in robotics a crucial problem is to automatically perceive the selected attributes. The need to correctly measure the diameter or classify deciduous trees seems to be of less importance in comparison to the need to find all trees and to identify damaged trees, which the four simulations with erroneous data stressed.

To decide whether the individual stem selections are acceptable (or if the DSS should be refined) the variables of current general cleaning follow-up are insufficient and further research must be conducted. A comparison on tree-level with cleaners that produce results accepted by landowners therefore has been done by Vestlund et al. (2005).

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