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KNOTS IN SCOTS PINE *(PINUS SYLVESTRIS* L.*)* AND NORWAY SPRUCE *(PICEA ABIES* (L.) KARST.) AND THEIR EFFECT ON THE BASIC DENSITY OF STEMWOOD

IRJA LEHTONEN

Seloste

MÄNNYN (*PINUS SYLVESTRIS* L.) JA KUUSEN (*PICEA ABIES* (L.) KARST.) SISÄOKSAT JA NIIDEN VAIKUTUS PUUN TIHEYTEEN

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The properties of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) knots and the effect of knots on the surrounding stemwood were examined in the study.

The volume percentage of the pine knots was 0,8—4,3 % ($\bar{x}$ 2,0 %) and the spruce knots 0,5—2,0 % ($\bar{x}$ 1,2 %). The weight percentage for pine varied from 2,3 to 11,5 % ($\bar{x}$ 6,4 %) and spruce from 1,1 to 6,7 % ($\bar{x}$ 3,5 %).

The basic density of the pine and spruce branch stumps were respectively 221 and 407 kg/m^3 higher than that of the stemwood. The basic density of the knot wood exceeded that of the stemwood by 351 kg/m^3 in pine and 490 kg/m^3 in spruce.

The density of the wood surrounding the knots was slightly lower than that of the knots and slightly higher than that of the knot-free stemwood. The density decreased on moving horizontally from the wood surrounding the knot into the wood lying between the knots. The average density of spruce and pine stemwood with knots was 5,4 and 2,1 % higher than stemwood without knots.

The density of the wood lying between two consecutive branch whorls reached a maximum immediately above and below the branch whorls. The density of both spruce and pine wood lying half-way between two branch whorls decreased. The effect of branches on the wood lying between two branch whorls extended over about 20 % of the distance above and below the whorls.

Tutkimuksessa selvitettiin männyn (*Pinus sylvestris* L.) ja kuusen (*Picea abies* (L.) Karst.) sisäoksien ominaisuuksia ja oksien vaikutusta niitä ympäröivään puuaineeseen.

Oksien tilavuusosuus oli männyllä 0,8—4,3 % ($\bar{x}$ 2,0 %) ja kuusella 0,5—2,0 % ($\bar{x}$ 1,2 %). Painoosuus vaihteli vastaavasti männyllä 2,3—11,5 % ($\bar{x}$ 6,4 %) ja kuusella 1,1—6,7 % ($\bar{x}$ 3,5 %).

Männyn oksantynkien tiheys oli 221 kg/m^3 ja kuusen 407 kg/m^3 suurempi kuin runkopuun. Sisäoksien puuaineen tiheys oli männyllä 351 kg/m^3 ja kuusella 490 kg/m^3 suurempi kuin runkopuun tiheys.

Oksaa ympäröivän puuaineen tiheys oli hieman pienempi kuin sisäoksien ja hieman suurempi kuin oksattoman runkopuun. Tiheys pieneni siirryttäessä vaakasuorassa suunnassa oksaa ympäröivästä puuaineesta oksien välillä olevaan puuhun. Oksaisen puuaineen tiheys oli männyllä keskimäärin 2,1 % ja kuusella 5,4 % suurempi kuin oksattoman puuaineen.

Vuosikasvaimen alueella oksattoman puuaineen tiheys oli suurin juuri oksakiehkuran ylä- ja alapuolella. Vuosikasvaimen keskivaiheilla sekä kuusen että männyn puuaineen tiheys oli pienimmillään. Oksien vaikutus vuosikasvaimen puuaineen tiheyteen ulottui noin 20 % oksakiehkuran ylä- ja alapuolelle.

Helsinki 1978. Valtion painatuskeskus

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1. INTRODUCTION

The degree of knottiness in trees and the effect of knots on wood has been primarily studied from the practical point of view. Knots even affect, for instance, sawing results and power consumption during sawing, pulp yield and chemical consumption. According to S i i m e s (1938), for instance, the most important factor in pine saw logs, as regards sawing results, is the largest knot and in spruce sawlogs the high degree of knottiness.

The effect of individual knots on the properties of the surrounding wood is dependant on a number of different factors, such as knot diameter and the length and angle of the knots. There are also important differences between tree species (K n i g g e and S c h u l t z 1966).

The proportion of knots out of the total volume of the stem can be estimated from the cross-sectional area of the branches and their number. The cross-sectional area or diameter is the best parameter since they correlate well with knot volume and, in addition, are easily measured (von W e d e l et al. 1968).

It has been found in studies concerning branchiness, that the southern-facing side of the tree has slightly more branches than the north-facing one (e.g. W e g e l i u s 1939). Branchiness also varies with forest site type and other environmental conditions. For example, if a tree grows at a fast rate when young then the wood will contain many knots.

The number of branches per unit stem length decreases in the lower part of the crown but then starts to increase from the middle of the crown upwards (W e s t e r n 1971). It has in general been found in Fenno-Scandia that spruce has its largest branches in the lower part of the crown, and pine in the middle of the crown (A g e r et al. 1964, W e s t e r n 1971, U u s v a a r a 1974). In corresponding studies carried out in Central Europe, the smallest branches have been found in the butt end of the stem and the thickest ones in the crown (e.g. A b e t z and M e r k e l 1968). This is due to the fact that in densely growing plantations, especially, the branch life in the upper part of the crown is longer than that in the lower part (e.g. R a p r a e g e r 1939), and hence the proportion of large branches increases at the expense of the smaller ones (K r a s t a n o v 1962, D e j m a l 1972a).

Under normal conditions, pine has less branches than spruce. This is due to the fact that the branch whorls of pine contain fewer branches than those of spruce and

the intermediate branches found between the branch whorls in spruce are lacking in pine. The length of the living crown is also shorter in pine (e.g. B o u t e l j e 1966, von W e d e l et al. 1968, H a k k i l a et al. 1972).

The basic density of pine and spruce branches is from two to three times higher than that of knot-free stemwood (B o u t e l j e 1966, H a k k i l a 1971). The stemwood in the immediate vicinity of the branch whorls has the highest basic density and the basic density of the wood between the branch whorls decreases uniformly towards the midpoint between two adjacent branch whorls. The branches also affect the basic density of the stemwood since the density of the knot-free wood in trees where there are many branches is lower than that of the wood in trees with few branches (K l e m 1933—37, V u o r i s t o 1937). Owing to the fact that the branches affect the physical properties of the wood, they have also been used to estimate the basic density of the stemwood. Statistically significant correlation has been found between the basic density of the stemwood and that of the branches (Z o b e l and R h o d e s 1956, 1957, P e r s s o n 1972). Z o b e l and R h o d e s are of the opinion that the basic density of branch wood can be safely used to estimate the basic density of stemwood, while, on the other hand, P e r s s o n does not consider the method to give satisfactory results.

The properties of knots in Scots pine and Norway spruce as well as their effect on the surrounding stemwood are examined in this study.

I would like to thank the following persons for the help they have given me during the different stages of this study: Karl-Erik M a l m b e r g (field work), Kaarina K o s k i n e n (laboratory work), Leena K u n n a r i (laboratory work and figures), Aune R y t k ö n e n and Leena T u r u n e n (typing). The manuscript was translated into English by John D e r o m e, B.Sc. Pentti H a k k i l a, Matti K ä r k k ä i n e n, Olli U u s v a a r a and Yrjö V u o k i l a have read the manuscript and given valuable advice.

2. MATERIAL AND METHODS

The study material was collected in spring 1975 from the Ruotsinkylä research area (60° 21′ N; 24° 50′ E) of the Finnish Forest Research Institute. Ten pine and ten spruce trees were chosen as sample trees from a stand growing on a site of the *Vaccinium*-type. The sample trees are described in detail in table 1. A mark was made on the southern side of each sample tree using a motor saw. Sample disks were cut on site from the living part of the crown, care being taken to ensure that as far as possible the knots were removed in one piece. The whole crown was sawn up into 5 cm long disks, all of them being included as samples. The first sample was taken from the site of the lowest branch whorl, the following samples consecutive after the first one. Branch stumps, extending out 2 cm from the surface of the stem were left on each disk bearing branches. Disk thickness was normalized when the results were being calculated.

Table 1. Description of the sample trees
Taulukko 1. Näytepuiden kuvaus

Tree species *Puulaji*	Number of tree *Puun numero*	$d_{1,3cm}$ $d_{1,3cm}$	Height, m *Pituus, m*	Length of the living crown *Elävän latvuksen pituus*
Pine *Mänty*	1	14	14,2	8,0
	2	14	15,5	7,8
	3	18	17,4	8,4
	4	19	18,5	10,0
	5	17	14,1	7,4
	6	12	12,7	5,4
	7	17	16,6	6,9
	8	17	10,5	7,0
	9	12	17,3	5,8
	10	12	7,4	4,2
Spruce *Kuusi*	1	11	12,1	9,2
	2	10	11,4	8,5
	3	18	13,7	10,7
	4	13	11,0	8,1
	5	14	11,6	9,5
	6	13	14,0	10,5
	7	12	12,7	7,1
	8	11	12,2	10,2
	9	12	13,0	9,2
	10	11	11,4	9,6

The protruding branch stumps were removed from the disks in the laboratory. The number of branches in each disk was also noted.

The number of stem and branch samples was as follows:

Sample	Pine	Spruce
Stem disks	514	568
Knots	209	219
Branch stumps	305	349
Number of sub-samples from the stem disks	420	448

The basic density (kg/cm^3) of the debarked disks and the branch stumps taken from the southern and northern sides of the disks was determined by the water displacement method. The knots were then cut out from the stem disks. Stemwood samples were taken from the vicinity of the knots and their density also measured by the water displacement method. The diameter of the branches in both the vertical and horizontal plane (vertical plane being equivalent to the vertical axis of the stem) were measured.

3. BRANCH STUMPS AND KNOTS

31. Irregularity and cross-sectional area of the branch stumps

The cross-section of branch stumps is rarely completely circular. In this study, the branch stumps of both pine and spruce had irregular cross-sections. The horizontal diameter of pine branch stumps was 5,3 % smaller than the vertical diameter; the corresponding value for spruce was 7,1 %. These differences are of the same order of magnitude as those reported by M e r k e l (1967), but to some extent larger

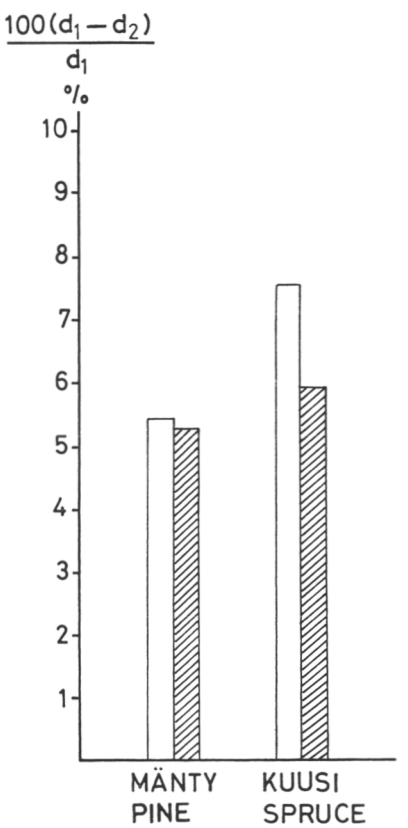


Fig. 1. Deviation of branch cross-section from circular form.
d_1 = horizontal diameter in the knot cross-section
d_2 = vertical diameter in the knot cross-section
Lined column = branch stump (about 2 cm long) taken from south-facing side
Non-lined column = branch stump (about 2 cm long) taken from north-facing side

Kuva 1. Oksien epäpyöreys.
d_1 = oksan poikkipinta-alan läpimitta vaakasuorassa suunnassa
d_2 = oksan poikkipinta-alan läpimitta pystysuorassa suunnassa
Viivoittamaton alue = rungon eteläpuolelta otettu n. 2 cm mittainen oksantynkä. Viivoitettu alue = rungon pohjoispuolelta otettu n. 2 cm mittainen oksantynkä.

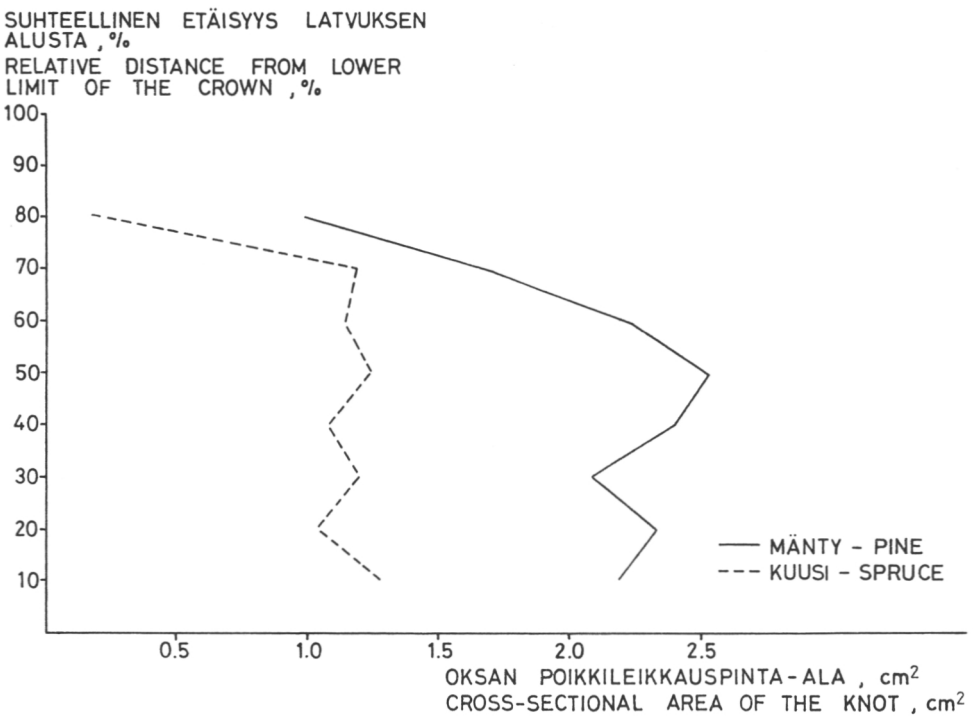


Fig. 2. The average branch cross-sectional area at different heights in the living crown.
Kuva 2. Oksan poikkileikkauspinta-alan vaihtelu elävän latvuksen alueella.

than those obtained by K ä r k k ä i n e n (1972). The diameter of both the pine and spruce branch stumps was small: 15 mm on average for pine and 11 mm for spruce.

The degree of irregularity of branch stumps varied from one side of the stem to another. Spruce branch stumps on the southern side of the stem were clearly more irregular than those on the northern side (Fig. 1.). On the other hand, the branch stumps of pine were almost equally irregular on both sides of the stem.

The irregularity of the branch stumps in the vertical plane differed in spruce and pine. The irregularity of pine branch stumps decreased and that of spruce increased on moving upwards or downwards from the center of the crown. The vertical diameter of the cross-section of spruce branch stumps in the crown was 3,5 . . . 7,4 % greater than the horizontal diameter. The corresponding value for pine was 4,3 . . . 8,5 %.

In spruce, branch cross-sectional irregularity appeared to be affected by the number of branches growing at that height, since the branch stumps in disks containing a relatively large number of branches were slightly more regular than those in disks containing few branches. On the other hand, degree of irregularity of pine branch stumps appeared to increase as the number of branches increased.

The mean cross-sectional area of branch stumps in the crown region remained fairly constant throughout the greater part of the crown (Fig. 2). Only in the upper part of the crown did the cross-sectional area start to decrease strongly. These results differ from those obtained in studies carried out in Central Europe in which the size of the branches was found to increase from the butt of the stem to the crown (von W e d e l et al. 1968, D e j m a l 1972b). As has already been mentioned, according to studies carried out in Fenno-Scandia the thickest branches are situated rather low down in the living crown (A g e r et al. 1964, W e s t e r n 1971, K ä r k k ä i n e n 1972).

32. Mass and volume of the knots

The size of the knots, expressed as volume, in the crown of both pine and spruce decreased on passing from the crown limit up to the crown; more sharply, however, in the case of pine (Fig. 3). The difference between the minimum and maximum volume of the branches was 4,6 cm^3 in pine and 3,6 cm^3 in spruce. D e j m a l (1972b) has also reported that branch size varies more in pine than in spruce.

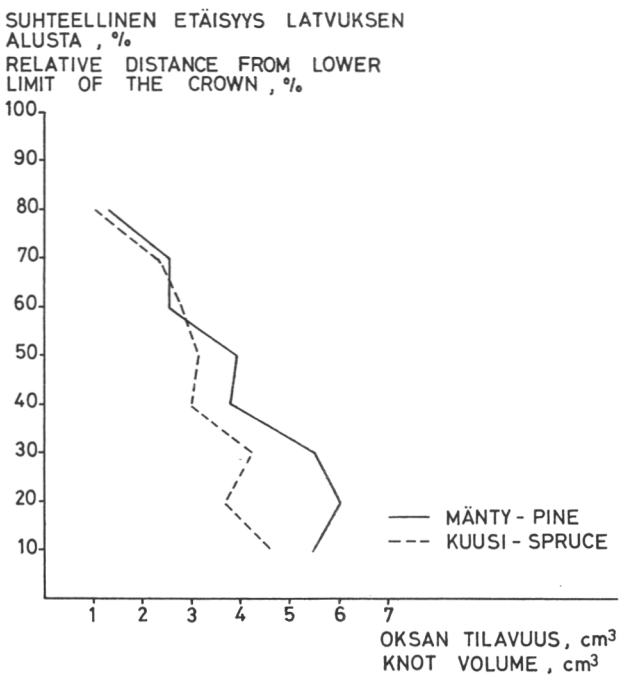


Fig. 3. The average knot volume at different heights in the living crown.

Kuva 3. Sisäoksien tilavuuden vaihtelu elävän latvuksen alueella.

The diameter of the cross-section of the branch stumps was well correlated with both knot mass and volume. The correlation with volume was slightly higher; the following regression equations describe the relationship between diameter and volume:

Tree species	Regression equation	Coefficient of determination %
Pine	$y = 2{,}84 \cdot x^2 - 7{,}140$	80,1
Spruce	$y = 2{,}98 \cdot x^2 - 3{,}706$	80,0

y = knot volume, mm^3
x = vertical diameter of debarked branch, mm

Since, in addition to branch cross-sectional diameter, knot size also varies according to stem diameter, then knot volume can also be determined from the following equations which were obtained by means of selective regression analysis:

Tree species	Regression equation	Coefficient of determination %
Pine	$y = 2{,}81 \cdot x^2 + 4{,}939 \cdot \lvert z \rvert - 15{,}771$	80,9
Spruce	$y = 2{,}98 \cdot x^2 + 3{,}620 \cdot (\sin z) - 1{,}411$	88,3

y = knot volume, mm^3
x = vertical diameter of debarked branch, mm
z = diameter of debarked stem at height of branch sample, mm

The coefficient of determination for both tree species is high, and inclusion of stem diameter in the equation increases it by only about 1 %. However, the cross-sectional diameter of a branch stump and the stem diameter are both easily determined parameters which are well-worth using when attempting to estimate the proportion of knots in timber.

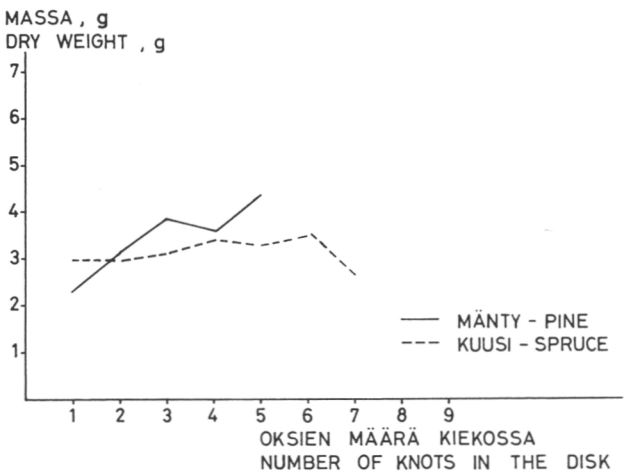


Fig. 4. The average knot dry mass at different heights in the living crown.

Kuva 4. Sisäoksien massan riippuvuus vastaavan rungonkohdan oksamäärästä.

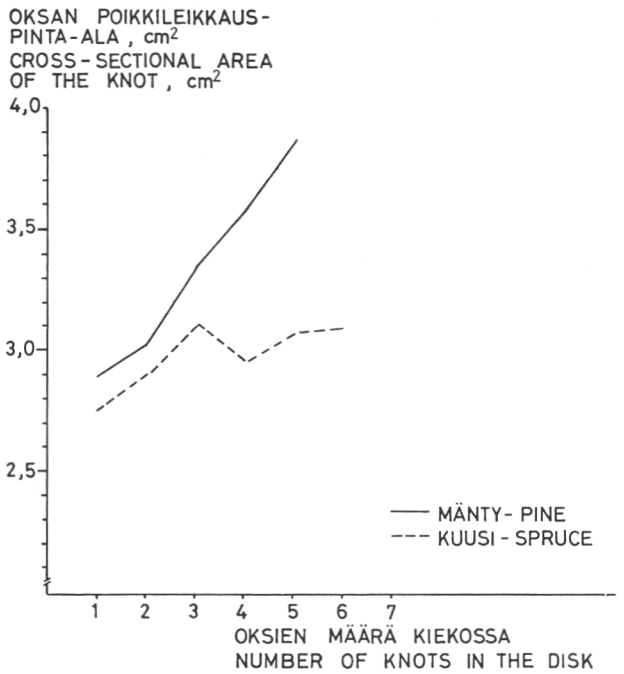


Fig. 5. The average knot cross-sectional area with increasing number of knots at height sampled.

Kuva 5. Oksan keskimääräisen poikkipinta-alan riippuvuus vastaavan rungonkohdan oksamäärästä.

It was found when examining the mass and volume of the knots that as the number of branches in a disk increased then the mass of the pine knots increased uniformly (Fig. 4). On the other hand, the knot number did not affect the mass of the spruce knots. There was clearly a larger difference between the mass and volume of the pine knots, the difference increasing slightly as the knot number increased. The corresponding difference in spruce, however, decreased.

The cross-sectional area of the pine branch stumps was greater, the more branches there were at the sampling point. The mean cross-sectional area of the spruce branch stumps also increased as the number of branches increased, but to some extent less than with pine (Fig. 5).

33. Number of branches and knots and knot content

Pine has fewer branches than spruce. The number of branches in each branch whorl can vary in different geographical regions: in general, however, pine has 3—5 and spruce 5—6 branches in each branch whorl (W e s t e r n 1971, A g e r 1972). The number of branches in a branch whorl does not, however, vary at different heights along the stem (N y l i n d e r 1958—1959).

Table 2. Number of knots in the disks
Taulukko 2. Kiekkojen oksaisuus

Number of knots *Oksia kiekossa*	Pine — *Mänty* % of all sample disks % *kaikista kiekoista*	Spruce — *Kuusi*
0	68,0	60,0
1	5,1	11,0
2	8,9	8,5
3	8,9	5,6
4	7,5	8,4
5	1,6	5,6
6		0,7
7		0,2

The most common type of disks in the pine material were those containing 2 or 3 branches — 17,8 % of all the pine samples studied (Table 2). After knot-free disks, the most common ones in the spruce material were those having one branch only. The reason for the large number of disks with one or two branches only, lies in the intermediate branches growing between the whorls.

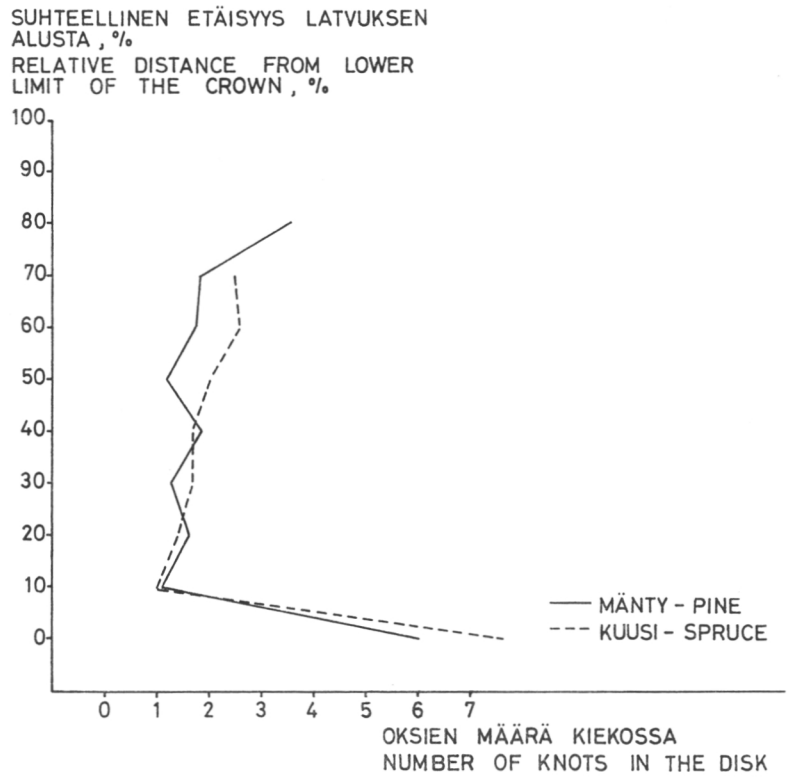


Fig. 6. Number of knots in the 10 cm thick sample disk taken from different heights in the living crown.
Kuva 6. Oksamäärän vaihtelu pystysuorassa suunnassa 10 cm paksuisissa kiekoissa elävän latvuksen alueella.

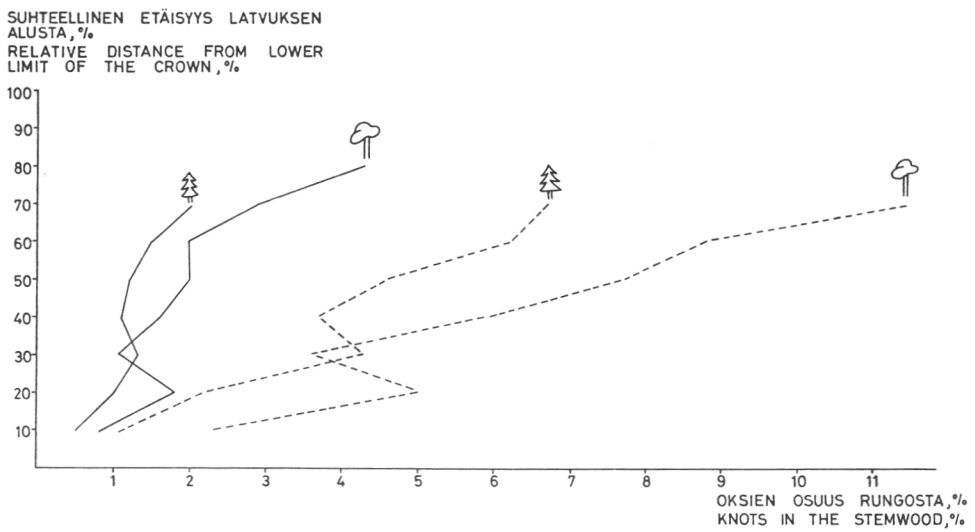


Fig. 7. Percentage of knots at different heights in the living crown. Single line = the volume per cent Dotted line = dry mass per cent

Kuva 7. Oksapuun osuus rungosta. Yhtenäinen viiva = tilavuusprosentti. Katkoviiva = painoprosentti

The number of branches varied from one side of the stem to the other. 56,5 % of the pine branches and, 56,7 % of the spruce branches were found on the southern side of the stem. W e g e l i u s (1939) and K ä r k k ä i n e n (1972) also report that spruce has more branches on the southern than northern side of the stem.

Variations in the number of branches in different parts of the crown were examined by dividing the crown stem into ten equal sections. The number of branches in the different sections of the living crown of pine clearly remained constant. On the other hand, the number of branches appeared to increase slightly in the upper part of the crown of spruce (Fig. 6). W e s t e r n (1971) has also found that the number of branches per unit length initially decreases on passing from the lower part of the living crown to the center and then starts to increase again higher up the crown (also P a l o v i c 1960).

The proportion of knots out of the total weight and volume of the stem was greater in pine than in spruce (Fig. 7). The branch percentage clearly increased in both tree species on passing from the lower limit of the crown up to the upper part of the crown weight percentage more strongly than volume percentage. Thus the proportion of knots out of the total volume of the stem wood of spruce was 1,5 % greater in the upper part of the crown than at the lower limit of the crown, and the proportion of knots out of the total weight of stem wood more than 5 % greater than in the lower part of the living crown. In the case of pine, the proportion out of the volume was almost 4 % greater and that out of the weight almost 10 % greater in the crown than in the lower part of the living crown. Since the dry-weight of the

knots is noticeably larger than that of normal stemwood, the weight percentages of the knots were as much as three times greater than the corresponding volume percentages.

The increase in the proportion of knots in the upper part of the stem was affected by, for instance, the increase in the number of knots (Fig. 6). Knot size and knot angle have also been found to affect the magnitude of the knot percentage.

The proportion of knots out of the stem volume of pine was, on average, 2 %, and for spruce 1,2 %. The corresponding weight percentage values were 6,4 and 3,5 respectively. These values correspond well with those obtained by K l e m (1933—37), N y l i n d e r and H ä g g l u n d (1955) and W e d e l et al. (1967). If the wood in the immediate vicinity of the knot is included, as well as the knot wood, then the percentage value becomes quite appreciable (e.g. von W e d e l et al. 1968, U u s v a a r a 1972).

34. Effect of branch position on the basic density of branch and knot wood

Spruce branch stump wood was denser than that of pine (Fig. 8). While the basic density of pine branch stumps varied from 600 to 620 kg/m³, the corresponding value for spruce varied from 810 to 818 kg/m³. Spruce branch stump wood has generally been found to be denser than that of pine (e.g. B o u t e l j e 1966, H a k k i l a 1971).

The location of the branches on different sides of the stem affected the basic density of branch stumps differently in pine and spruce. The branch stumps on the southern side of pine stems were 20 kg/m³ denser than those on the northern side, while the branches growing on the northern side of the spruce stems were denser than (8 kg/m³) those on the southern side. Rather conflicting results have in general been presented about the effect of branch location on wood density. For example, G ö h r e (1955 and 1958) found that location had no apparent effect on variations in the basic density of the sapwood of Douglas-fir or pine. According to S t e r n (1961), location appeared to have an effect on the basic density of spruce wood since the density of over half of the sample trees at a height of two meters was different on different sides of the stem. On the other hand, N y l i n d e r (1953) has found that the basic density of wood on the southern side of spruce stems is 4 % greater than that on the northern side (similarly O l e s e n 1973).

The basic density of the branch stump wood, obtained in this study, was clearly greater than that of the stem wood. The basic density of pine branches stumps was on average 221 kg/m³ higher and that of the knots 351 kg/m³ higher than that of the knot-free stemwood. The corresponding values for spruce were 407 and 490 kg/m³. The values for the basic density of the branch stumps obtained in this study are surprisingly high in comparison to values obtained in other studies. The mean basic density of branch stumps has usually been found to be approximately the same as that of the stemwood (e.g. H o s i a et al. 1971, K ä r k k ä i n e n 1976). These results, however, can be explained by the fact that while the branch samples measured

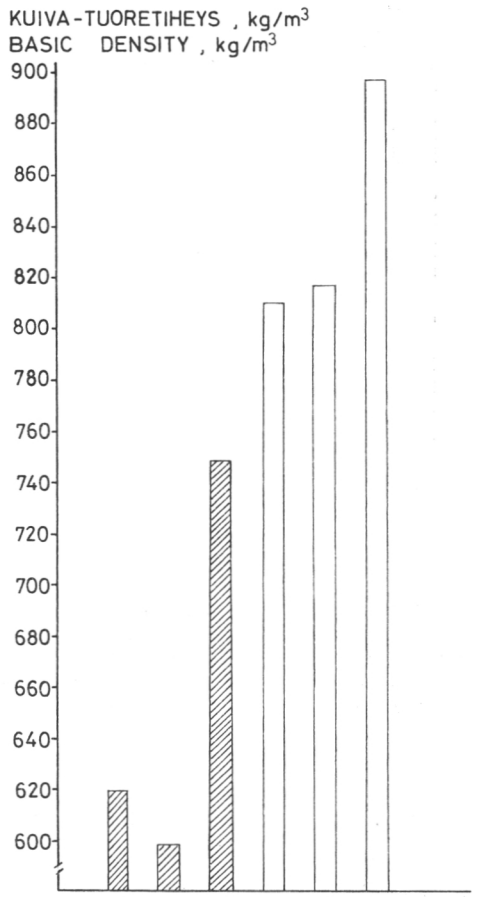


Fig. 8. Basic density of knots. The lined columns = pine. The non-lined columns = spruce. EO = branch stump (about 2 cm long) taken from south-facing side. PO = branch stump (about 2 cm long) taken from north-facing side. SO = the knot

Kuva 8. Oksien kuiva-tuoretiheys. Viivoitetut alueet = mänty. Viivoittamattomat alueet = kuusi. EO = eteläpuolelta runkoa otettu oksantynkä. PO = pohjoispuolelta runkoa otettu oksantynkä. SO = sisäoksa

in this study were taken from right next to the stem and the basic density of branch wood clearly decreases from the base to the tip of the branch (Hakkila 1969).

The high basic density of the knots in comparison to that of the stemwood is partly due to the large amounts of extractables in the branch wood. For instance, the resin content of coniferous branches is only a couple of percent, while that of the knots may be as high as 30 % (Hägglund and Larsson 1937, Jayme and Blischnok 1938, Lindgren and Norin 1969). Enčev (1962) has found that the high basic density of pine knots is due to their high resin content. On the other hand, the more the knots are compressed in the wood, the denser is the knotwood (Wegelius 1939). Further support for the idea that the increase in density partly is caused by compression of the knots in the wood is provided by the fact that branches do not swell up as much as knots do during soaking (Ylinen 1971).

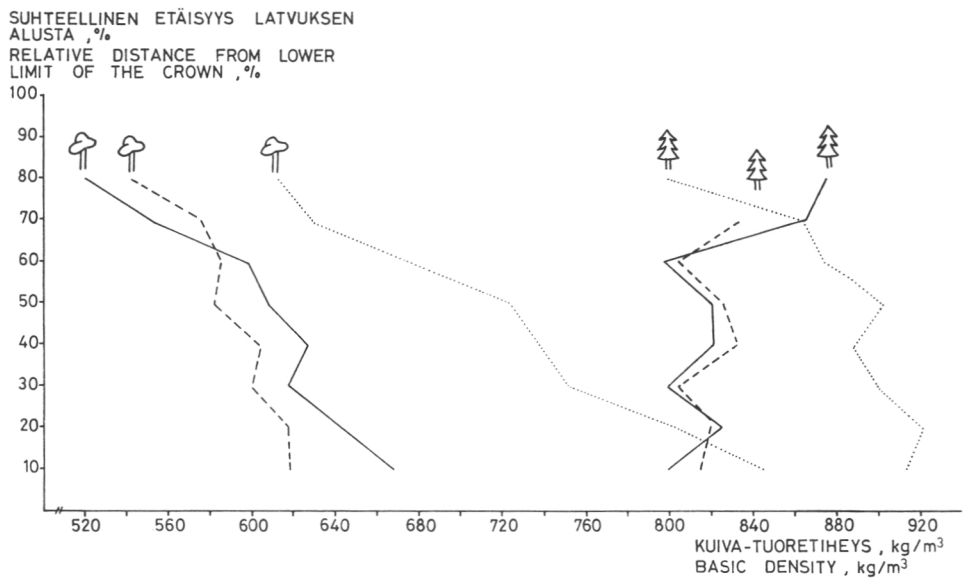


Fig. 9. Basic density of knots at different heights in the living crown. Single line = branch stump (about 2 cm long) taken from south-facing side. Broken line = branch stump (about 2 cm long) taken from north-facing side. Dotted line = the knot

Kuva 9. Oksien kuiva-tuoretiheyden vaihtelu latvuksen alueella. Yhtenäinen viiva = eteläpuolelta runkoa otettu oksantynkä. Katkoviiva = pohjoispuolelta runkoa otettu oksantynkä. Pisteviiva = sisäoksa

The basic density of pine branch stump wood clearly decreased on passing from the crown limit to the upper part of the crown (Fig. 9). This decrease in density was most evident in the knots, the difference in density between the lower and upper knot samples being 220 kg/m³. On the other hand, the differences between the basic density of the branch stump wood were smaller. The wood taken from branch stumps located in the lower part of the crown on the southern side of the stem was denser than that of the branch stumps on the northern side. However, this difference was no longer evident at heights greater than the middle point of the crown. Differences in density between the wood of branch samples taken from the lower and upper parts of the crown on the southern side of the stem were greater than those in the wood of branches taken from the northern side.

The basic density of spruce knotwood decreased only in the upper parts of the crown, although the change in density was smaller than that for pine, i.e. 120 kg/m³. The basic density of the branch stump wood did not, on the other hand, vary at different heights in the crown. The basic density of the branch stump wood from the southern side of the stem appeared, however, to be slightly lower than that of branch stumps from the northern side.

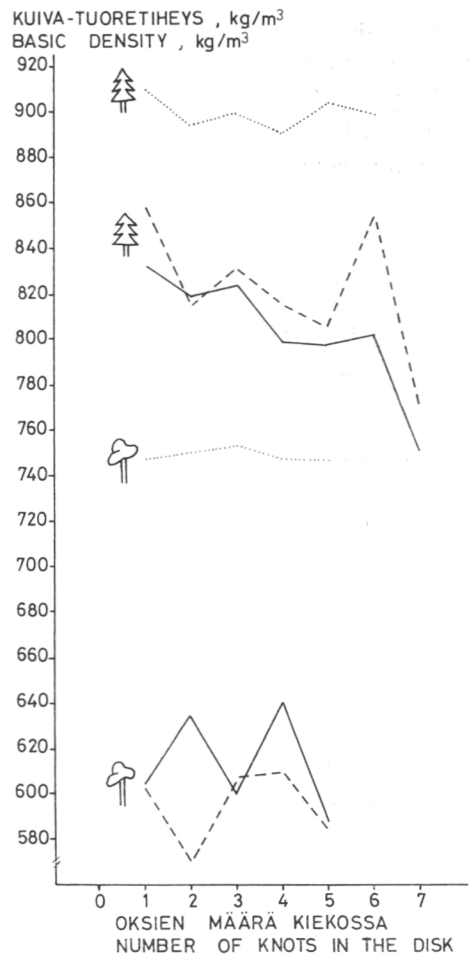


Fig. 10. Basic density of knots with increasing number of knots at height sampled. Single line = branch stump (about 2 cm long) taken from south-facing side. Broken line = branch stump (about 2 cm long) taken from north-facing side, Dotted line = theknot

Kuva 10. Oksien kuiva-tuoretiheyden riippuvuus vastaavan rungonkohdan oksamäärästä. Yhtenäinen viiva = eteläpuolelta runkoa otettu oksantynkä. Katkoviiva = pohjoispuolelta runkoa otettu oksantynkä. Pisteviiva = sisäoksa.

35. Effect of knot number on the basic density of branch and knot wood

Since knot number affected the average size of the branches, it also appears likely that it affected the basic density of the branch wood. The decrease in the basic density of spruce branch stump wood with increasing knot number was especially clear (Fig. 10), the range being from 745 to 860 kg/m³. The basic density of spruce knotwood decreased slightly less than that of the branch stumps, varying from 890 to 910 kg/m³.

The basic density of pine branch stump wood appeared to vary rather randomly as the number of knots increased. The density varied from 570 to 640 kg/m³, the wood of the branch stumps from the southern side of the stem appearing to be

slightly denser than that of branche stumps from the northern side. On the other hand, the number of knots did not affect the basic density of the knot wood (748—745 kg/m³). The density of pine branch wood immediately decreased, on moving from inside the stem to the outside slightly more than with spruce, as can be seen from following table.

	Knot		Branch stump	
	Pine	Spruce	Pine	Spruce
		kg/m³		
Boutelje (1966)	1 115	923	803	825
Hakkila (1971)[1])	689	836	653	713
Lehtonen (1978)	722	883	631	880

[1]) Calculated from Hakkila's study (1971), figure 20 page 48.

36. Effect of branch size on the basic density of branch and knotwood

Changes in the basic density of branch stumps and knots with increases in size were examined by taking knot volume as the size variable for the knots, and branch cross-sectional area for the branch stumps. The basic density of spruce branch stump wood taken from the southern side of the stem decreased slightly with increasing branch size (846—782 kg/m³). The basic density of the knotwood followed a similar trend (919—844 kg/m³). The basic density of the branch stump wood from the southern side of the stem, on the other hand, did not vary with different sized branches (825—815 kg/m³).

The basic density of pine branch stump wood taken from the southern side of the stem clearly increased with increasing branch size (548—620 kg/m³). The variation in the basic density of the branch stumps from the northern side was irregular, even though the range was quite large (546—655 kg/m³). The branch stumps with a small cross-sectional area were slightly denser on the northern side while the density of the wood of large branch stumps was higher on the southern side of the stem. The basic density of pine knotwood increased strongly with increasing knot size (708—820 kg/m³).

It is evident, that the basic density of pine branch stumps increases and that of spruce branches decreases with increasing branch size. However, Enčev (1962) and Kärkkäinen (1976) have found that the basic density of both spruce and pine branch wood increases with increasing branch diameter. On the other hand, according to Boutelje (1966), the basic density of branch wood is negative correlated with the size of both spruce and pine branches. The results obtained in this study for pine are thus in complete contrast to those obtained by Boutelje (1966) and for spruce to those obtained by Enčev (1962). The varying results obtained in different studies cannot easily be explained, but they may be due to geographical variations and differences caused by genetic factors.

4. STEMWOOD

41. Basic density of branch whorl wood

The properties of wood lying in the immediate vicinity of knots differ from those of wood from both the knots and the normal type of wood in the stem. The properties of such wood represent an intermediate form between the two earlier mentioned types of wood (K i n i n m o n t h 1961, B a k e r 1962, M e t t e and K o m m e r t 1964, B o u t e l j e 1966, G ö t z e 1969, S c h u l t z e - D e v i t z and G ö t z e 1973).

The basic density of the wood surrounding the knots changed in such a way that the densest wood was found in the immediate vicinity of the knots. The density decreased slightly on moving to the wood lying between two knots at the same level (Fig. 11). The wood in the vicinity of both pine and spruce knots was about 2 % (8 kg/m³) denser than that of wood further away. The stemwood of spruce was on average 20 kg/m³ denser than that of pine. The higher basic density of the spruce

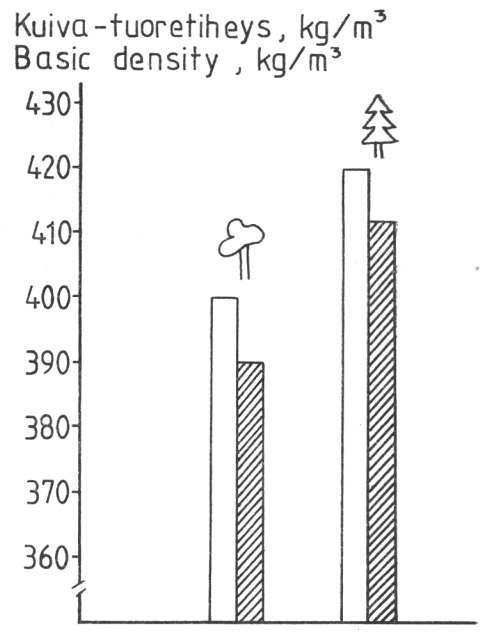


Fig. 11. Basic density of stemwood. Non-lined column = stemwood sample surrounding the knot. Lined column = stemwood sample taken from between the two knots lying on the same horizontal level

Kuva 11. Oksien vaikutus runkopuun kuiva-tuoretiheyteen. Viivoittamaton alue = sisäoksan vierestä otettu runkopuunäyte. Viivoitettu alue = kahden samassa tasossa olevan sisäoksan välistä otettu runkopuunäyte.

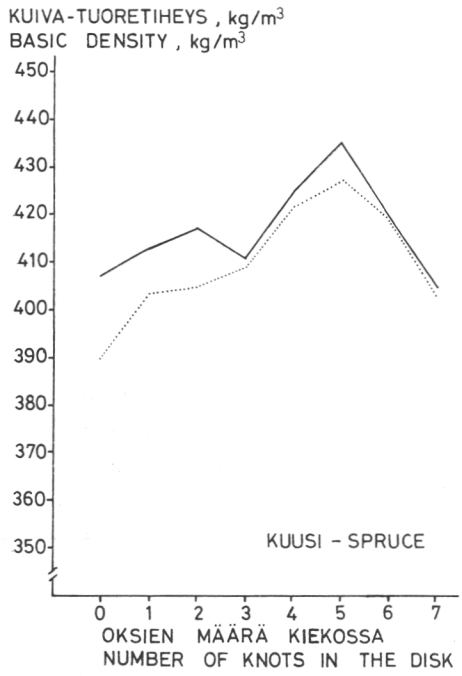


Fig. 12. Basic density of stemwood with increasing number of knots at height sampled. Single line = stemwood sample surrounding the knot. Dotted line = stemwood sample taken from between the two knots lying on the same horizontal level

Kuva 12. Runkopuun kuiva-tuoretiheyden riippuvuus vastaavan rungonkohdan oksamäärästä. Yhtenäinen viiva = sisäoksan vierestä otettu runkopuunäyte. Pisteviiva = kahden samassa tasossa olevan sisäoksan välistä otettu runkopuunäyte

wood is not, however, to be taken as general, but may be due in this case to the large variation in density between different stems and the fact that the site was rather unfavourable for spruce.

The basic density of the wood lying between the knots increased with increasing knot number (Fig. 12). As the number of branches in the branch whorls increased, the difference between the basic density of the wood taken from between the knots and that of the wood surrounding the knots became smaller. Changes in the basic density of pine, with increasing knot number, were irregular and the range was large: 377—409 kg/m³ for the wood taken from next to the knots, and 381—400 kg/m³ for the wood taken from between the knots.

42. Basic density in the crown region

Variations in stemwood basic density in the crown region were examined by dividing the crown into ten section (Fig. 13). Since both disks containing knots and those without were included in the study, the basic density of the wood in the sample disk taken from the height of the first branch whorl was to some extent higher than that of the wood sampled at other points. The basic density of both spruce and pine wood decreased in the crown region right up to the middle of the crown. The decrease in the basic density of spruce wood appeared to cease at a slightly lower point in the

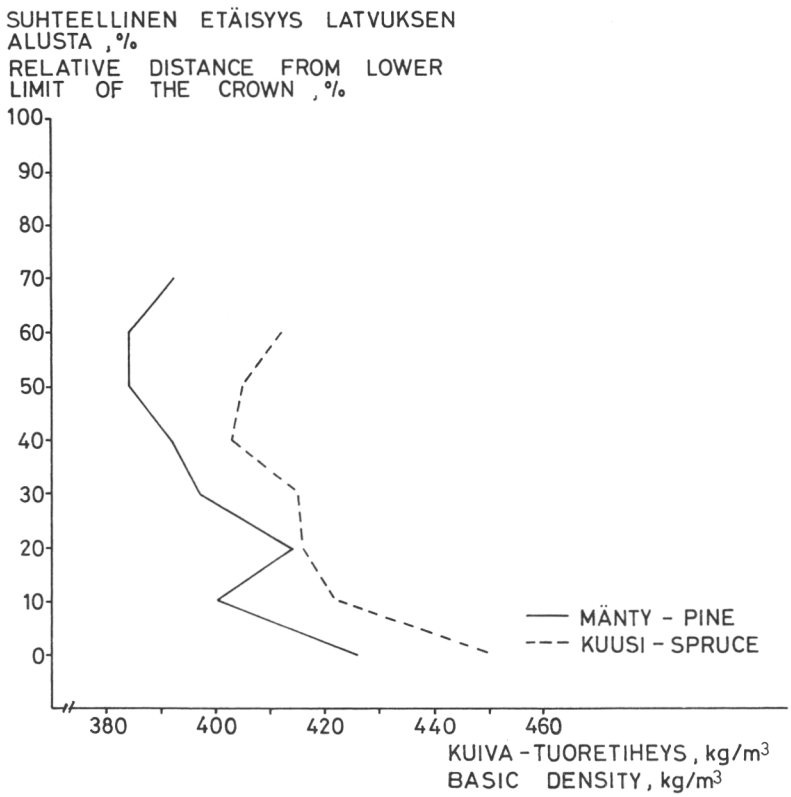


Fig. 13. Basic density of stemwood in the living crown.
Kuva 13. Runkopuun kuiva-tuoretiheyden vaihtelu elävän latvuksen alueella.

crown than in pine. The slight increase in the basic density of spruce wood which started above the middle of the crown may be due to the increase in knot number in the upper part of the crown (Fig. 6).

The spruce wood, in this case, was denser than that of pine. However, there was quite large variation between individual trees of both tree species. The basic density of pine stemwood varied in different parts of the stem from 358 to 464 kg/m^3, and that of spruce from 368 to 450 kg/m^3. The densities of the individual pine stems were distributed uniformly throughout the whole of the above-mentioned density range. With spruce, however, there were two distinct density groups, one of them falling in the lower part of the density scale and the other in the upper (e.g. Fig. 15).

In general, the basic density of knot-free stemwood completely free from defects has been found to be higher than that of corresponding pine stemwood. The basic density also decreases in both species on passing from the stem butt up to the crown (e.g. Hakkila 1966, Hakkila and Uusvaara 1968, Uusvaara 1974).

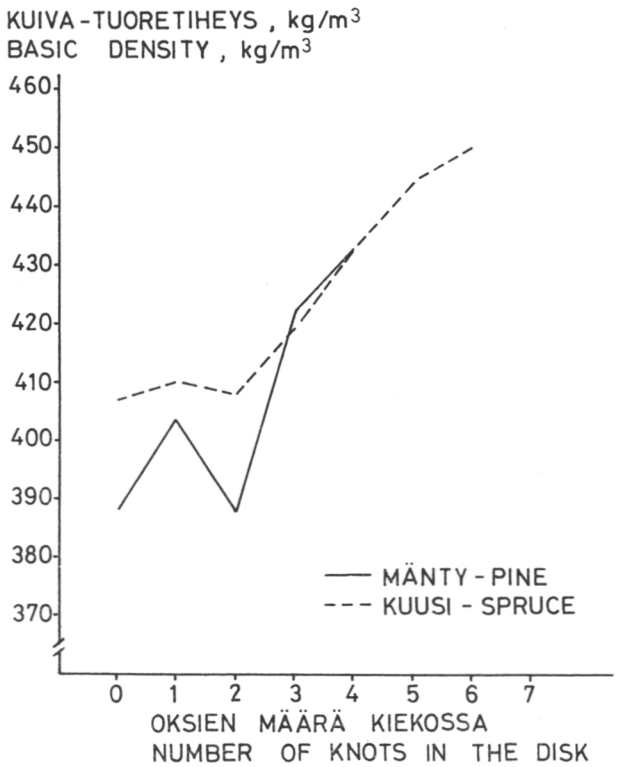


Fig. 14. Basic density of stemwood with increasing number of knots at height sampled.
Kuva 14. Runkopuun kuiva-tuoretiheyden riippuvuus oksamäärästä.

However, the basic density of spruce wood in the crown region can be greater than that of pine (H a k k i l a 1966).

On an average, the basic density of the stemwood was the greater, the more knots there were in the sample disk of standard thickness (Fig. 14). The difference between the lowest and highest density values was 45 kg/m³ for pine and 43 kg/m³ for spruce. The basic density of wood from knot-free pine disks and those with only a few knots was lower than that of corresponding spruce wood samples. However, with increasing knot number the density increased such that the density of pine and spruce sample disks containing four branches were the same. The basic density of knotty pine wood was on average 2,1 %, and that of spruce 5,4 %, higher than that of knot-free wood. The increase in the basic density of the wood from stem disks, with increasing knot number, was partly due to the high density of the knotwood. The basic density of knotwood can be as much as 2—3 times higher than that of stemwood (e.g. W e g e l i u s 1939, B o u t e l j e 1966, L e v č e n k o 1969). The increase in the basic density was also partly due to the increase in density of the stemwood lying between the

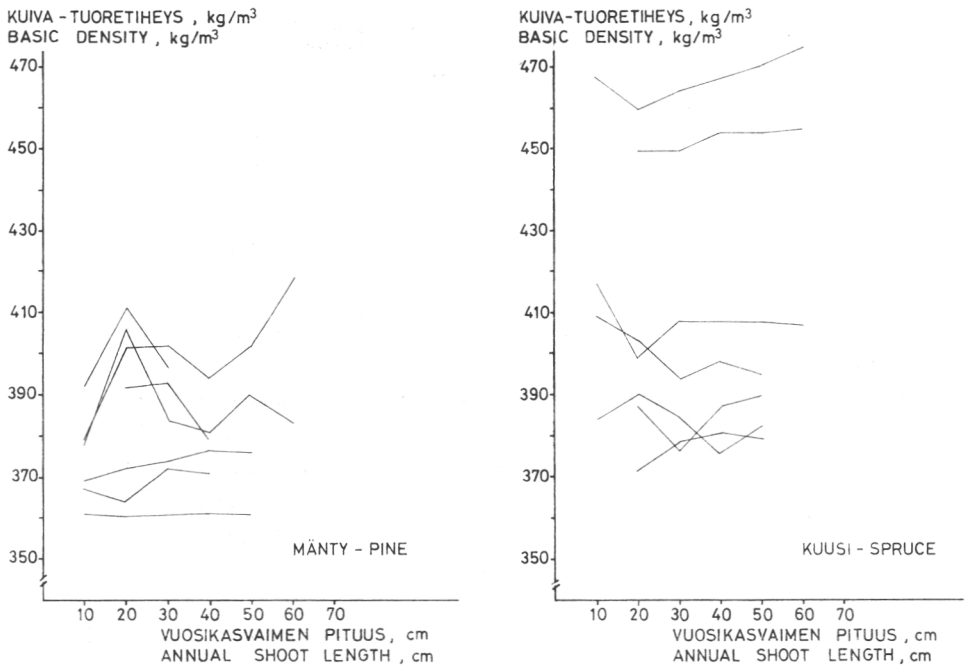


Fig. 15. Basic density of shoot wood. The shoot is divided into ten parts.
Kuva 15. Runkopuun kuiva-tuoretiheyden vaihtelu vuosikasvaimen alueella. Kahden peräkkäisen oksakiehkuran väli on jaettu 10 osaan.

knots; the number of knots in a disk, however, did not affect the basic density of the knotwood. As the amount of wood differing from normal wood lying around the knots increases, then the properties of the complete knotty region change, too.

Density variations in the wood lying between the branch whorls do not appear to be dependant on the number of branches in the branch whorl. K l e m (1935—1937) and V u o r i s t o (1937) have in fact shown that there is negative correlation between the density and the degree of knottiness; the more knots there are in the wood, the lower is the density of the knot-free stemwood.

43. Variations in the basic density of the wood lying between consecutive branch whorls

Both the spruce and pine material was studied by dividing the stemwood lying between the branch whorls into 10-cm long sections. The most common distance between two consecutive pine branch whorls was found to be 20 . . . 30 cm. Spacings of 30 . . . 40 cm were almost as common. The distribution of the material into different length classes was as follows:

Distance between two consecutive branch whorls, cm	Percentage out of whole material	
	Pine	Spruce
—20	8,5	4,9
21—30	30,0	21,0
31—40	27,3	29,3
41—50	13,3	20,8
51—60	18,9	13,7
61—70	2,0	10,3

Spacings of 30 . . . 40 cm and 20 . . . 30 cm were also the most common in the spruce material.

As the distance between two branch whorls did not appear to have any effect on the basic density of the wood lying between them (Fig. 15), it was possible to examine the density variations occurring through out the wood without having to take into account the varying distances between the branch whorls. The basic density of both pine and spruce wood clearly decreased on passing upwards from the disk taken from just above the lower branch whorl and then started to increase again as the next branch whorl approached (Fig. 16). The basic density of the pine wood taken from different sample trees varied by 10 . . . 50 kg/m³. The variation in spruce was slightly larger, from 5 to 50 kg/m³. The smallest variations in the basic density of wood taken from between two branch whorls of both pine and spruce were found in those trees which had a large mean stem density.

The basic density of the wood above the branch whorls of pine decreased gradually, the decrease below the whorl being smaller. The basic density changes in the wood of spruce showed a similar trend, although the difference between the density of the wood next to the branch whorls and that of the wood lying half-way between two branch whorls was slightly larger than that for pine. The difference between the densities at these two points was 32 kg/m³ for spruce and 25 kg/m³ for pine. The effect of the branch whorls on the basic density of the wood lying between two branch whorls extended over about 20 % of the distance above and below the branch whorls.

It is worth mentioning for comparison purposes, that according to B a k e r (1968), the basic density of *Pinus resinosa* wood decreases uniformly above and below the branch whorls. G ö t z e (1969) has found that the basic density decreases sharply above the branch whorls of spruce and gradually in the case of pine. The density of the wood below spruce branch whorls decreases gradually and slightly more sharply in pine. The gradual decrease in the density of spruce wood has been attributed to the large needle mass of spruce branches, which is so large in comparison to pine that it affects the properties of the wood (S c h u l t z e - D e w i t z and G ö t z e 1973).

The basic density of a sample taken from half-way between two branch whorls in pine is 1,2 % lower than the mean density of the stemwood in the crown region. The corresponding decrease for spruce is 0.6 %. The number of branches in the branch whorls was not found to have affected these values.

5. DISCUSSION

When drawing general conclusions about the results obtained in this study, it should be borne in mind that the sample trees were growing on a relatively infertile site, especially compared to the type of site where spruce is normally to be found. The low fertility of the site may in particular have had an effect on the average knot number and on the density values obtained for the crown region. Great care should be taken in making generalisations about these results. Owing to the lack of broader studies, these results can certainly be considered to give some indication of general trends. In addition, the number of stems included in the material was relatively small.

The inclusion of a site which is less fertile than usual for spruce makes it rather difficult to compare the values obtained for both tree species. The mean density for spruce was to some extent greater than that of pine owing to the fact that the material included some unusually dense stems. The overall density of pine stemwood is usually higher than that of spruce (e.g. H a k k i l a 1966), although there is large variation between individual stems. On the other hand, the density of spruce stemwood has been found to be higher than that of pine in the crown region (H a k k i l a 1966).

It is interesting, from the practical point of view, to find that the volume and weight percentage of the knots increases greatly in the upper part of the crown. Since knots increase chemical consumption during cellulose production, reduce the quality of the pulp and effect the quality of the saw-timber, it would be of great benefit to be able to estimate the probable knot percentage from the external surface of the logs. The analysis carried out in this study on a rather low number of stems, showed that this is possible to some extent. The number of branches analysed increased to a noticeably larger figure than the number of stems. Branch diameter in the vertical direction and stem diameter at the same height are both easily measured and give good estimates of the knot volume. It has also been found in other studies (e.g. von W e d e l et al. 1968), that branch diameter is very suitable for the estimation of knottiness.

Another interesting feature is the effect of knots on the surrounding wood. It has also been found in other studies (e.g. G ö t z e 1969), that the density decreases on moving upwards or downwards from branch whorls into the wood lying between adjacent branch whorls. If the effect of knots is to be minimised, for instance, in sampling, it is best to take the sample from midway between branch whorls in the

crown region, since the effect of the branch whorls extends only for a distance of 20 % above and below the branch whorls. The density value obtained for a sample taken from next to a branch whorl may be a few percent higher than that of the normal stemwood which, from the point of view of the cellulose industry for instance, may result in lower than expected pulp yields. Correspondingly, if the sample is taken from half-way between two branch whorls, then the result may differ from the mean density of the wood in the tree crown by about one percent.

6. SUMMARY

The properties of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) knots and the effect of knots on the surrounding stemwood were examined in the study. The material consisted of 10 pine and 10 spruce stems which had been growing on a site of the *Vaccinium*-type. The results can be summarised as follows.

The branches of both pine and spruce had irregular cross-sections. The pine branches, however, were less irregular than those of spruce. Branches growing on the northern side of the stems were clearly more irregular in shape than those growing on the southern side. This trend was especially clear in the case of spruce.

The branches had small diameters; the mean cross-sectional diameter for the pine branches was 15 mm and for spruce 11 mm. Branch size, measured as diameter, volume and dry-weight, decreased in the upper part of the crown. As the number of branches per unit length, however, increased in the upper part of the crown, the relative proportion of the branches out of the total weight and volume of the wood also increased. The volume percentage of the pine knots was 0,8—4,3 % ($\bar{x}$ 2,0 %) and the spruce knots 0,5—2,0 % ($\bar{x}$ 1,2 %). The weight percentage for pine varied from 2,3 to 11,5 % ($\bar{x}$ 6,4 %) and spruce from 1,1 to 6,7 % ($\bar{x}$ 3,5 %).

The density of spruce branch wood was clearly higher than that of pine. The branch stump wood of both pine and spruce was denser than the corresponding stemwood. The density of the pine and spruce branch stumps were respectively 221 and 407 kg/m^3 higher than that of the stemwood. The density of the knot wood exceeded that of the stemwood by 351 kg/m^3 in pine and 490 kg/m^3 in spruce.

Branch density varied at different heights and positions along the stem. Pine branch wood was denser on the southern side of the stem and spruce branch wood denser on the southern side. The density of pine branch wood decreased on passing from the lower crown limit upwards through the length of the crown. The clearest decrease in density occurred in the knots. In spruce, only the density of the knots decreased in the upper part of the crown.

The density of pine knot wood increased and that of spruce decreased with increasing branch size. The number of knots in a sample disk did not affect the density of pine knot wood. On the other hand, the density of spruce knot wood decreased as the number of knots in the sample disk increased.

The density of the wood surrounding the knots was slightly lower than that of the knots and slightly higher than that of the knot-free stemwood. The density decreased on moving horizontally from the wood surrounding the knot into the wood lying between the knots. The density of spruce stemwood increased with increasing knot number, while that of pine remained unchanged.

The density of the wood lying between two consecutive branch whorls reached a maximum immediately above and below the branch whorls. The density of both spruce and pine wood lying half-way between two branch whorls decreased. The effect of branches on the wood lying between two branch whorls extended over about 20 % of the distance above and below the whorls.

The density of spruce and pine stemwood with knots was 5,4 and 2,1 % higher than that of stemwood without knots.

7. SELOSTE

Tutkimuksessa selvitettiin männyn (*Pinus sylvestris* L.) ja kuusen (*Picea abies* (L.) Karst.) sisäoksien ominaisuuksia ja oksien vaikutusta niitä ympäröivään puuaineeseen. Tutkimusaineisto käsitti 10 mänty- ja 10 kuusi-runkoa, jotka kasvoivat Vaccinium-tyypin metsikössä.

Sekä männyn että kuusen oksat olivat selvästi epäpyöreitä. Männyllä epäpyöreys oli kuitenkin pienempi kuin kuusella. Rungon pohjoispuolella oksat olivat varsinkin kuusella selvästi epäpyöreämpiä kuin eteläpuolella.

Oksat olivat läpimitaltaan pieniä; männyllä oksan poikkileikkauspinta-alan halkaisija oli keskimäärin 15 mm ja kuusella 11 mm. Sekä läpimittana ja tilavuutena että kuivapainona mitattu oksan koko pieneni latvuksen yläosassa. Kun oksamäärä jakoyksikköä kohti kuitenkin kasvoi latvuksen yläosassa, kasvoi samalla oksien suhteellinen osuus puun painosta ja tilavuudesta. Oksien tilavuusosuus oli männyllä 0,8—4,3 % ($\bar{x}$ 2,0 %) ja kuusella 0,5—2,0 % ($\bar{x}$ 1,2 %). Paino-osuus vaihteli vastaavasti männyllä 2,3—11,5 % ($\bar{x}$ 6,4 %) ja kuusella 1,1—6,7 % ($\bar{x}$ 3,5 %).

Kuusen oksien puuaineen tiheys oli selvästi suurempi kuin männyn. Sekä kuusen että männyn oksien puuaine oli tiheämpää kuin vastaava runkopuu. Männyn oksantynkien tiheys oli 221 kg/m^3 ja kuusen 407 kg/m^3 suurempi kuin runkopuun. Sisäoksien puuaineen tiheys oli männyllä 351 kg/m^3 ja kuusella 490 kg/m^3 suurempi kuin runkopuun tiheys.

Oksien tiheys vaihteli eri puolilla runkoa. Männyn oksien puuaine oli tiheämpää rungon eteläpuolella ja kuusen oksien rungon pohjoispuolella. Männyn oksien puuaineen tiheys laski rungon pituussuunnassa latvusrajasta sen yläosaa kohti. Selvintä tiheyden väheneminen oli sisäoksissa. Kuusella vain sisäoksien tiheys pieneni latvuksen yläosassa.

Oksan koon kasvaessa männyn oksien puuaineen tiheys kasvoi ja kuusen oksien pieneni. Kiekon oksamäärä ei vaikuttanut männyn oksien tiheyteen. Sen sijaan kuusen oksien tiheys väheni kiekon oksamäärän kasvaessa.

Oksaa ympäröivän puuaineen tiheys oli hieman pienempi kuin sisäoksien ja hieman suurempi kuin oksattoman runkopuun. Tiheys pieneni siirryttäessä vaakasuorassa suunnassa oksaa ympäröivästä puuaineesta oksien välillä olevaan puuhun. Oksamäärän kasvaessa kuusen runkopuun tiheys kasvoi, mutta männyn puuaineen tiheys ei muuttunut. Oksaisen puuaineen tiheys oli männyllä keskimäärin 2,1 % ja kuusella 5,4 % suurempi kuin oksattoman puuaineen.

Vuosikasvaimen alueella oksattoman puuaineen tiheys oli suurin juuri oksakiekuran ylä- ja alapuolella. Vuosikasvaimen keskivaiheilla sekä kuusen että männyn puuaineen tiheys oli pienimmillään. Oksien vaikutus vuosikasvaimen puuaineen tiheyteen ulottui noin 20 % oksakiehkuran ylä- ja alapuolelle.

8. LITERATURE

ABETZ, P. & MERKEL, O. 1968. Aststärken und Schaftovalität in Fichten-Reihenbeständen. Summary: Branch thickness and stem excentricity in Norway spruce line plantings. Allg. Forst- u. Jagdztg. 139 (1): 138—145.

AGER, B. H. 1972. Träd- och kvistdata för skogstekniska kalkyler. Ett internordiskt (NSR-) projekt. Summary: Tree and branch data relevant to logging operations. Rapp. Uppsats. Instn. Skogsteknik. Skogshögsk. 50: 1—48.

AGER, B. H., NILSON, N. E. & von SEGEBADEN, G. 1964. Beskrivning av vissa skogstekniskt betydelsefulla bestånds- och trädegenskaper samt terrängförhållanden. Summary: Description of some for logging operations important characteristics of forest stands, trees and terrain in Sweden. Stud. For. Suec. 20: 1—159.

BAKER, G. 1968. Effect of proximity to limb whorls on wood density. For Prod. J. 18 (9): 112—113.

BOUTELJE, J. B. 1966. On the anatomical structure, moisture content, density, shrinkage and resin content of the wood in and around knots in Swedish pine (*Pinus silvestris* L.). Svensk PappTidn. 69: 1—10.

ENČEV, E. A. 1962. Obemno teglo: jakost na natisk na drvecinat na klonite na belija bor, smrtša i elata. Zusammenfassung: Rohwichte und Druckfestigkeit des Astholzes der Weisskiefer, Fichte und Tanne. Naučni Trudove 10: 177—191.

DEJMAL, J. 1972a. Beitrag zur Erkenntnis der Ästigkeit von Stämmen der bedeutendsten wirtschaftlichen Holzarten. Acta Univ. Agric., Brno 4 (1): 3—32.

—»— 1972b. Untersuchung einiger physikalisch-mechanischer Eigenschaften der Äste von Nadelhölzern. Holztechnologie 13 (4): 232—236.

GÖHRE, K. 1955. Die Rohwichte des Douglasienholzes, ihre Verteilung im Stamm und Abhängigkeit vom Abstand vom Mark. Jahrringbreite und Spätholzanteil. Arch. Forstw. 4 (7/6): 639—661.

—»— 1958. Über die Verteilung der Rohwichte im Stamm und ihre Beeinflussung durch Wuchsgebiet and Standort. Holz als Roh- u. Werkstoff 16 (2): 77—90.

GÖTZE, H. 1969. Untersuchungen zum physikalisch-technischen Eigenschaftsbild dünner Durchforstungshölzer der Baumarten Kiefer und Fichte. Arch. Forstw. 18 (9/10): 1 155—1 161.

HAKKILA, P. 1966. Investigations on the basic density of Finnish pine, spruce and birch wood. Lyhennelmä: Tutkimuksia männyn, kuusen ja koivun puuaineen tiheydestä. Commun. Inst. For. Fenn. 61 (5): 1—98.

—»— 1971. Coniferous branches as a raw material source. A sub-project of the joint nordic research programme for the utilizations of logging residues. Tiivistelmä: Havupuun oksat raaka-ainelähteenä. Yhteispohjoismainen hakkuutähdetutkimuksen alaprojekti. Commun. Inst. For. Fenn. 75 (1): 1—60.

—»— & UUSVAARA, O. 1968. On the basic density of plantation-grown Norway spruce. Lyhennelmä: Viljelykuusikoiden puuaineen tiheydestä. Commun. Inst. For. Fenn. 66 (6): 1—22.

HAKKILA, P., LAASASENAHO, J. & OITTINEN, K. 1972. Korjuuteknisiä oksatietoja. Summary: Branch data for logging work. Folia For. 147: 1—15.

HOSIA, M., LINDHOLM, C-A., TOIVANEN, P. & NEVALAINEN, K. 1971. Undersökningar rörande utnyttjandet av barrträdsgrenar som råmaterial för kemisk massa och hård fiberskiva I. Paperi ja Puu 53 (2): 49—66.

HÄGGLUND, E. & LARSSON, S. 1937. Om grankvistens kemiska sammansättning och dess förhållande vid sulfitkokningsprocessen. Svensk PappTidn. 40: 356—360.

JAYME, G. & BLISCHNOK, B. 1938. Über die chemische Zusammensetzung der verschiedenen Anteile des Kiefernholzes. Holz als Roh- u. Werkstoff 1 (14): 538—543.

KININMONTH, J. A. 1961. Checking of intergrown knots during seasoning of Radiata pine sawn timber. Tech. Pap. For. Res. Inst. N. Z. For. Serv. 30: 1—16.

KLEM, G. G. 1933—1937. Untersøkelser av granvirkets kvalitet. Referat: Untersuchungen über die Qualität des Fichtenholzes. Medd. Norske Skogforsøksv. 5: 197—348.

KNIGGE, W. & SCHULTZ, H. 1966. Grundriss der Forstbenutzung. Hamburg und Berlin. pp. 170—237.

KRASTANOV, K. N. 1962. (The extent and distribution of some defects in Fagus orientalis). Izv. Inst. Gorata Balg. Akad. Nauk. Sofia. 9: 145—174.

KÄRKKÄINEN, M. 1972. Havaintoja kuusen oksaisuudesta. Summary: Observations on the branchiness of Norway spruce. Silva Fenn. 6 (2): 90—115.

—»— 1976. Puun ja kuoren tiheys ja kosteus sekä kuoren osuus koivun, kuusen ja männyn oksissa. Summary: Density and moisture content of wood and bark, and bark percentage in the branches of birch, Norway spruce, and Scots pine. Silva Fenn. 10 (3): 212—236.

LEVČENKO, V. P. 1969. (Physical and mechanical properties of the wood of pine knots). Lesn. Ž., Arhangel'sk 12 (1): 93—96.

LINDGREN, B. & NORIN, T. 1969. Hartsets kemi. Svensk PappTidn. 72 (5): 143—153.

MERKEL, O. 1967. Der Einfluss des Baumabstandes auf die Aststärke der Fichte. Summary: The effect of tree spacing on branch sizes in spruce. Allg. Forst- u. Jagdztg. 138 (6): 113—125.

METTE, H. J. & KOMMERT, R. 1964. (Abrasion resistance of spruce wood), Wiss. Z. Tech. Univ. Dresden. 13 (2): 615—618. Sit. FA. 27 no. 6 744.

NYLINDER, P. 1953. Volumviktsvariationer hos planterad gran. Medd. SkogsforskningsInst. 43 (3): 1—44.

—»— 1958—1959. Synpunkter på produktionens kvalitet. Skogen 45: 100—102, 714—717.

NYLINDER, P. & HÄGGLUND, E. 1955. Ståndorts- och trädegenskapers inverkan på utbyte och kvalitet vid framställing av sulfitmassa av gran. Summary: The influence of stand and tree properties on yield and quality of sulphite pulp of Swedish spruce (*Picea excelsa*). Medd. Stat. SkogsforsknInst. 44 (1): 1—184.

OLESEN, P. O. 1973. The influence of the compass direction on the basic density of Norway spruce (*Picea abies* L.) and its importance for sampling for estimating the genetic value of plus trees. Forest Tree Improvement, Arboretet, Hørsholm. 6: 1—58.

PALOVIC, J. 1960. Rozmiestenie h'rě na smreku a ich vzťah k vývoju jeho technológie. Summary: The location of knots in spruce wood and their relation to the development of technology. Drev. Výskum 5 (2): 167—193.

PERSSON, A. 1972. Studies on the basic density in mother trees and progenies of pine. Stud. For. Suec. 96: 1—37.

RAPRAEGER, E. F. 1939. Development of branches and knots in Western white pine. J. For. 37: 239—245.

SCHULTZE-DEWITZ, G. & GÖTZE, H. 1973. Untersuchungen zur Faserlänge, Raumdichte und Druckfestigkeit inter- und circumnodialen Holzes der Baumarten Kiefer (*Pinus sylvestris* L.) Fichte (*Picea abies* Karst.) und Douglasie (*Pseudotsuga mentziesii Franco*). Drev. Výskum 18 (1): 33—44.

SIIMES, F. E. 1938. Suomalaisen mäntypuun rakenteellisista ja fysikalisista ominaisuuksista. Erikoisesti kutistumis- ja laajenemisilmiöstä puun vesipitoisuuden vaihdellessa. Summary: On the structural and physical properties of Finnish pine wood. Puutekniikan kannatusyhdistys Julk. 29: 1—221.

STERN, K. 1961. Einfluss der Himmelsrichtung auf die Verteilung der Raumdichte des Holzes in Fichtenbeständen. Holz als Roh- u. Werkstoff 19 (6): 213—218.

UUSVAARA, O. 1972. Sahanhakkeen ominaisuuksia. Keski- ja Pohjois-Suomesta kerättyyn aineistoon perustuva tutkimus. Summary: On the properties of sawmill chips. Commun. Inst. For. Fenn. 75 (4): 1—55.

—»— 1974. Wood quality in plantation-grown Scots pine. Lyhennelmä: Puun laadusta viljelymännikössä. Commun. Inst. For. Fenn. 80 (2): 1—105.

von WEDEL, K. W., ZOBEL, B. J. & SHELBOURNE, C. J. A. 1967. Knotwood in Loblolly pine. Tech. Rep. Sch. For. N. C. St. Univ. 36: 1—45.

—»— 1968. Prevalence and effects of knots in young Loblolly Pine. For. Prod. J. 18 (9): 97—103.

WEGELIUS, TH. 1939. The presence and properties of knots in Finnish spruce. Investigations concerning the origin and characteristics of branch and knot wood in Finnish spruce with particular consideration given to the raw material needs of the paper industry. Acta For. Fenn. 48 (1): 1—191.

WESTERN, H. 1971. Tre- og kvist data. Summary: Tree and branch study. Norske Skogforsøksv. Driftstekn. Rapp. 10: 83—93.

VUORISTO, I. 1937. Paperipuiden laatuluokituksesta. Suomen Paperi- ja Puutavaralehti 19 (23): 968—972.

YLINEN, A. 1971. Kuusen oksapuun ominaisuuksista. Puuteknologian harjoitustyö. Metsäteknologian laitos. Helsingin yliopisto. Unpublished manuscript.

ZOBEL, B. J. & RHODES, R. 1956. Spesific gravity estimations of mature Loblolly pine from juvenile wood and seedling limb sections. Forest Sci. 2: 107—112.

ZOBEL, B. J. & RHODES, R. R. 1957. Spesific gravity indicessor use in breeding Loblolly pine. Forest Sci. 3 (3): 281—285.

VIILUSAANNON TEOREETTINEN MALLI

MATTI KÄRKKÄINEN

Summary

THEORETICAL MODEL FOR THE VENEER YIELD

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KÄRKKÄINEN, M. 1978. Viilusaannon teoreettinen malli. Summary: Theoretical model for the veneer yield. Commun. Inst. For. Fenn. 95(2): 1—42.

Tutkimuksessa kehitetään malli, joka kuvaa viilusaantoa erilaisista pölkyistä niitä kuvaavien muuttujien funktiona. Pölkkyä käsitellään mallissa katkaistuna kartiona, joka voi kuitenkin olla käyristynyt (lenko). Muuttuvina tekijöinä voidaan tarkastella kuorellista tai kuoretonta pölkyn keskeltä mitattua läpimittaa, purilaan läpimittaa, pölkyn kapenemista, pituutta, työvaraa syiden suunnassa, viilun paksuutta sekä pölkyn epäpyöreyttä, kuoren määrää, lenkoutta ja sydänlahoa. Saanto esitetään em. tekijöiden funktiona kaavana, joka on helposti käytettävissä pienten ohjelmoitavien laskinten avulla.

A model describing the rotary cutting of veneer is developed. The veneer yield is presented as a function of several variables describing the bolt and the process. The bolt is supposed to have the form of a truncated cone, the axis of which, however, can be curved. The analyzed variables are the diameter at the mid-point of the bolt (with or without bark), core diameter, taper, length of bolt, waste in bolt length, thickness of veneer, irregularity of the cross-section, bark percentage, crookedness of the bolt, and heart rot. The veneer yield is presented as a function of these variables. The formula is easily applied using programmable small desk calculators.

Helsinki 1978. Valtion Painatuskeskus

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TÄRKEIMMÄT SYMBOLIT — *MOST IMPORTANT SYMBOLS*

b = kuorikorjauskerroin. Jos se saa arvon 1,00, läpimitta d_3 oletetaan kuorettomaksi ja saanto lasketaan kaavalla (8) kuoretonta pölkyn tilavuutta kohti. Muutoin b on kuorettoman ja kuorellisen leskusläpimitan suhde, jolloin saanto lasketaan kuorellista tilavuutta kohti.
= *bark coefficient. If 1,00, d_3 is supposed to be without bark, and the yield is calculated on a bark-free basis. Otherwise b is the ratio between the diameters without bark and with bark, and the yield is calculated as percentage of the volume with bark.*

c = pölkyn lenkous, mm. Lenkous määritellään suurimmaksi sivuviivapoikkeamaksi.
= *crookedness of the bolt, mm. Crookedness is defined as the distance between the bolt surface and the line connecting the butt and the top of the bolt.*

d_3 = pölkyn kuorellinen keskusläpimitta, mm
= *diameter of the bolt at the mid-point, mm*

d_6 = purilaan paksuus, mm
= *core diameter, mm*

k = kapeneminen pituusyksikköä kohti, mm/mm
= *taper per unit length, mm/mm*

L = pölkyn pituus, mm
= *length of the bolt, mm*

L_1 = vanerin valmistuksessa käyttökelpoisen viilun pituus, mm
= *length of the veneer usable in plywood production, mm*

r = sydänlahon läpimitta, mm
= *heart rot diameter, mm*

t = viilun paksuus, mm
= *veneer thickness, mm*

1. JOHDANTO

Sahatavaran valmistusprosessin kuvaamiseksi on kehitetty lukuisia sahaussimulaattoreita, joilla pyritään mm. selvittämään eri raaka-ainetekijöiden vaikutusta sahaustuloksen määrään ja arvoon (esim. Heiskanen ja Asikainen 1969, Asikainen ja Heiskanen 1970, Heiskanen 1976). Simulaattorit eivät yleensä ole realistisia siinä mielessä, että niillä voitaisiin täsmällisesti ennustaa sahaustulos. Tämä johtuu mm. raaka-aineen vioista: lenkoudesta, mutkaisuudesta jne. Tarvittaessa tulokset voidaan korjata käytäntöä vastaaviksi sahoilta saatavien tilastotietojen avulla (Heiskanen 1976).

Sahaussimulaattoreista saadut kokemukset kuitenkin osoittavat, että epätarkkuudesta huolimatta tuloksia voidaan hyödyntää suunnittelussa ja tuotannon ohjauksessa. Teoreettisen simulaattorin etuna on mm. se, että voidaan nopeasti kokeilla myös sellaisten tekijöiden vaikutusta, joita ei voida ainakaan edullisesti tutkia empiirisesti.

Toistaiseksi vaneriteollisuutta varten kehitetyt simulaattorit ovat jääneet harvinaisiksi, eikä sorvauksen matemaattista kuvausta ole juuri kehitetty. On tosin runsaasti laskelmia, joissa on tarkasteltu mm. läpimitan vaikutusta saantoon, purilashäviöön jne. Yksinkertaisimmillaan esim. purilashäviön laskeminen on perustunut siihen, että on todettu, kuinka suuri on pikkuympyrän (= purilaan poikkileikkaus) pinta-ala ison ympyrän (= koko pölkyn poikkileikkaus) pinta-alasta, kun ison ympyrän läpimitta kasvaa. Vastaavasti on voitu laskea pyöristyksen osuus eri tapauksissa, kun määräosa ympyrän reunaosasta katsotaan pyöristykseksi (esim. Lehonkoski 1937). Nämä tasogeometrian alaan kuuluvat laskelmat eivät anna kuitenkaan oikeaa kuvaa vaikuttavista tekijöistä.

Eräät nykyaikaisemmat laskelmat ovat epätyydyttäviä siksi, että ne on kehitetty järeämpää raaka-ainetta varten. Tällöin mm. kapenemisen vaikutus saattaa olla niin pieni, että se on jätetty huomiotta (esim. Peters 1976). Nämä mallit eivät sovellu suomalaisiin, pieniläpimittaisiin sorvipölkkyihin.

Empiriaan pohjautuvien regressioyhtälöiden käyttöalue voisi periaatteessa olla laaja, jos selittävät muuttujat valitaan huolellisesti. Kirjallisuudessa esitetyt mallit soveltuvat kuitenkin huonosti yleistarkastelun pohjaksi, kun on pyritty saamaan aikaan ao. populaation kannalta käytännönläheisiä yhtälöitä ja laiminlyöty teorian kehittäminen. Oman maansa oloissa yhtälöt voivat silti olla käyttökelpoisia (esim. Schroeder ja Clark 1970, Dobie ja Hancock 1972).

Ilman hyvää teoreettista pohjaa empiiristen yhtälöiden sokea soveltaminen on arveluttavaa olosuhteiden erilaisuuden vuoksi. Esim. Bethel ja Hart (1960) huomauttavat, että amerikkalaisissa oloissa läpimitan ja saannon yhteys vaihtelee. Luonnonmetsien puutavarassa läpimitan järeytyminen merkitsee saannon suurenemista. Sen sijaan harvennushakkuin hoidetuissa metsissä tilanne saattaa olla päinvastainen, koska suuriläpimittaisen puun tapaaminen indikoi sitä, että se on hylätty aikaisemmissa hakkuissa vikojen takia. Suuri läpimitta voi liittyä tällöin alhaiseen saantoon. — Suomen oloissa tällainen pohdiskelu ei yleensä liene aiheellinen.

Käsillä olevassa työssä pyritään kehittämään yksinkertainen malli, jota voidaan käyttää arvioitaessa sorvipölkyn ominaisuuksien vaikutusta viilun saantoon. Tavoitteena on niin pelkistetty kuvaus, että mallia voidaan soveltaa raaka-ainetekijöiden tutkimiseen jopa pienien ohjelmoitavien laskimien avulla.

Työssä ovat avustaneet tutkimusapulaiset Tarja Björklund (ohjelmointi ja laskenta) ja Leena Kunnari (piirrokset) sekä MH Anna-Liisa Raunio (kirjallisuus). Englanninkielisen tekstin on kääntänyt ja tarkastanut MMK, B.Sc. John Derome. Konekirjoituksesta ovat huolehtineet rva Aune Rytkönen ja nti Leena Turunen. Käsikirjoituksen ovat lukeneet vs. prof. Pertti Harstela (Metsäntutkimuslaitos), prof. Jouko Hämäläinen (Metsäntutkimuslaitos), prof. Risto Juvonen (Helsingin Teknillinen Korkeakoulu), MMT Pekka Kilkki (Suomen Akatemia), MH Jorma Laitinen (Metsäntutkimuslaitos), tuotealajohtaja Risto Lähteenmäki (Oy Wilh. Schauman Ab), MML Pentti Nisula (Metsäntutkimuslaitos), DI Pentti Rinne (Suomen Vaneriyhdistys) ja MH Juhani Salmi (Metsäntutkimuslaitos). — Kiitän saamastani tuesta.

2. VIILUN SORVAUKSEN TEOREETTINEN MALLI

Viilua valmistetaan tavallisesti sorvilla, jonka karojen päissä oleviin kouriin sorvattava pölkky kiinnitetään keskityksen jälkeen. Leikkaava terä on pyörintäakselin suuntainen ja se liikkuu akselia kohti pölkyn säteen suunnassa määränopeudella. Nopeus on sellainen, että pölkyn pyörähdyskertaa kohti terä liikkuu viilun paksuuden verran. Pyörintäakselia vastaan kohtisuorassa olevaan tasoon terän suu piirtää Arkhimedeen spiraaliksi sanotun kuvion. Helposti voidaan todeta, että tämän spiraalin pituus saadaan kaavasta (1), kun spiraalin tekeminen lopetetaan määräetäisyydellä pyörintäakselista.

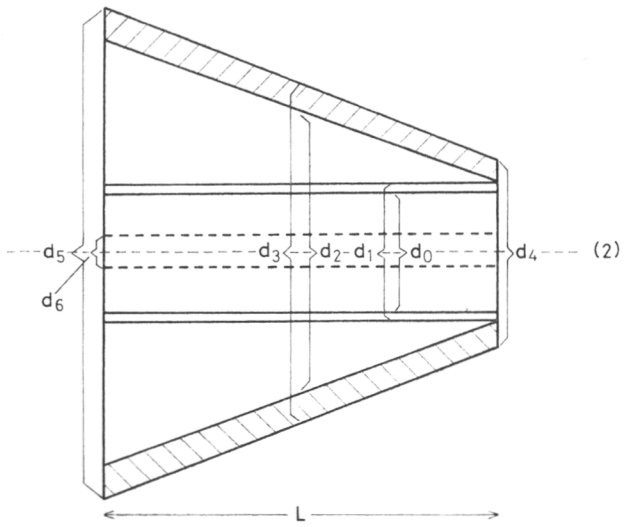
$$(1)\quad s = \frac{\pi (D^2 - d^2)}{4t} \qquad \text{jossa}$$

s = spiraalin pituus (= viilun poikkisyinen pituus)
D = ympyrän kokonaisläpimitta (= pölkyn paksuus)
d = ympyrän pienempi läpimitta spiraalin loppuessa (= purilaan paksuus)
t = viilun paksuus

Jos sekä sorvattava pölkky että sorvauksen päätyttyä jäävä purilas ovat täysin pyöreitä, viilu ei ole tasapaksua, vaan alussa viilun paksuus kasvaa nollasta nimellismittaansa ja lopussa vastaavasti alenee. Tämän poikkeuksellisen viilun poikkisyinen määrä on π (D+d). — Kun viilumaton molemmista päistä leikataan viilua pois epäkelpoisuuden vuoksi, tämän leikattavan osan minimimääränä voidaan pitää teoreettisesti liian ohuen osan pituutta (esim. P e t e r s 1976).

Viilun sorvauksen teoreettista mallia kehitettäessä on tarkoituksenmukaista tarkastella suhteellisen lyhyttä sorvipölkkyä katkaistuna kartiona. Etenkään tyvipölkyissä tämä olettamus ei pidä tarkasti paikkaansa. Mainittakoon kuitenkin, että jopa pitkien tukkien sahaussimuloinneissa on katsottu voitavan käyttää tukin muotona katkaistua kartiota (esim. H e i s k a n e n ja A s i k a i n e n 1969, s. 38).

Jäljempänä tarkastellaan alkuaan kuorellista, katkaistun kartion muotoista pölkkyä, jonka tilavuuden suhteen kaikki saannot yms. lasketaan. — Aiemmin sorvipölkyt kuorittiin vasta sorvissa leikkausterän avulla (esim. R i n n e 1950), ja jotta tulosten vertailu vanhoihin tutkimuksiin olisi tarvittaessa mahdollinen, on käytetty samaa lähtökohtaa. Nykyisin pölkyt kuoritaan tavallisesti erikseen ennen sorvausta. — Jäljempänä esitettävällä mallilla saadaan tulokset haluttaessa myös kuoretonta kiintotilavuutta kohti, kun kuorikorjauskertoimeksi merkitään 1,0.



Kuva 1. Sorvattavaa pölkkyä kuvaavat muuttujat
Fig. 1. Bolt variables

d_0 = pyöristetyn pölkyn läpimitta — *bolt diameter at roundup*
d_1 = pölkyn kuoreton latvaläpimitta — *diameter under bark at crown end*
d_2 = kuoreton keskusläpimitta — *diameter under bark at mid-point*
d_3 = kuorellinen keskusläpimitta — *diameter over bark at mid-point*
d_5 = kuorellinen tyviläpimitta — *diameter over bark at butt end*
d_6 = purilaan läpimitta — *core diameter*
L = pituus — *length*
(2) = pyörintäakseli — *rotation axis*

Kuvassa 1 on esitetty sorvattava pölkky ja eräät sen mitoista. Kun sorvattavan pölkyn pituus on L, sen kuorellinen tyviläpimitta d_5 ja kuorellinen latvaläpimitta d_4, kuorellinen tilavuus V on katkaistun kartion kaavalla

$$(2) \quad V = \frac{\pi L\ (d_5^2 + d_4^2 + d_5\, d_4)}{12}$$

Keskeltä mitattu kuorellinen läpimitta d_3 on katkaistussa kartiossa tyvi- ja latvaläpimittojen keskiarvo eli 0,5 (d_5+d_4). Kapeneminen pituusyksikköä kohti k on em. läpimittojen ero jaettuna pölkyn pituudella eli $k = L^{-1}(d_5 - d_4)$. Näin ollen kaava (2) voidaan kirjoittaa myös keskusläpimitan d_3 ja kapenemisen k funktiona kaavan (3) osoittamalla tavalla.

$$(3) \quad V = \frac{\pi L}{12} \quad \frac{(12 d_3^2 + k^2 L^2)}{4}$$

Jos lyhyessä sorvipölkyssä kuoren paksuus ei olennaisesti muutu tyvipäästä latvaan päin, kuoreton kuutiomäärä saadaan lasketuksi kaavalla (3), kun kuorellinen läpimitta d_3 korvataan kuorettomalla läpimitalla d_2. Jos kuoriprosentti on B_v tilavuudesta, niin tunnetusti sen ja läpimitasta lasketun kuoriprosentin B_d välillä vallitsee seuraava yhteys.

$$(4) \qquad B_v = 2B_d - \frac{B_d^2}{100}$$

Esim. jos $B_v = 13$ %, B_d on kaavan (4) mukaan 6,726 %.

Jäljempänä kuoren määrää kuvataan kuorikorjauskertoimella b. Se on $1-(B_d/100)$, esimerkkitapauksessa siis 0,93274. Yleisesti siis $d_2 = bd_3$ eli kuoreton keskusläpimitta on kuorellinen keskusläpimitta kuorikorjauskertoimella kerrottuna.

Kuoreton latvaläpimitta d_1 määrittelee sen sorvauspölkyn paksuuden, josta teoriassa (jos pölkyn poikkileikkaus on pyöreä) voidaan saada täysikokoista viilua. Sitä vastaavan sylinterin tilavuus on $0{,}25\,\pi\,Ld^2_1$. Kun tämä tilavuus vähennetään kaavan (3) osoittamasta tilavuudesta, saadaan kuoresta ja kapenemisesta aiheutuva häviö. Kun kaavassa (3) käytetään kuoretonta keskusläpimittaa d_2, saadaan erotuksena pelkästään kapenemisesta aiheutuva käviö.

Kuoreton latvaläpimitta d_1 voidaan esittää myös kaavalla (5), joka saadaan seuraavasti.

$$(5) \qquad d_1 = d_2 - \frac{kL}{2} = bd_3 - \frac{kL}{2} = \frac{2bd_3 - kL}{2}$$

jossa k = kapeneminen pituusyksikköä kohti
b = kuorikorjauskerroin
L = pölkyn pituus

Pölkyn poikkileikkauksen epäpyöreydestä johtuu, että pölkky joudutaan pyöristämään pienemmäksi kuin puutavaran mittauksessa todettu latvaläpimitta edellyttää[1]). — Jäljempänä käytetään epäpyöreyskerrointa z, joka osoittaa pyöristetyn pölkyn läpimitan ja pölkyn alkuperäisen latvaläpimitan suhteen. Pyöristetyn pölkyn läpimitta d_0 on näin ollen zd_1.

Edellä on mainittu, että kuoren paksuutta on pidetty sorvipölkyn eri kohdissa vakiona. Tämä ei ole kuitenkaan välttämätön oletus. On parempi käsitellä kuoren *osuutta* eikä sen *paksuutta* vakiona. Helposti voidaan todeta, että tämä aiheuttaa muutoksen kaavassa (5) vain termiin kL: termi muuttuu muotoon bkL. — Tätä versiota käytetään jäljempänä.

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[1]) Puutavaran kappaleittainen mittaus perustuu mittaussäännön mukaan läpimitan toteamiseen vaakasuorassa suunnassa. Tämä vastaa likimain satunnaisessa suunnassa mittaamista. — Mainittakoon, että pyöristyksen jälkeen pölkyn läpimitta on pienempi kuin poikkileikkauksen pienin läpimitta sorvaamattomassa pölkyssä (esim. Mette ja Boss 1964). Syynä on mm. se, että ympyrä on vain eräs orbiformi eli saman läpimitan omaava tasokuvio. Myös poikkileikkauksen epäkonveksisuus vaikuttaa samalla tavalla (ks. Kärkkäinen 1974, s. 49—54).

Jotta pölkyn pituuden vaikutusta saantoon voitaisiin tarkastella järkevästi, on vielä otettava huomioon, että valmiissa vanerissa syiden suuntainen pituus on alhaisempi kuin pölkyn pituus. Tämä johtuu siitä, että sorvin karojen, pölkynpäävaurioiden, viiluarkkeihin kohdistuvien toimien yms. syiden vuoksi joudutaan sorvaamaan viilua, jonka syiden suuntainen pituus on suurempi kuin mitä voidaan käyttää hyväksi valmiissa vanerissa. Jäljempänä tätä tehollista viilun syiden suuntaista pituutta merkitään kirjaimella L_1. Näin ollen $L—L_1$ on em. syistä aiheutuva ylimitta eli työvara. Tähän työvaraan voidaan laskea myös pölkkyjen katkaisutarkkuudesta riippuva työvara, joskaan sillä ei ole käytännöllistä merkitystä pienuutensa vuoksi (esim. Meriluoto 1968).

Aiemmin esitettyjen perusteiden mukaisesti vanerin valmistuksessa käytettävän viilun tilavuus voidaan kirjoittaa kaavan (6) mukaisesti

$$(6) \qquad V_1 = \frac{\pi L_1 (d_0^2 - d_6^2)}{4} = \frac{\pi L_1 \left[\left(zb \frac{2d_3 - kL_1}{2} \right)^2 - d_6^2 \right]}{4}$$

Tästä viilun tilavuudesta on kuitenkin vähennettävä aiemmin todetun mukaisesti liian ohuen viilun tilavuus V_2, joka on esitetty kaavana (7).

$$(7) \qquad V_2 = \pi L_1 t(d_0 + d_6) = \pi L_1 t \left[zb \left(\frac{2d_3 - kL_1}{2} \right) + d_6 \right]$$

Kun kaavat (3), (6) ja (7) otetaan huomioon, sorvauksen kokonaissaanto S eli vanerin valmistukseen tulevan täysilevyisen viilun määrä prosentteina koko sorvipölkyn tilavuudesta voidaan määritellä kaavana (8). — Tällöin ei mahdollisia vikoja ole otettu huomioon.

$$(8) \qquad S = \frac{100\ (V_1 - V_2)}{V}\ \% \qquad \text{eli}$$

$$S = \frac{100 \left(\frac{\pi L_1 \left[(zb \frac{2d_3 - kL_1}{2})^2 - d_6^2 \right]}{4} - \pi L_1 t \left[zb \left(\frac{2d_3 - kL_1}{2} \right) + d_6 \right] \right)}{\frac{\pi L}{12} \left(\frac{12 d_3^2 + k^2 L^2}{4} \right)}\ \%$$

Kokonaishäviö on luonnollisesti 100-S %. Sen osia ovat kuorintahäviö H_1, kartiokkuushäviö H_2, epäpyöreyshäviö H_3 ja purilashäviö H_4. Kuorintahäviö on likimain sama kuin kuoren osuus prosentteina sorvipölkyn tilavuudesta. Kartiokkuushäviö on taas latvalieriön ulkopuolelle jäävän kuorettoman osan tilavuus prosentteina pölkyn tilavuudesta. Epäpyöreyshäviö on puolestaan pyöristämättömän latvapoikkileikkausta vastaavan lieriön tilavuuden ja pyöristetyn sylinterin tilavuuden ero prosentteina pölkyn tilavuudesta. Purilashäviö on tietysti purilaan osuus pölkyn tilavuudesta. — Eräät käsitteet on esitetty kaavoina (9), (10) ja (11).

$$(9) \qquad H_1+H_2 = \frac{100(V-\frac{\pi L d_1^2}{4})}{V} = \frac{25(4V-\pi L d_1^2)}{V}$$

$$(10) \qquad H_3 = \frac{100\pi L(\frac{d_1^2-d_0^2}{4})}{V} = \frac{25\pi L(d_1^2-d_0^2)}{V}$$

$$(11) \qquad H_4 = \frac{100\pi L\frac{d_6^2}{4}}{V} = \frac{25\pi L d_6^2}{V}$$

Edellä esitetyn mukaisesti tietyllä tavalla määriteltyä viilun kokonaissaantoa sekä tärkeimpiä raaka-ainehäviöitä voidaan tarkastella sorvipölkkyä ja sorvaustapahtumaa kuvaavien muuttujien avulla. Nämä muuttujat ovat keskitetysti esittäen seuraavat.

d_3 = kuorellinen pölkyn keskeltä mitattu läpimitta
d_6 = purilaan läpimitta
k = pölkyn kapeneminen pituusyksikköä kohti
L = pölkyn pituus
$L-L_1$ = työvara syiden suuntaisessa pituudessa
t = viilun nimellispaksuus
b = kuorikorjauskerroin
z = epäpyöreyskerroin

Mallia voidaan kehittää edelleen luopumalla olettamuksesta, että sorvattava pölkky on katkaistun kartion muotoinen. Kun lenkous eli sorvipölkyn tasainen käyryys on yleisimpiä vikoja (K o i v u m ä k i 1962, H e i s k a n e n 1966, s. 19), voidaan ajatella sen ottamista huomioon tarkastelemalla taivutetun katkaistun kartion muotoista pölkkyä. Sen kokonaistilavuus saadaan edelleen ilman olennaista virhettä katkaistun kartion kaavalla. Hyödynnettävissä olevan viilun määrä saadaan lasketuksi ottamalla huomioon, että oikein keskitetystä lengosta pölkystä saadaan pyöristyksen jälkeen sylinteri, jonka läpimitta on vähän lengoissa pölkyissä latvaläpimitan mukainen, tai enemmän lengoissa pölkyissä keskusläpimitan ja lenkouden erotus (L a p p i - S e p p ä l ä 1933, K o i v u m ä k i 1962). — Lenkoudella tarkoitetaan tällöin pölkyn koveran puolen reunaviivan etäisyyttä tyvi- ja latvaleikkausta sivuavasta janasta.

Atk- tai laskinohjelmassa lenkous voidaan ottaa huomioon siten, että pyöristetyn pölkyn läpimittana pidetään joko epäpyöreyskertoimella kerrottuna latvaläpimittaa tai keskusläpimitan ja lenkouden erotusta riippuen siitä, kumpi niistä on pienempi ja siten määrää pyöristyksen suuruuden.

Lenkouden lisäksi mallissa voidaan ottaa huomioon toinenkin yleinen vika, sydänlaho. Lahoisuuden esiintyminen merkitsee mallin kannalta yksinkertaisesti sitä, että laho runsaana esiintyessään lisää purilaan paksuutta. — Liitteenä olevaan ohjel-

maan on otettu mahdollisuus määritellä lahokuvion läpimitta, jonka perusteella purilaan läpimittaa vastaavasti suurennetaan.[1]) Periaatteessa sydänlahon tavoin vaikuttavat sydänhalkeamat, joita esiintyy erityisesti talvella kaadettujen koivujen järeissä tyviosissa (A r o 1960, 1962).

[1]) Käytännössä sydänlaho vaikuttaa usein koko läpimitan verran, ts. koko pölkky joutuu jätteisiin sen alkaessa pyöriä sorvin kourissa. Etenkin suurilla pölkyillä käy helposti näin, koska leikkausta vastustavan voiman momentti pyörimisakselin suhteen on suuri.

3. MALLILLA SAATAVIA TULOKSIA

31. Empiirisiä tietoja mallia varten

Jotta edellä esitetyllä mallilla voitaisiin saada käyttökelpoisia tuloksia, tarvitaan tietoja käytettyjen parametrien keskimääräisistä arvoista ja niiden vaihtelusta. — Jäljempänä käsitellään Suomen osalta pelkästään koivua ja kuusta koskevia tietoja, koska Suomessa sorvataan pääasiassa näitä puulajeja.

Kapenemisesta on käytettävissä useita tutkimuksia. Koivun tyvitukeissa kuorellinen keskimääräinen kapeneminen on 7—8 mm (7,6 mm/m, Nisula 1967; 7,2 mm/m, Heiskanen ja Salmi 1976), kun kapeneminen on mitattu pitkän vaneritukin keskelta latvaan (latvakapeneminen). Tyvikapeneminen eli kapeneminen tyvestä tukin keskelle on huomattavasti suurempi, esim. Nisulan (1967) aineistossa keskimäärin 10,9 mm/m. Muissa kuin tyvitukeissa keskimääräiseksi kapenemiseksi on saatu esim. 9,6 mm/m (Heiskanen ja Salmi 1976).

Latvakapenemisen keskihajonta on huomattavan suuri, esim. Heiskasen ja Salmen (1976) aineistossa tyvitukeissa 3,6 mm/m ja muissa tukeissa 4,3 mm/m.

Eteläsuomalaisten kuusityvitukkien kuoreton latvakapeneminen on Aron ja Rikkosen (1966) mukaan noin 8—11 mm/m latvaläpimitasta riippuen. Heiskasen ja Rikkosen (1971) aineistossa vastaava luku oli 7,1 mm/m. Muiden kuin tyvitukkien keskimääräinen latvakapeneminen on esim. 9—13 mm/m (Aro ja Rikkonen 1966; 11,0 mm/m, Heiskanen ja Rikkonen 1971). — Kuusityvitukkien tyvikapeneminen on suuruusluokaltaan 12—24 mm/m (Aro ja Rikkonen 1966).

Kuusitukkien kapenemisen vaihtelusta ei ole tietoa. Oletettavasti se on samaa suuruusluokkaa koivun kanssa. — Kuorelliset kapenemiset ovat luonnollisesti hieman suuremmat kuin em. kuorettomat kapenemiset, koska paksua kaarnaa on rungon alaosassa.

Kuoren osuus poikkileikkauksen pinta-alasta tai pölkyn tilavuudesta oli koivuvaneritukeilla Nisulan (1967) aineistossa tyvessä 15,9 %, tukin keskellä 12,7 % ja latvassa 12,6 %. Kuusella kuoren osuus on sama tyvitukeissa ja muissa tukeissa, n. 9,9 % (Heiskanen ja Rikkonen 1976). — Tukkien välisestä kuoren osuuden keskihajonnasta ei ole selvityksiä.

Pölkyn läpimitta on suomalaisella koivulla tavallisesti yli 15 cm, kun kauppasopimuksissa mainittu tukin minimiläpimitta on 17 cm. Erään julkaisemattoman aineiston

mukaan tehtailla tavataan vain poikkeuksellisesti yli 45 cm koivupölkkyjä. Keskikoko on yleensä 21—25 cm pölkyn keskeltä em. julkaisemattoman aineiston mukaan. Pölkkyjen koko ei liene juuri alentunut 1930-luvulta, jolloin ainakin eräässä laajassa aineistossa keskiläpimitta oli 22 cm (Enarvi 1939). Mahdollista kuitenkin on, että viimeisten 15 vuoden aikana pölkyt ovat pienentyneet (Vaneriteollisuuden . . . 1977, s. 169). Kuusi on olennaisesti järeämpää. Keskiläpimitta lienee n. 30 cm, eikä yli 70 cm tyvipölkkyjä pidetä harvinaisina (Roine 1970).

Kansainvälisesti katsoen Suomessa sorvattavat pölkyt ovat poikkeuksellisen pieniläpimittaisia. Eräällä ruotsalaisella havupuuta sorvaavalla tehtaalla minimiläpimitta on 28 cm (Europas modernaste . . . 1971), joskin pienempääkin mäntyä sorvataan (Englesson 1956). Italiassa on poppelin minimiläpimitta 20 cm ja pyökin 30 cm (Lozzi 1966). Yhdysvalloissa yleisiä minimiläpimittoja ovat 25 ja 30 cm (Carpenter 1969, Lutz 1974), ja eräissä tutkimuksissa todetut keskiläpimitat olivat puulajista riippuen 51—66 cm (Woodfin 1973, 1974, Woodfin ja Pong 1974). Australiassa keskiläpimitat olivat eräissä tutkimuksissa puulajista riippuen 45—77 cm (Veneer species . . . 1973). Malesiassa keskiläpimitaksi on arvioitu 67 cm (Harlan 1976). Eräillä jalopuilla keskiläpimitta voi olla metrin suuruusluokkaa (esim. Kollmann ja Schulte-Brader 1954).

Purilaan läpimitta on Suomen oloissa koivulla tavallisesti 60 mm suuruusluokkaa. Kuusella se on korkeampi lähinnä silloin, kun sorvataan pitkiä pölkkyjä (yli 2,5 m). Tällöin purilas on 100 mm tai enemmän. Jos sorvattaessa kourat alkavat pyöriä pölkyssä päiden heikkouden vuoksi, purilaan läpimitta voi olla suurempikin.

Kansainvälisesti arvostellen 60 mm purilas on ohut. Yhdysvalloissa ja Kanadassa on pieniläpimittaisia, lyhyitä pölkkyjä sorvaavien nykyaikaisten laitosten purilas yleensä 100 mm suuruusluokkaa (Bowland ym. 1968, Baldwin 1975). Yhdysvaltain länsirannikon suuria puita sorvattaessa purilas saattaa olla jopa 230 mm, joskin tyypilliset arvot ovat n. 150 mm uudenaikaisemmilla laitoksilla (Bergwall ja Gedney 1970). Eräs syy purilaiden suuruuteen voi olla se, että niistä tehdään sahatavaraa. Kun pölkyn pituus on usein 8 jalkaa (n. 2 400 mm) sekä tasausvara, purilaasta sahataan usein kaksi 50×100 mm kappaletta (Yerkes ja Woodfin 1972, Dobie ja Neilson 1973, Fahey 1974). Australiassa myös lyhyempiä purilaita on ehdotettu sahattavaksi esim. pallettien tekemistä varten (Krilov ja Ironside 1973). — Toinen syy purilaiden paksuuteen on pölkkyjen pituus. Pituuden kasvaessa leikkausta vastustava voima nimittäin kasvaa ja kourien sekä purilaan on myös oltava suurempia. Kun pölkkyjen pituus on toinen yleinen mitta, 4 jalkaa (n. 1 200 mm), purilas voi olla 80—90 mm (esim. Mueller ym. 1968). Kun tyypillinen levykoko on 4×8 jalkaa, amerikkalainen käytäntö on ymmärrettävissä myös taloudellisin perustein (Juvonen 1969).

Epäpyöreydestä olevat tiedot ovat puutteellisia. Pyökin sorvauksessa Mette ja Boss (1964) totesivat, että tavanomaisilla pölkyillä läpimitta pyöristyksen jälkeen oli keskimäärin 3,4 % pienempi kuin pienin pölkyn läpimitta. Vikoja sisältävillä pölkyillä ero oli suurempi, 7,9—11,1 %.

Viitteitä epäpyöreyden suuruusluokasta saa myös tarkastelemalla pienimmän ja suurimman läpimitan eroa poikkileikkauksessa. Kärkkäisen (1975 a) koivuaineistossa ero oli keskimäärin 17,5 mm eli 8,3 % suurimmasta läpimitasta. Kuusella ero lienee pienempi, eräiden havupuita koskevien tietojen perusteella 4—6 % (Heikkilä 1913 a, b, Bøhmer 1935, Heiskanen ja Tiihonen 1958, s. 29, Kärkkäinen 1975 b).

Sorvipölkyn pituus on Olavisen (1964) mukaan Suomessa tavallisesti 54″, 64″ tai 76″ eli 1 370, 1 630 tai 1 930 mm. Nykyiset vanerikoot ovat hieman muuttuneet 300 mm modulin vuoksi. Monissa muissa maissa pituudet ovat suuremmat etenkin suuremmista läpimitoista johtuen. Yleinen pituus on 8 jalkaa (noin 2 400 mm) tai sen puolikas pieniläpimittaisille pölkyille.

Vanerin valmistuksessa käyttökelpoinen syiden suuntainen pituus lienee tavallisesti 50—100 mm alhaisempi kuin pölkyn pituus. Teoreettinen työvara on yleensä 100 mm (esim. Heikkilä 1976, s. 68), mutta levyt voidaan sahata työvaran edellyttämää suuremmiksi eli pienentää alkuperäistä työvaraa. Tarkkoja nykytilannetta kuvaavia lukuja ei ole saatavissa, mutta esimerkkinä voidaan pitää Olavisen (1964) esittämiä lukuja. — Nykyisin kutakin pituutta olevista pölkyistä tehdään yleensä vain yhtä mittaa, ts. työvara on vakio.

Pölkyn pituus	64″	
Puristinmitta	62″	43 %
»	61″	23 %
»	60″	25 %
»	58″	9 %
Yhteensä		100 %

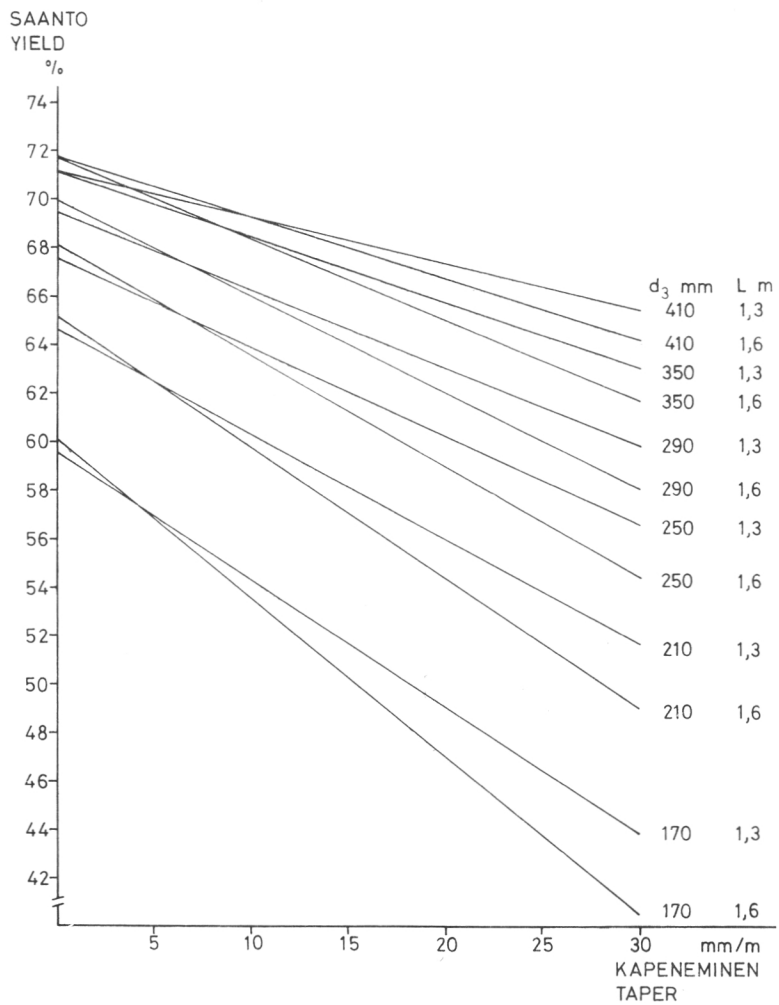
Lenkouden vaihteluvälistä ei ole tarkkoja tietoja. Mainittakoon kuitenkin, että Meriluodon (1965) aineistossa lenkous oli suurimmillaan yli 90 mm. Heiskanen (1966) on taas esittänyt tuloksia lenkouden vaikutuksesta, kun lenkous on ollut välillä 0—30 % (ilmeisesti kuorellisesta keskusläpimitasta).

Viilun paksuus on koivun sorvauksessa esim. 1,5 mm, kuusen sorvauksessa esim. 1,4 mm, 2,8 mm jne. — Viilun paksuudella ei ole olennaista vaikutusta mallin antamiin saantolukuihin.

32. Kapenemisen vaikutus

Tunnettua on, että kapenemisen lisääntyessä viilusaanto alenee. Kun kysymyksessä on katkaistu kartio, riippuvuus on lineaarinen. Kapenemisen vaikutus kasvaa pölkyn pituuden kasvaessa ja läpimitan pienentyessä.

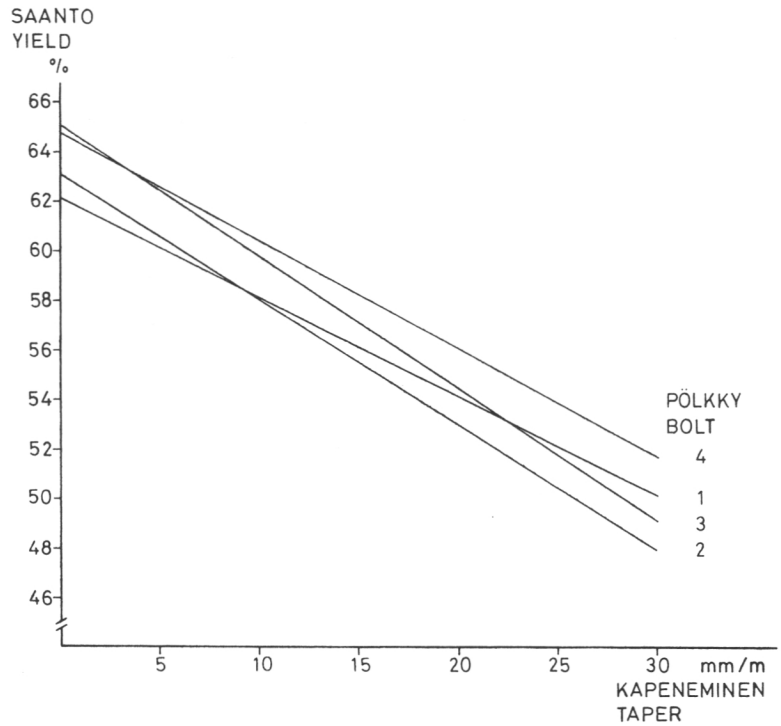
Kuvassa 2 on esimerkki kapenemisen vaikutuksesta, kun työvara on 50 mm, pölkyn pituus 1 320 tai 1 625 mm, purilaan läpimitta 60 mm ja muut, vähemmän vaikuttavat tekijät kuten kuvatekstissä on ilmoitettu. — Kuvasta voidaan havaita, että



Kuva 2. Viilusaanto kapenemisen funktiona, kun kuorellinen keskusläpimitta on 170—410 mm (d_3), pölkyn pituus 1 320 tai 1 625 mm (L) ja hyödyksi käytetyn viilun syiden suuntainen pituus 50 mm alhaisempi (työvara 50 mm). Purilas on 60 mm, epäpyöreyskerroin 0,95, kuoriprosentti 13 ja viilun paksuus 1,4 mm. Lenkous oletetaan niin vähäiseksi, ettei se vaikuta tuloksiin.

Fig. 2. Veneer yield as a function of taper, when diameter over bark at mid-point is 170—410 mm (d_3), bolt length 1 320 or 1 625 mm (L) and the length of the utilizable veneer along the grain 50 mm smaller (length wastage 50 mm). Core is 60 mm, cross-sectional irregularity coefficient 0,95, bark percentage 13 and veneer thickness 1,4 mm. Crookedness is assumed to be so small that it does not affect the results.

pölkyn pituuden kasvaessa saanto kasvaa ainoastaan silloin, kun kapeneminen on poikkeuksellisen alhainen. Jos kapeneminen on suuri, siitä aiheutuva saannon aleneminen on vaikutukseltaan merkittävämpi kuin se saannon lisääntyminen, joka aiheutuu pölkyn pituuden kasvusta eli siitä, että työvaran osuus pienenee pölkyn pituuden kasvaessa.



Kuva 3. Viilusaanto kapenemisen funktiona, kun työvara on 100 mm pölkyissä 1 ja 2 sekä 50 mm pölkyissä 3 ja 4. Pölkkyjen 1 ja 4 pituus on 1 320 mm ja pölkkyjen 2 ja 3 taas 1 625 mm. Keskusläpimitta on 210 mm. Muut tiedot ovat samat kuin kuvassa 2.

Fig. 3. Veneer yield as a function of taper when length wastage in bolts 1 and 2 is 100 mm and in bolts 3 and 4 50 mm. The length of bolts 1 and 4 is 1 320 mm and of bolts 2 and 3 1 625 mm. Diameter at mid-point is 210 mm. Other parameters are the same as in Fig. 2.

Kuvassa 2 olevien eripituisia pölkkyjä tarkoittavien suorien leikkauspisteet tarkoittavat niitä kapenemisarvoja, joita enemmän kapenevat vaneritukit kannattaa katkoa lyhyiksi pölkyiksi pelkästään raaka-aineen käyttösuhdetta ajatellen. Kuvan mukaan leikkauspisteet siirtyvät suurempaan kapenemiseen päin läpimitan kasvaessa. Suuret tukit saavat siis olla kapenevampia kuin pienet tukit, jotta ne silti kannattaisi vielä katkoa pitkiksi sorvipölkyiksi. Edelleen voidaan kuvasta todeta, että virheellinen katkaisupituus vaikuttaa saantoon voimakkaasti vain pieniläpimittaisissa tukeissa. — Tältä pohjalta on sangen perusteltu se käytäntö, että tyvestä lukien ensiksi katkotaan pitkät sorvipölkyt vaneritukkia tehtaalla jaettaessa (K o i v u m ä k i 1964).

Jos työvara on alhainen, esim. juuri 50 mm, huomattava osa tukeista kannattaa sorvata lyhyinä pölkkyinä pelkästään raaka-aineen kulutusta ajatellen. Jos työvara on suuri, esim. keskimäärin 100 mm, vain selvästi keskimääräistä enemmän kapenevat tukit kannattaa katkoa lyhyiksi sorvipölkyiksi. Tämä näkyy kuvassa 3 siitä, että eripituisia pölkkyjä tarkoittavien suorien leikkauspisteet siirtyvät suurempaan kapenemiseen päin keskimääräisen työvaran kasvaessa.

Kuvan 2 perusteella voidaan edelleen päätellä, että työvaran ollessa kohtuullisen alhainen pölkyn pidentäminen kasvattaa saantoa suhteellisen vähän. Tämän vuoksi on pääteltävissä ja laskelmin osoitettavissa, ettei pölkyn pituuden kasvuun saa liittyä olennaista purilaan suurentumista. Käytännössä saanto on 1,3 m pituisia pölkkyjä 60 mm purilaaseen saakka sorvattaessa suurempi kuin silloin, kun pölkyn pituus on 2,5 m ja purilas 100 mm. Näin on jopa silloin, kun työvara on keskimäärin 100 mm eikä olennaista kapenemista ole.

Kansainvälisesti katsoen Suomessa sorvattava raaka-aine on pieniläpimittaista. Mielenkiintoista on todeta, että myös sorvipölkyt ovat lyhyitä (Proceedings . . . 1976). Edellä esitetyn valossa tällainen käytäntö on raaka-aineen käytön kannalta sangen ymmärrettävää ja myös oppikirjoissa perusteltu (esim. R i n n e 1944, s. 57).

33. Läpimitan vaikutus

Läpimitan kasvaessa viilusaanto kasvaa jatkuvasti hidastuvalla nopeudella. Saannon lisääntyminen pieniläpimittaisista pölkyistä suuriläpimittaisiin on sitä suurempi, mitä voimakkaampi on kapeneminen. Tästä on esimerkki kuvassa 4.

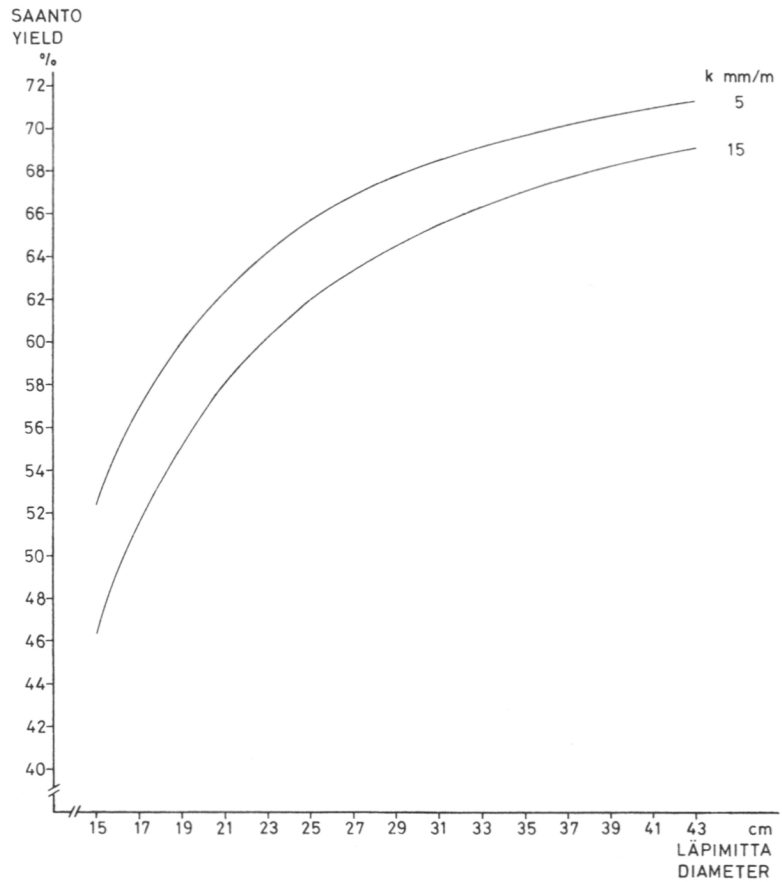
Pölkyn pituus vaikuttaa samalla tavalla kuin kapeneminen: pituuden lisääntyessä läpimitan vaikutus kasvaa. Esimerkiksi kun kapeneminen on 5 mm/m ja purilaan läpimitta 60 mm sekä muut parametrit kuten kuvassa 2, saadaan pituuden vaikutuksesta läpimitan vaikutukseen seuraavat tulokset.

Pölkyn pituus, mm	Läpimitta kuoren päältä, mm 170	270	370
		Viilusaanto, %	
1 320	56,9	66,8	70,2
1 625	56,6	66,9	70,4
2 540	55,3	66,4	70,3

Kun läpimitan vaikutus saantoon riippuu kapenemisesta ja sorvipölkyn pituudesta, tästä seuraa, että saannon kannalta optimaalinen sorvipölkyn pituus riippuu kapenemisesta ja läpimitasta. — Yleisesti ottaen voidaan sanoa, että suurimmat saantoprosentit saadaan kaikissa läpimittaluokissa lyhyitä sorvipölkkyjä käytettäessä, jos kapeneminen on voimakasta. Jos kapeneminen on vähäistä, suurin saanto saadaan sorvaamalla pieniläpimittaiset pölkyt lyhyinä sorvipölkkyinä ja suuret pölkyt pitkinä.

Tarkat läpimittarajat riippuvat kuitenkin työvaran suuruudesta. Jos työvara on suuri, jo suhteellisen pieniläpimittaiset, vähän kapenevat pölkyt kannattaa sorvata pitkinä sorvipölkkyinä. Jos työvara on pieni, läpimittaraja on korkeampi.

Esimerkiksi jos vaihtoehtoiset pölkyn pituudet ovat 1 320, 1 625 ja 2 540 mm ja purilas on kaikissa tapauksissa 60 mm, 50 mm keskimääräistä työvaraa käytettäessä kaikki läpimitaltaan yli 250 mm olevat pölkyt kannattaa sorvata 1 625 mm pituisina, kun kapeneminen on 5 mm/m tai vähemmän. Jos työvara on keskimäärin 100 mm, pieniläpimittaisetkin pölkyt kannattaa sorvata 1 625 mm pituisina ja läpimitaltaan yli 330 mm pölkyt peräti 2 540 mm pituisina.



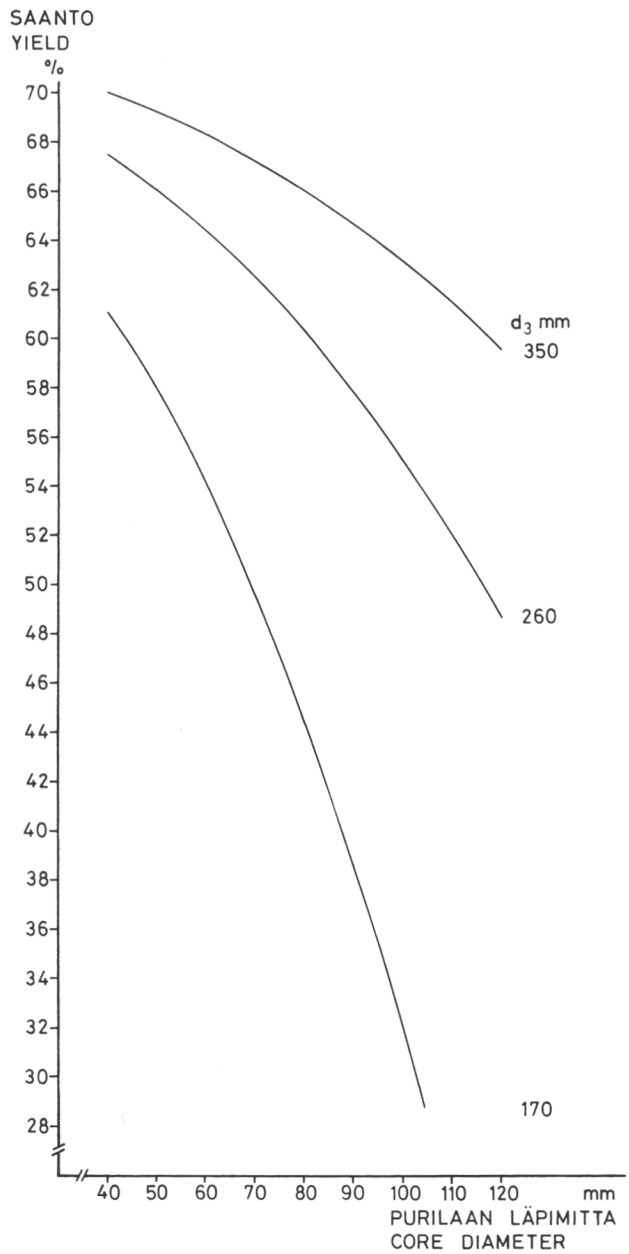
Kuva 4. Viilusaanto kuorellisen keskusläpimitan funktiona, kun pölkyn pituus on 1 320 mm, työvara 50 mm ja kapeneminen (k) 5 tai 15 mm/m. Muut parametrit ovat kuten kuvassa 2.

Fig. 4. Veneer yield as a function of diameter over bark at mid-point, when bolt length is 1 320 mm, length wastage 50 mm and taper (k) 5 or 15 mm/m. Other parameters are the same as in Fig. 2.

Käytännössä on muuttuvaksi tekijäksi otettava vielä purilaan paksuus. Jos em. pituuksia vastaavat purilaat ovat 60, 80 ja 100 mm, pelkästään raaka-aineen käyttöä ajatellen kaikenläpimittaiset pölkyt kannattaa sorvata 1 320 mm pituisina, olipa keskimääräinen työvara sitten 50 tai 100 mm. — Pitkien sorvipölkkyjen teoreettinen etu menetetään siis herkästi, jos purilaan läpimittaa joudutaan suurentamaan pituuden vuoksi.

34. Purilaan paksuuden vaikutus

Kuvassa 5 on esitetty esimerkkejä siitä, kuinka purilaan paksuus vaikuttaa viilusaantoon eri läpimittaluokissa. Selvää on, että vaikutus on suurin pieniläpimittaisissa pölkyissä, joissa huomattava osa pölkyn tilavuudesta on purilasta.

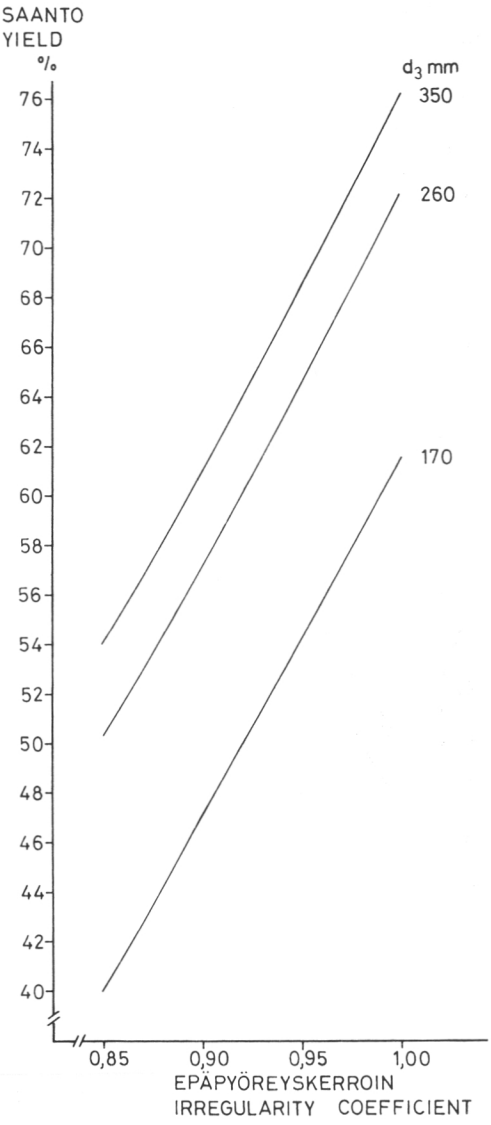


Kuva 5. Viilusaanto purilaan läpimitan funktiona, kun pölkyn pituus on 1 320 mm, työvara 50 mm, kapeneminen 10 mm/m ja kuorellinen keskusläpimitta (d_3) 170, 260 tai 350 mm. Muut parametrit ovat kuten kuvassa 2.

Fig. 5. Veneer yield as a function of core diameter, when bolt length is 1 320 mm, length wastage 50 mm, taper 10 mm/m and diameter over bark at mid-point (d_3) 170, 260 or 350 mm. Other parameters are the same as in Fig. 2.

Kuva 6. Viilusaanto epäpyöreyskertoimen funktiona, kun läpimitta (d_3) on 170, 260 tai 350 mm. Muut tiedot ovat kuten kuvassa 2.

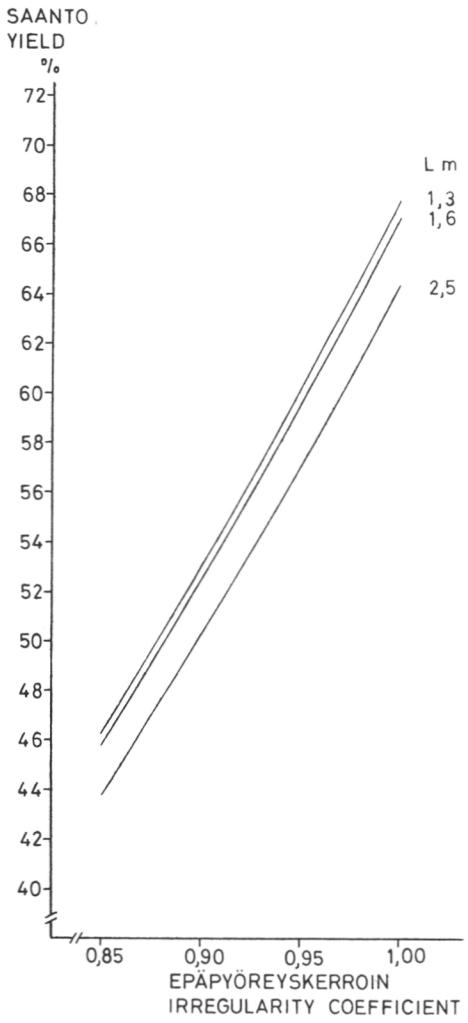
Fig. 6. Veneer yield as a function of cross-sectional irregularity coefficient when diameter (d_3) is 170, 260 or 350 mm. Other data is the same as in Fig. 2.



35. Epäpyöreyden vaikutus

Kuvassa 6 on esitetty epäpyöreyden vaikutus viilusaantoon. Epäpyöreyskertoimella epäpyöreyttä kuvattaessa riippuvuus on likimain lineaarinen ja suhteellisesti samanlainen eri läpimittaluokissa. Absoluuttiset erot ovat tietysti suuret, koska saanto riippuu läpimitasta.

Epäpyöreyden vaikutus on suhteellisesti samanlainen myös eripituisilla sorvipölkyillä (kuva 7).



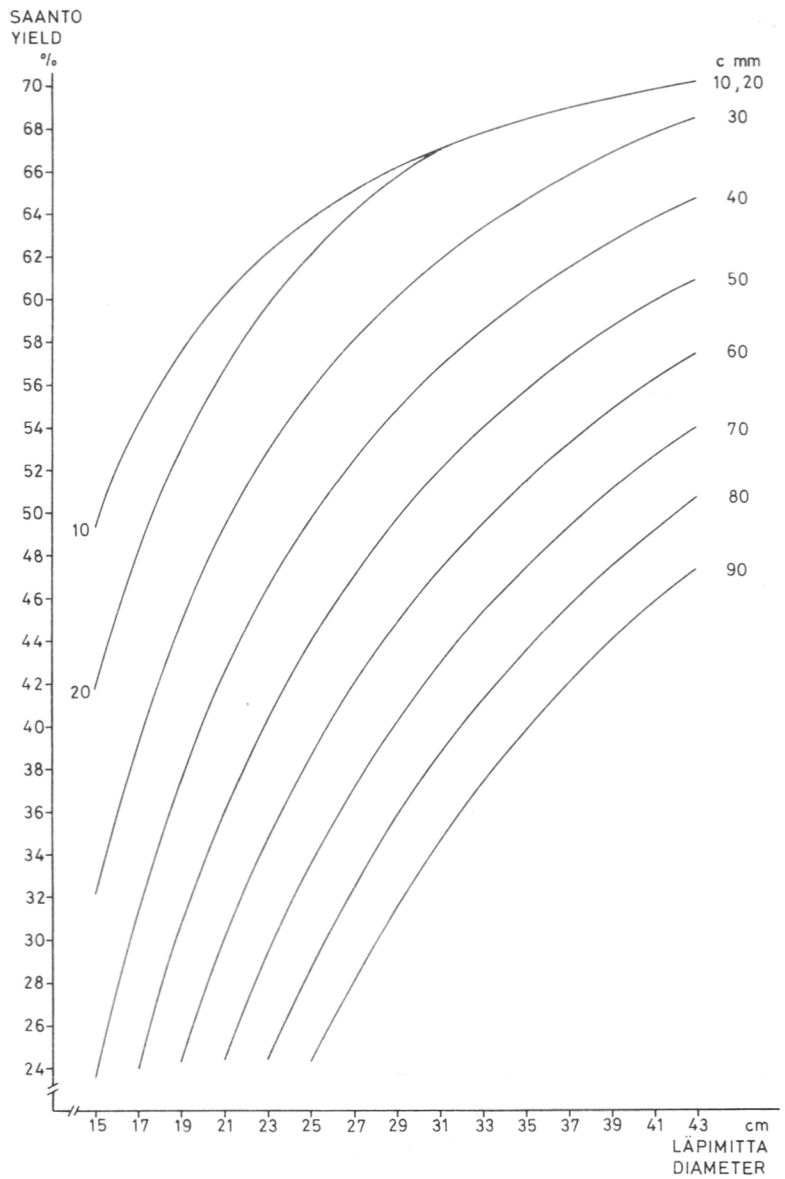
Kuva 7. Viilusaanto epäpyöreyskertoimen funktiona, kun pölkyn pituus (L) on 1 320, 1 625 tai 2 540 mm. Muut tiedot ovat kuten kuvassa 2.

Fig. 7. Veneer yield as a function of cross-sectional irregularity coefficient, when bolt length (L) is 1 320, 1 625 or 2 540 mm. Other data is the same as in Fig. 2.

36. Lenkouden vaikutus

Kuvassa 8 on esitetty viilusaannon riippuvuus lenkoudesta ja läpimitasta. — Huomattavin vaikutus lenkoudella on pienissä pölkyissä. Suurissa pölkyissä vähäinen lenkous ei vaikuta lainkaan saantoon, vaan peittyy epäpyöreyden alle. Pölkyn pituudella on vain vähäinen vaikutus, kun tarkastellaan saman läpimitan ja lenkouden omaavia pölkkyjä.

Jos kokonainen tukki tai runko on lenko, se pyritään katkomaan lyhyiksi sorvipölkyiksi. Näin ollen on olennaisempaa tarkastella pitkiä ja lyhyitä sorvipölkkyjä siten, että ne edustavat samaa kaarevuussädettä. Tällöin lyhyiden pölkkyjen lenkous on alhaisempi kuin pitkien pölkkyjen.



Kuva 8. Viilusaannon riippuvuus läpimitasta ja lenkoudesta (c). Pölkyn pituus on 1 320 mm. Muut tiedot ovat kuten kuvassa 2.

Fig. 8. Dependence of veneer yield on diameter and crookedness (c). Bolt length is 1 320 mm. Other data is the same as in Fig. 2.

Lenkouden (c) riippuvuus pölkyn pituudesta (L) (= katkaisupintojen lyhin etäisyys) ja kaarevuussäteestä (y+c) voidaan johtaa seuraavasti. — Lenko pölkky on osa ympyrän kaarta. Sitä vastaava keskuskulma on 2f. Kun tarkastellaan sektoria, jonka

muodostavat osa ympyrän kaaresta (pölkky) ja sen näitä ympyrän keskipisteeseen yhdistävät säteet (pituus y+c), ja etäisyys ympyrän keskipisteestä pölkyn tyvi- ja latvaleikkausta yhdistävään suoraan on y (jolloin lenkous on c), saadaan

$$\frac{0{,}5L}{y+c} = \sin f \qquad \text{ja} \qquad \frac{y}{y+c} = \cos f$$

Ratkaisuksi saadaan yhtälö (12), joka osoittaa lenkouden (c) riippuvuuden pölkyn pituudesta ja keskuskulmasta.

$$(12) \qquad c = \frac{0{,}5L - 0{,}5L \cos f}{\sin f}$$

Kun tarkastellaan pölkyn pituuden lyhentämisen vaikutusta lenkouteen, se vastaa tilannetta, jolloin kaarevuussäde y+c on vakio ja keskuskulma muuttuu. Em. yhtälön perusteella saadaan tällöin lasketuksi seuraava jaotelma.

Pölkyn pituus, mm	Lenkous, mm								
1 320	15	16	17	19	21	23	26	29	34
1 625	23	25	26	29	32	35	39	44	51
2 540	56	60	65	70	77	85	95	108	125

Esim. jos rungon lenkous olisi sellainen, että 1 625 mm pölkyssä lenkous olisi 32 mm, lyhyemmässä 1 320 mm sorvipölkyssä vastaava lenkous olisi 21 mm.

Kuvan 8 perusteella tämä lenkouden väheneminen merkitsee saannon kohoamista 2—10 prosenttiyksikön verran läpimitasta riippuen.

37. Mallin yhteys empiirisiin tuloksiin

Empiirisissä tutkimuksissa raaka-ainehäviön jaottelua ei ole yleensä viety niin pitkälle, että suora vertaaminen mallin antamiin tuloksiin olisi mahdollinen. Tavallisesti on erotettu vain pyöristyshäviö ja purilashäviö sekä lisäksi erilaiset leikkaushäviöt viilun osalta, mikäli on haluttu selvittää viilun kokonaismäärän lisäksi myös sen jakautuminen ehyisiin arkkeihin ja saumauskappaleisiin.

Pyöristyshäviön osia ovat aiemmin esitetyn mukaisesti kuoresta (mikäli kyseessä on kuorellinen pölkky), kapenemisesta ja epäpyöreydestä riippuvat osat. Suuri pyöristyshäviö voi johtua näin ollen esim. suuresta epäpyöreydestä ja/tai erityisen voimakkaasta kapenemisesta — tai suuresta pölkyn pituudesta, koska pituuden lisääntyessä kapenemisen vaikutus pyöristyshäviöön kasvaa. Eri tekijöiden osuudesta ei voida tehdä tarkkoja päätelmiä, elleivät niiden saamat arvot ole tiedossa.

Kun empiirisissä tutkimuksissa ei ole tarkasteltu esim. juuri pyöristyshäviön syitä siihen vaikuttavien tekijöiden tasolla, niistä ei saada myöskään viitteitä epäpyöreyden, kapenemisen jne. suuruudesta. Yleensä tiedetään vain lopputulos (esim. pyöristys-

häviön suuruus), mutta ei siihen vaikuttavien tekijöiden tasoa. Tämän vuoksi jäljempänä pidättäydytään varsinaisista vertailuista. Esimerkinomaisesti voi kuitenkin sanoa, että yksittäisistä häviölajeista pyöristyshäviö on suurin Suomen oloissa. Esim. J a l a v a (1957) totesi ilmeisesti 1930-luvun lopun olosuhteissa tehtyjen tutkimusten perusteella, että pyöristyshäviö (ml. leikkausjätteet, mutta ei kuori) on koivulla 10—30 % kuorellisesta tilavuudesta siten, että häviö kasvaa läpimitan suurentuessa. O l a v i s e n (1964, s. 572) esimerkin mukaan koivulla voi tyypillinen pyöristyshäviö (ilman kuorta) olla 16 % kuorellisesta tilavuudesta. Em. lukuihin on vielä lisättävä n. 12 prosenttiyksikköä, jos pyöristyshäviöön luetaan myös kuorimishäviö. Täten määritellyn pyöristyshäviön suuruudeksi M e r i l u o t o (1966, s. 39) sai hyvälaatuisilla koivupölkyillä 20—35 % läpimitasta riippuen. — Kuusella pyöristyshäviöksi on saatu 16 % (+ kuori 13 %) ja männyllä vain 6 % (+ kuori 17 %) (H e i k k i l ä 1976, s. 72). — Epävarmaa mäntyä koskevaa lukua lukuunottamatta pyöristyshäviöitä voidaan pitää merkittävän suurina.

4. TULOSTEN TARKASTELUA

Edellä esitettyä viilusaannon suuruuteen vaikuttavia tekijöitä kuvaavaa kaavaa (8) tarkasteltaessa on otettava huomioon, että viilun määrällä tarkoitetaan märän viilun määrää, josta on kuitenkin vähennetty työvarasta ja viilumaton päiden leikkaamisesta johtuva tilavuus. Sen sijaan mm. kuivumista, eri vikojen vaikutusta yms. ei ole voitu ottaa huomioon. Kun vikoja aina esiintyy käytännössä, pölkyn keskittämisessä tehdään virheitä jne., saantoluvut ovat käytäntöä ajatellen ilmeisesti liian suuria käytettyjen parametrien eri arvoilla.

Toisaalta on otettava huomioon, etteivät kaikki saantoa alentavat tekijät vaikuta samalla tavalla, vaikka esitetyssä kaavassa ei tehdäkään eroa erityyppisten hävikkien välillä. Esimerkiksi voimakkaasta kapenemisesta aiheutuu, että ennen lopullisen pyöristysläpimitan saavuttamista saatava viilu on periaatteessa poikkisyiden suuntaan laajenevaa nauhaa. Lyhyillä pölkyillä sen käyttökelpoisuus on käytännössä vähäinen. Sen sijaan esim. sopivasti sijoittunut epäpyöreys aiheuttaa syiden suunnassa täysimittaisia sälöjä, joita voidaan käyttää hyväksi silloin, kun niiden leveys on noin 100 mm tai enemmän (O l a v i n e n 1964, s. 459). Tältä osin sorvipölkkyjen kapeneminen tai epäpyöreys ei siis merkitse samaa lopputuloksen kannalta, vaikka varsinaisen ehyen viilun saanto olisikin sama. Tähän on kiinnittänyt huomiota mm. L u t z (1971). — Mainittakoon, että kapenemisen aiheuttaman hukkamateriaalin pienentämiseksi on ehdotettu, että voimakkaasti kapenevat pölkyt sijoitetaan tavalliseen sorviin siten, että pölkyn reunaviiva on terän suuntainen. Tällöin saadaan pyöristyksen tuloksena samanlaisia käyttökelpoisia liitoskappaleita kuin silloin, kun aiheuttajana on epäpyöreys (W a s h b u r n 1976). Selvää kuitenkin on, että tällä tavalla sorvatun viilun lujuus on tavanomaista alhaisempi syiden suunnan poiketessa levyn suunnasta.

Kapenemisen osalta malliin saattaa sisältyä saannon aliarvioimista etenkin silloin, kun sorvipölkyt ovat pitkiä. Viilukappaleita voidaan nimittäin jatkaa, ja tästä seuraa, ettei pyöristyksessä tarvitse mennä aivan niin pieneen läpimittaan, että koko syiden suuntainen pituus saadaan puhdasta viilua. Toisaalta käytännössä tehdyt silmävaraiset havainnot viittaavat siihen, että prosessin häiriöttömän sujumisen vuoksi pyöristys tehdään tehdasolosuhteissa mieluummin liian pitkälle kuin liian vähän (L a a k s o 1977, suull. lausunto). Tämän vuoksi aliarviointi ei voi olla olennaisen suuri. Tätä käsitystä tukee pääleikattavan viilun alhainen määrä koivun sorvauksessa (M e r i l u o t o 1966, s. 39). Pitkiä kuusipölkkyjä sorvattaessa kapenemisesta johtuva lyhyt viilu voidaan kuitenkin ottaa talteen jatkettaviksi kappaleiksi (H e i k k i l ä 1976,

s. 43). — Tarvittaessa voidaan pitkille sorvauspölkyille käyttää empiirisiä korjauskertoimia tämän saantovirheen eliminoimiseksi. Teoreettisesti pääleikkauskelpoisen viilun määrää ei voida päätellä, koska se riippuu lyhimmästä jatkettavan viilun pituudesta.

Mallin puutteena on myös se, ettei huomiota kiinnitetä erilaisista pölkyistä ja pölkyn eri osista saatavan viilun laatueroihin. Kuitenkin tiedetään, että mm. epäpyöreiden ja voimakkaasti kapenevien pölkkyjen viilun laatu (esim. sileys) on heikompi kuin pyöreiden ja vähän kapenevien pölkkyjen (esim. Meriluoto 1965, s. 63, Lutz 1971, s. 15). Samoin tiedetään, että purilaan läheisyydestä sorvatun viilun lujuus on heikompi kuin enemmän ulkokehältä sorvatun viilun (esim. Kovanen 1962, Cade ja Choong 1969, Palka 1974, s. 6). Toisaalta eräät laatutunnukset saattavat parantua ulkokehältä pölkyn keskiosiin (Meriluoto 1965, s. 86). — Selvä on luonnollisesti oksaisuuden vaikutus laatuun: aivan erityisen kaunis pölkyn pintaosasta sorvatun viilun kuvio voi merkitä pahaa oksaisuutta purilaan läheltä sorvatussa viilussa (esim. Newall 1960).

Mitään periaatteellista estettä viilun laadun mukaan ottamiselle ei kuitenkaan ole. — Jos pölkystä saatavan viilun arvo tilavuusyksikköä kohti voidaan ennustaa esim. juuri epäpyöreyden, kapenemisen ja läpimitan perusteella, voidaan helposti siirtyä malliin, jossa tilavuussaannon sijasta tarkastellaan arvoa. Kun tällaisia ennusteyhtälöitä ei ole käytettävissä, tässä vaiheessa mallia ei ole ryhdytty kehittämään tähän suuntaan.

Väärinkäsityksien välttämiseksi on vielä korostettava, että kaikki esitetyt laskelmat jonkin tekijän muuttumisen vaikutuksesta on tehty sillä periaatteella, että kaikki muut paitsi tarkastellut tekijät pysyvät muuttumattomina. Esim. kun on esitetty viilusaannon kuvaajia pölkyn läpimitan funktiona, on jouduttu vakioimaan mm. epäpyöreys, kapeneminen jne. Jos eri tekijät korreloivat luonnossa, käytetty *ceteris paribus*-malli ei vastaa niitä tuloksia, joita saataisiin esim. koesorvauksin, ts. sorvaamalla populaatiosta arvottuja eri läpimittaluokkiin kuuluvia pölkkyjä. Jälkimmäisessä tapauksessa eri tekijöiden välinen korreloituminen vaikuttaisi tuloksiin, vaikka tarkasteltavana tekijänä olisi pelkkä läpimitta. — Em. syyn vuoksi mallin hyvyyttä ei voida arvostella sellaisten empiiristen tutkimusten avulla, joiden aineistoissa eri tekijöiden korreloituminen on ollut mahdollista.

Tiedot eri tekijöiden korreloitumisesta ovat niukat. Luultavaa kuitenkin on, että epäpyöreys ja lenkous korreloituvat, koska rungon poikkileikkaukseen vaikuttavaa reaktiopuuta syntyy kallistuneisiin runkoihin, ja reaktiopuun syntyminen samalla käyristää runkoa. Empiiristen tietojen mukaan tähän näyttäisi liittyvän myös kapenemisen kasvu (Meriluoto 1965, s. 51).

Edelleen, kun rungon järein tyviosa kapenee keskirunkoa voimakkaammin, kapenemisen ja läpimitan negatiivinen korreloituminen on ainakin mahdollinen. Tuovinen (1954) on opinnäytetyössään arvioinut, että tämä saattaisi selittää sen useissa tutkimuksissa todetun ilmiön, että saanto pysyy ennallaan tai jopa laskee läpimitan kasvaessa yli määrärajan. Myös käytännön sorvauksista tehdyt havainnot viit-

taavat eräiden tekijöiden korreloitumiseen. Esim. kun E n a r v i n (1940), J a l a v a n (1957) ja M e r i l u o d o n (1965) mukaan kuorimis- ja pyöristyshäviö kasvaa läpimitan kasvaessa, tämä viittaa siihen, että kapeneminen ja/tai epäpyöreys lisääntyy läpimitan kasvaessa — vaikuttavathan juuri nämä tekijät pyöristyshäviön suuruuteen.

Mikäli eri tekijöiden riippuvuus toisistaan tunnettaisiin, malli olisi laajennettavissa myös tällaisiin monimuutoksisiin tapauksiin, jolloin siis yhden tekijän muuttumiseen liittyy muiden tekijöiden muuttuminen. Esim. kun saantoa tarkasteltaisiin läpimitan funktiona, voitaisiin ottaa samalla huomioon ne yhtälöt, jotka määrittelevät kapenemisen, epäpyöreyden jne. riippuvuuden läpimitasta. — *Ceteris paribus*-rajoituksesta on siis mahdollista luopua.

Esitetyn mallin tai sen kaltaisten mallien soveltaminen käytäntöön ei tuota nykytekniikalla vaikeuksia. Voidaan ajatella järjestelmä, jossa vaneritukeista mitataan määrävälein läpimittoja useassa suunnassa. Näiden tietojen perusteella voidaan automaattisesti laskea epäpyöreys, kapeneminen ja minimiläpimitta eripituisille sorvipölkyille. Mikäli mittausasema on katkontalaitteistosta erillään, suhteellisen yksinkertaisin ohjelmin pystytään laskemaan optimaalinen tukin jakaminen sorvipölkyiksi raaka-aineen käyttöä ajatellen. — Tiettävästi tällaisia ratkaisuja on jo kaavailtu Yhdysvalloissa (Vaneriteollisuuden . . . 1977, s. 164).

Nykymuodossaan malli antaa aiheen päätelmiin eri tekijöiden vaikutuksen suuruudesta. — Tärkein tekijä on epäilemättä pölkyn *läpimitta*, joka tavanomaisella vaihteluvälillään voi aiheuttaa yli 10 prosenttiyksikön suuruisia eroja viilusaannossa. Tämä on myös yleisesti tunnettua, ja käytännön toiminnassa pyritään luonnollisesti saamaan raaka-aineeksi suuriläpimittaisia pölkkyjä, ellei niissä ole lahovikaa tms. — Eri asia sitten on, että tekijöiden korreloitumisen vuoksi empiirisissä tutkimuksissa on voitu havaita saannon jopa alenevan määrärajan jälkeen läpimitan kasvaessa, kuten edellä on todettu.

Sen sijaan vastaavaa huomiota ei ole kiinnitetty mm. *epäpyöreyteen*, jonka vaikutus saattaa samoin olla yli 10 prosenttiyksikön suuruusluokkaa tavanomaisella vaihteluvälillään. Tämä saattaa tuntua yllättävältä: eihän esim. 5 % suuruinen läpimitan pieneneminen aiheuta saannon laskua enemmällä kuin noin prosenttiyksiköllä keskikokoisessa sorvipölkyssä, mutta vastaava epäpyöreys (epäpyöreyskerroin muuttuu arvosta 1,00 arvoon 0,95) aiheuttaa noin 7 prosenttiyksikön laskun viilusaannossa. — Syy on luonnollisesti siinä, että läpimitan pieneneminen alentaa sekä koko pölkyn tilavuutta että siitä saatavan viilun tilavuutta, mutta epäpyöreys alentaa olennaisesti vain viilun tilavuutta. Tällöin saanto todellakin voimakkaasti laskee epäpyöreyden lisääntyessä. — Vastaavia empiirisiä tuloksia ovat esittäneet M e t t e ja B o s s (1964) sekä M e r i l u o t o (1965, s. 49).

Jossakin määrin epäpyöreyden vaikutus riippuu sorvipölkyn pituudesta ja läpimitasta, mutta kokonaisuuden kannalta vähän.

Sen sijaan *kapenemisen* vaikutus riippuu voimakkaasti sorvattavan pölkyn läpimitasta. Tavanomaisella kapenemisen vaihteluvälillä saanto vaihtelee suurissa pölkyissä muutaman prosenttiyksikön verran, mutta pienissä pölkyissä erot voivat olla

10 prosenttiyksikön suuruusluokkaa. Käytännössä tämä merkitsee sitä, että erityisesti pieniläpimittaiset, voimakkaasti kapenevat pölkyt kannattaa katkoa lyhyiksi sorvipölkyiksi, koska pituutta pienentämällä kapenemisen vaikutusta voidaan pienentää. — Myös empiirisissä tutkimuksissa kapenemisen vaikutus on voinut olla 10 prosenttiyksikön suuruusluokkaa (esim. Meriluoto 1965, s. 48). Kapenemisen ohella myös *lenkouden* vaikutus riippuu voimakkaasti läpimitasta. Ainakin pienissä pölkyissä voidaan olettaa, että usein esiintyvä lenkouden vaihteluväli merkitsee ainakin 10 prosenttiyksikön vaihtelua saantoluvuissa. Tätä käsitystä tukevat empiiriset tulokset (esim. Meriluoto 1965, s. 47, Heiskanen 1966, s. 68).

Myös *purilaan paksuuden* vaikutus on erityisen huomattava pieniläpimittaisissa pölkyissä. Erityisen mielenkiintoinen on tulos, ettei suurtakaan työvaraa käytettäessä juuri kannata pidentää sorvipölkkyä, jos muutokseen samalla liittyy purilaan läpimitan kasvu.

On vielä korostettava, että kaikki edellä esitetyt näkökohdat perustuvat pelkästään raaka-aineen käyttösuhteen pohjalle. Lopullisia ratkaisuja tehtäessä on erikseen otettava huomioon muut sorvausprosessin tekijät. Esimerkiksi kun harkitaan, millaisiksi sorvipölkyiksi tukki kannattaa katkoa, raaka-aineen säästeliään käytön lisäksi on otettava huomioon mm. sorvauskustannusten riippuvuus pölkyn pituudesta. Selvää nimittäin on, että pölkyn keskittämiseen ja työstämiseen kuluva aika on likimain riippumaton pölkyn pituudesta. Näin ollen sorvauskustannukset tuotetun viilun tilavuusyksikköä kohti ovat sitä suuremmat, mitä lyhyempi pölkky on. Näitä kustannuksia on verrattava raaka-aineen säästämisen aiheuttamiin tuottoihin ja tehtävä päätös kokonaisuuden kannalta. — Ilmeisesti useimmissa tapauksissa raaka-aineen merkitys on ratkaiseva, onhan sen osuus vanerin valmistuksen muuttuvista kustannuksista yli 40 % (Vaneriteollisuuden . . . 1977, s. 179).

Samoin on sopivaa pölkyn pituutta arvioitaessa otettava huomioon, missä määrin viilua joudutaan jatkamaan riittävän levykoon saavuttamiseksi. Jos tiedetään, kuinka usein määräkokoista viilua joudutaan jatkamaan, malliin voidaan ottaa helposti vähennystekijä, joka osoittaa jatkamisessa menetettävän viilun määrän. Esimerkiksi jos 10 % jostakin viilun pituusluokasta jatketaan ja teknisistä syistä menetetään viilun tehollisesta pituudesta viistoamisessa esim. 80 mm, malliin liitetään vähennystekijä 8 mm, joka vähennetään pituudesta L_1. — Vastaavasti voidaan ottaa huomioon työkustannukset.

Selvää myös on, että käytännöllisessä vaneritehtaan töiden suunnittelussa raaka-ainenäkökohdat ovat vain yksi tekijä muiden joukossa. Etenkin voimakas riippuvuus vaneritilauksista vaikuttaa huomattavasti suunnitteluun. Tämä ilmenee hyvin esimerkiksi Mutasen (1974) selostuksesta.

5. TAULUKKOJA JA OHJELMIA

Taulukoissa 1—6 on kaavalla (8) laskettuja saantolukuja pölkyn pituuden, kapenemisen ja läpimitan sekä myös purilaan paksuuden ja työvaran funktiona. Näiden taulukkojen avulla voidaan helposti todeta, millainen on eri tekijöiden yhteisvaikutus. Taulukkoja laskettaessa lenkous on oletettu merkityksettömän pieneksi. Kuori, epäpyöreys ja viilun paksuus on pidetty vakioina. Mikäli halutaan tarkastella niiden vaikutusta, on käytettävä alkuperäistä kaavaa (8).

Kaavan (8) käytön helpottamiseksi liitteessä 1 esitetään ohjelmoitavalle pöytälaskimelle laadittu ohjelma, joka tulostaa viilusaannon malliin sisältyvien tekijöiden funktiona. Tässä tapauksessa ohjelma on laadittu laskimelle HP-97, mutta kaava on luonnollisesti ohjelmoitavissa mille tahansa laitteelle, jonka kapasiteetti riittää tarkoitukseen.

Taulukko 1. Viilusaanto pölkyn pituuden, kuorellisen keskusläpimitan ja kapenemisen funktiona, kun kuoriprosentti on 13, työvara 50 mm, epäpyöreyskerroin 0,95, viilun paksuus 1,4 mm ja purilaan paksuus 60 mm.

Table 1. Veneer yield as a function of bolt length, diameter over bark at mid-point and taper, when bark percentage is 13, length wastage 50 mm, cross-sectional irregularity coefficient 0,95, veneer thickness 1,4 mm and core diameter 60 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield, %*			
1 320	150	52,42	49,37	46,38	43,44
	170	56,88	54,17	51,50	48,88
	190	60,07	57,64	55,23	52,66
	210	62,45	60,23	56,05	55,89
	230	64,26	62,24	60,23	58,25
	250	65,69	63,82	61,97	60,14
	270	66,83	65,10	63,38	61,68
	290	67,76	66,15	64,54	62,95
	310	68,54	67,02	65,52	64,02
	330	69,18	67,76	66,34	64,94
	350	69,73	68,39	67,05	65,72
	370	70,21	68,93	67,66	66,41
	390	70,61	69,40	68,20	67,00
	410	70,97	69,82	68,67	67,53
	430	71,28	70,18	69,09	68,00
1 625	150	52,07	48,28	44,58	40,97
	170	56,64	53,28	49,97	46,74
	190	59,92	56,90	53,92	50,99
	210	62,37	59,62	56,91	54,24
	230	64,25	61,72	59,24	56,78
	250	65,72	63,39	61,10	58,83
	270	66,91	64,75	62,61	60,50
	290	67,87	65,86	63,86	61,89
	310	68,68	66,79	64,92	63,07
	330	69,35	67,57	65,81	64,07
	350	69,92	68,25	66,58	64,93
	370	70,42	68,83	67,25	65,69
	390	70,84	69,33	67,84	66,35
	410	71,21	69,78	68,35	66,93
	430	71,54	70,17	68,81	67,46
2 540	150	50,43	44,50	38,80	33,37
	170	55,30	50,01	44,90	39,98
	190	58,82	54,05	49,42	44,94
	210	61,46	57,12	52,89	48,77
	230	63,49	59,51	55,62	51,82
	250	65,10	61,42	57,82	54,29
	270	66,40	62,98	59,62	56,34
	290	67,46	64,27	61,13	58,05
	310	68,35	65,36	62,41	59,51
	330	69,10	66,28	63,50	60,77
	350	69,74	67,07	64,45	61,86
	370	70,29	67,76	65,27	62,82
	390	70,76	68,37	66,00	63,66
	410	71,18	68,90	66,64	64,41
	430	71,55	69,37	67,22	65,09

Taulukko 2. Tiedot kuten taulukossa 1, mutta purilaan paksuus on 80 mm.
Table 2. Parameters same as in Table 1, but core diameter 80 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield*, %			
1 320	150	39,97	36,93	33,94	31,02
	170	47,19	44,48	41,82	39,20
	190	52,31	49,88	47,48	45,11
	210	56,09	53,88	51,70	49,54
	230	58,97	56,94	54,94	52,96
	250	61,21	59,34	57,49	55,66
	270	62,99	61,26	59,54	57,84
	290	64,43	62,82	61,21	59,62
	310	65,62	64,11	62,60	61,11
	330	66,61	65,19	63,77	62,37
	350	67,45	66,10	64,77	63,44
	370	68,16	66,88	65,62	64,36
	390	68,77	67,56	66,36	65,16
	410	69,30	68,15	67,00	65,87
	430	69,77	68,67	67,57	66,49
1 625	150	39,53	35,75	32,06	28,48
	170	46,88	43,52	40,23	37,01
	190	52,11	49,08	46,11	43,20
	210	55,97	53,22	50,51	47,85
	230	58,91	56,39	53,90	51,46
	250	61,21	58,88	56,58	54,32
	270	63,03	60,88	58,74	56,63
	290	64,52	62,50	60,51	58,54
	310	65,74	63,85	61,98	60,13
	330	66,76	64,98	63,22	61,48
	350	67,62	65,94	64,28	62,63
	370	68,35	66,77	65,19	63,63
	390	68,99	67,48	65,98	64,49
	410	69,53	68,10	66,67	65,26
	430	70,01	68,64	67,28	65,93
2 540	150	37,75	31,84	26,18	20,80
	170	45,43	40,16	35,07	30,18
	190	50,92	46,16	41,54	37,08
	210	54,99	50,65	46,43	42,33
	230	58,10	54,12	50,23	46,44
	250	60,54	56,86	53,26	49,74
	270	62,48	59,07	55,71	52,43
	290	64,07	60,88	57,74	54,67
	310	65,38	62,39	59,44	56,55
	330	66,48	63,66	60,88	58,15
	350	67,41	64,74	62,12	59,53
	370	68,20	65,68	63,19	60,74
	390	68,89	66,49	64,12	61,79
	410	69,49	67,20	64,95	62,72
	430	70,01	67,83	65,68	63,55

Taulukko 3. Tiedot kuten taulukossa 1, mutta purilaan paksuus on 100 mm.
Table 3. Parameters same as in Table 1, but core diameter 100 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield, %*			
1 320	150	24,10	21,07	18,09	15,19
	170	34,83	32,13	29,48	26,87
	190	42,42	39,99	37,59	35,24
	210	48,00	45,79	43,61	41,45
	230	52,22	50,19	48,19	46,21
	250	55,49	53,63	51,78	49,95
	270	58,09	56,36	54,64	52,94
	290	60,19	58,57	56,97	55,38
	310	61,91	60,39	58,89	57,40
	330	63,33	61,91	60,49	59,09
	350	64,53	63,19	61,85	60,52
	370	65,55	64,28	63,01	61,75
	390	66,42	65,21	64,01	62,82
	410	67,18	66,03	64,88	63,74
	430	67,83	66,74	65,64	64,55
1 625	150	23,54	19,77	16,11	12,55
	170	34,43	31,08	27,80	24,60
	190	42,14	39,12	36,16	33,25
	210	47,81	45,07	42,36	39,71
	230	52,11	49,59	47,11	44,67
	250	55,45	53,12	50,83	48,57
	270	58,10	55,94	53,81	51,70
	290	60,24	58,23	56,23	54,26
	310	62,00	60,11	58,24	56,39
	330	63,45	61,68	59,92	58,18
	350	64,68	63,01	61,34	59,70
	370	65,73	64,14	62,56	61,00
	390	66,62	65,11	63,62	62,13
	410	67,39	65,96	64,53	63,12
	430	68,07	66,70	65,34	63,99
2 540	150	21,59	15,70	10,10	4,78
	170	32,85	27,59	22,53	17,68
	190	40,84	36,09	31,49	27,05
	210	46,74	42,41	38,20	34,12
	230	51,22	47,25	43,37	39,59
	250	54,71	51,04	47,45	43,94
	270	57,49	54,08	50,73	47,45
	290	59,74	56,55	53,42	50,37
	310	61,59	58,60	55,66	52,77
	330	63,14	60,32	57,55	54,82
	350	64,44	61,78	59,15	56,57
	370	65,54	63,02	60,53	58,08
	390	66,50	64,10	61,73	59,40
	410	67,32	65,04	62,78	60,56
	430	68,04	65,86	63,71	61,58

Taulukko 4. Tiedot kuten taulukossa 1, mutta työvara on 100 mm ja purilaan paksuus 60 mm.
Table 4. Parameters same as in Table 1, but length wastage 100 mm and core diameter 60 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield, %*			
1 320	150	50,48	47,66	44,88	42,16
	170	54,75	52,24	49,77	47,34
	190	57,80	55,55	53,33	51,13
	210	60,07	58,03	56,00	54,01
	230	61,81	59,94	58,08	56,25
	250	63,17	61,45	59,74	58,04
	270	64,27	62,66	61,08	59,50
	290	65,16	63,66	62,18	60,71
	310	65,90	64,50	63,11	61,73
	330	66,51	65,20	63,89	62,59
	350	67,04	65,80	64,56	63,33
	370	67,49	66,31	65,14	63,98
	390	67,88	66,76	65,65	64,54
	410	68,22	67,15	66,10	65,04
	430	68,52	67,50	66,49	65,49
1 625	150	50,53	46,98	43,50	40,10
	170	54,95	51,79	48,68	45,64
	190	58,12	55,27	52,47	49,72
	210	60,47	57,89	55,34	52,83
	230	62,28	59,92	57,58	55,27
	250	63,71	61,52	59,36	57,23
	270	64,85	62,82	60,82	58,83
	290	65,78	63,89	62,02	60,16
	310	66,55	64,78	63,03	61,29
	330	67,20	65,54	63,88	62,24
	350	67,76	66,18	64,62	63,07
	370	68,23	66,74	65,26	63,79
	390	68,64	67,22	65,82	64,42
	410	69,00	67,65	66,31	64,98
	430	69,31	68,03	66,75	65,48
2 540	150	49,53	43,83	38,34	33,10
	170	54,30	49,21	44,29	39,55
	190	57,74	53,15	48,69	44,37
	210	60,31	56,14	52,06	48,10
	230	62,30	58,47	54,72	51,06
	250	63,87	60,33	56,86	53,47
	270	65,13	61,85	58,62	55,45
	290	66,17	63,10	60,09	57,12
	310	67,04	64,16	61,33	58,54
	330	67,77	65,06	62,39	59,76
	350	68,39	65,83	63,31	60,82
	370	68,92	66,50	64,11	61,74
	390	69,39	67,09	64,81	62,56
	410	69,80	67,61	65,44	63,29
	430	70,16	68,07	65,99	63,94

Taulukko 5. Tiedot kuten taulukossa 1, mutta työvara on 100 mm ja purilaan paksuus 80 mm.
Table 5. Parameters same as in Table 1, but length wastage 100 mm and core diameter 80 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield*, %			
1 320	150	38,52	35,70	32,94	30,23
	170	45,43	42,93	40,47	38,05
	190	50,35	48,10	45,88	43,69
	210	53,97	51,93	49,91	47,91
	230	56,72	54,85	53,00	51,17
	250	58,87	57,14	55,43	53,74
	270	60,57	58,97	57,39	55,81
	290	61,96	60,46	58,98	57,51
	310	63,10	61,70	60,31	58,93
	330	64,04	62,73	61,42	60,12
	350	64,84	63,60	62,37	61,14
	370	65,52	64,35	63,18	62,01
	390	66,11	64,99	63,88	62,78
	410	66,62	65,55	64,50	63,44
	430	67,06	66,05	65,04	64,03
1 625	150	38,39	34,84	31,38	28,00
	170	45,49	42,34	39,24	36,22
	190	50,55	47,71	44,91	42,17
	210	54,28	51,70	49,15	46,65
	230	57,12	54,75	52,42	50,12
	250	59,33	57,15	54,99	52,86
	270	61,10	59,07	57,07	55,09
	290	62,53	60,64	58,77	56,92
	310	63,71	61,94	60 18	58,45
	330	64,69	63,03	61,38	59,74
	350	65,52	63,95	62,39	60,84
	370	66,23	64,74	63,26	61,80
	390	66,84	65,43	64,02	62,63
	410	67,37	66,02	64,69	63,36
	430	67,83	66,55	65,27	64,00
2 540	150	37,11	31,42	25,98	20,79
	170	44,62	39,55	34,65	29,94
	190	49,99	45,41	40,97	36,67
	210	53,97	49,80	45,74	41,79
	230	57,01	53,18	49,45	45,80
	250	59,39	55,86	52,39	49,01
	270	61,30	58,01	54,79	51,63
	290	62,85	59,78	56,76	53,80
	310	64,13	61,25	58,42	55,63
	330	65,20	62,49	59,82	57,19
	350	66,10	63,55	61,02	58,54
	370	66,88	64,46	62,07	59,70
	390	67,55	65,25	62,97	60,73
	410	68,13	65,94	63,77	61,63
	430	68,65	66,55	64,48	62,43

Taulukko 6. Tiedot kuten taulukossa 1, mutta työvara on 100 mm ja purilaan paksuus 100 mm.
Table 6. Parameters same as in Table 1, but length wastage 100 mm and core diameter 100 mm.

Pölkyn pituus *Length of bolt* mm	Läpimitta *Diameter* mm	Kapeneminen, mm/m *Taper, mm/m*			
		5	10	15	20
		Saanto, % — *Yield, %*			
1 320	150	23,27	20,46	17,71	15,02
	170	33,56	31,07	28,61	26,20
	190	40,84	38,60	36,38	34,20
	210	46,19	44,15	42,13	40,14
	230	50,24	48,37	46,52	44,69
	250	53,38	51,65	49,95	48,25
	270	55,87	54,27	52,68	51,11
	290	57,88	56,39	54,90	53,44
	310	59,53	58,13	56,74	55,36
	330	60,89	59,58	58,27	56,97
	350	62,04	60,80	59,57	58,34
	370	63,02	61,84	60,67	59,51
	390	63,85	62,74	61,63	60,52
	410	64,58	63,51	62,45	61,40
	430	65,20	64,19	63,18	62,18
1 625	150	22,91	19,37	15,93	12,58
	170	33,44	30,29	27,21	24,20
	190	40,90	38,06	35,28	32,55
	210	46,38	43,80	41,26	38,77
	230	50,53	48,17	45,84	43,54
	250	53,76	51,58	49,43	47,30
	270	56,32	54,30	52,29	50,32
	290	58,39	56,50	54,63	52,78
	310	60,09	58,31	56,56	54,82
	330	61,50	59,83	58,18	56,54
	350	62,68	61,11	59,55	58,00
	370	63,69	62,20	60,72	59,25
	390	64,55	63,14	61,73	60,34
	410	65,30	63,95	62,61	61,29
	430	65,95	64,66	63,39	62,12
2 540	150	21,27	15,61	10,74	5,09
	170	32,29	27,23	22,84	17,69
	190	40,12	35,55	31,56	26,85
	210	45,89	41,73	38,08	33,74
	230	50,27	46,45	43,09	39,08
	250	53,69	50,16	47,04	43,32
	270	56,41	53,12	50,22	46,75
	290	58,61	55,54	52,83	49,57
	310	60,42	57,54	54,99	51,93
	330	61,92	59,22	56,82	53,93
	350	63,19	60,64	58,37	55,63
	370	64,28	61,85	59,70	57,10
	390	65,21	62,91	60,86	58,39
	410	66,01	63,82	61,87	59,51
	430	66,72	64,63	62,76	60,51

KIRJALLISUUTTA

ARO, P. 1960. Koivuvaneritukkien ja sorvipölkkyjen halkeaminen. Referat: Die Rissbildung in Furnierblöcken und Furnierabschnitten. Commun. Inst. For. Fenn. 52 (4): 1—41.

—»— 1962. Einige Beobachtungen über die Kernrisse bei der Birke. Commun. Inst. For. Fenn. 55 (10): 1—10.

—»— & RIKKONEN, P. 1966. Havusahatukkien latvamuotoluvut. Summary: Top form factors of softwood logs. Commun. Inst. For. Fenn. 61 (7): 1—77.

ASIKAINEN, K. & HEISKANEN, V. 1970. Havusahatukkien laadun mukaiset arvosuhteet. Summary: The value relationships of coniferous sawlogs on the basis of their grade. Commun. Inst. For. Fenn. 70 (3): 1—77.

BALDWIN, R. F. 1975. Plywood manufacturing practices. 260 s. Miller Freeman Publications.

BERGVALL, J. A. & GEDNEY, D. R. 1970. Washington mill survey 1968. Wood consumption and mill characteristics. Washington State Department of Natural Resources, and Pacific Northwest Forest and Range Experiment Station, Portland, Ore. 119 s.

BETHEL, J. S. & HART, C. A. 1960. Techniques for the development of a rational grading system for hardwood veneer logs. For. Prod. J. 10 (6): 296—301.

BOWLAND, J. G., TAYLOR, D. E. & SUDBURY, A. E. G. 1968. The use and production of construction-grade plywood in Canada. Dep. Publ. For. Br. Can. 1233: 1—28.

BØHMER, J. G. 1935. Furuens flattrykning og tømmerinnhold. Tidskr. Skogbruk 43 (12): 342—352.

CADE, J. C. & CHOONG, E. T. 1969. Influence of cutting velocity and log diameter on tensile strength of veneer across the grain. For. Prod. J. 19 (7): 52—53.

CARPENTER, R. D. 1969. Bolt, log, and tree grades for birch. Teoksessa: Birch symposium proceedings, Northeastern Forest Experiment Station, s. 26—32.

DIMOCK, E. J., II & HASKELL, H. H. 1962. Veneer grade yield from pruned Douglas-fir. U. S. For. Serv. Res. Pap. Pacif. Nthwest. For. Range Exp. Sta. 48: 1—15.

DOBIE, J. & HANCOCK, W. V. 1972. Veneer yields from B. C. interior Douglas fir and white spruce. Canad. For. Ind. 92 (7): 32—33.

—»— & NEILSON, R. W. 1973. These equations tell when to cut larger veneer cores for more lumber. Canad. For. Ind. 93 (2): 50—51.

ENARVI, R. 1939. Vaneritehtaan sorvaushäviöiden suuruus. Suomen Puu 14 (21): 396—399.

—»— 1940. Sorvaushäviöihin vaikuttavat tekijät. Suomen Puu 15 (1): 1—4.

ENGLESSON, T. 1956. Virkesutnyttjningen vid plywoodproduktion. Paperi ja Puu 38 (3): 89—95.

Europas modernaste plywoodfabrik. 1971.Svensk Trävarutidn. 87 (3): 126—132, 135.

FAHEY,T. D. 1974. Veneer recovery from second-growth Douglas-fir. U. S. For. Serv. Res. Pap. Pacif. Nthwest. For. Range Exp. Sta. 173: 1—22.

HARLAN, R. L. 1976. Technical developments in use of Asian veneers. Teoksessa: Lambert, H. G. Modern plywood techniques, vol. 4: 44—59. Miller Freeman Publications.

HEIKKILÄ, J. 1976. Tukin järeyden ja laadun vaikutus sahauksen ja viilunvalmistuksen hyötysuhteeseen. Diplomityö Teknillisen korkeakoulun puunjalostusosastolla. 102 s. Julkaisematon.

HEIKKILÄ, T. 1913 a. Koealojen kaulaamisesta. Tapio 6 (5): 139—143.
—»— 1913 b. Koealojen kaulaamisesta ja puiden poikkileikkauspinnan soikeudesta. Tapio 6 (11): 324—331.
HEISKANEN, V. 1966. Tutkimuksia koivujen vikaisuuksista, niiden vaikutuksesta sorvaustulokseen sekä niiden huomioonottamisesta laatuluokituksessa. Summary: Studies on the defects of birch, their influence on the quality and quantity of rotary cut veneer, and their consideration in veneer birch grading. Acta For. Fenn. 80 (3): 1—128.
—»— 1976. Havusahatukkeja koskevia arvolaskelmia vuosina 1974—1975. Summary: Value calculations for softwood sawlogs in 1974—1975. Folia For. 251: 1—64.
—»— & ASIKAINEN, K. 1969. Havusahatukkien järeyden mukaiset arvosuhteet ja hinnoittelu-perusteet. Summary: The value relationships and pricing principles of coniferous sawlogs on the basis of their diameter. Commun. Inst. For. Fenn. 69 (3): 1—122.
—»— & RIKKONEN, P. 1971. Havusahatukkien todellisen kiintomitan määrittäminen latvaläpimitan perusteella. Summary: Determination of the true volume of coniferous saw logs on the basis of top diameter. Folia For. 128: 1—42.
—»— & RIKKONEN, P. 1976. Havusahatukkien kuoren määrä ja siihen vaikuttavat tekijät. Summary: Bark amount in coniferous saw logs and factors affecting it. Folia For. 250: 1—67.
—»— & SALMI, J. 1976. Koivutukkien latvamuotoluvut ja yksikkökuutiot. Summary: Top form factors and unit volumes of birch logs. Folia For. 287: 1—46.
—»— & TIIHONEN, P. 1958. Rinnankorkeusläpimittaan perustuvat sahapuiden kuutioimistaulukot. Summary: Volume tables for saw timber stems based on breast height diameter. Commun. Inst. For. Fenn. 49 (5): 1—76.
JALAVA, M. 1957. Vaneriteollisuus. Teoksessa: Metsäkäsikirja, 2. osa, s. 877—888. Helsinki.
JUVONEN, K. 1969. Havaintoja Kanadan ja USA:n vaneriteollisuudesta. Paperi ja Puu 51 (4): 406—409.
KOIVUMÄKI, P. 1962. Koivuraaka-aineen viat valmistajan näkökannalta. Puumies 7 (10): 296—300.
—»— 1964. Mitä näkökohtia on huomioitava vanerirunkojen katkaisussa tehtaalla. Puumies 9 (10): 327—331.
KOLLMANN, F. & SCHULTE-BRADER, H.-J. 1954. Studien über die Ausbeute in der deutschen Sperrholzindustrie. Holz Roh- u. Werkstoff 12 (12): 465—471.
KOVANEN, M. 1962. Vaneriviilun sorvauksesta. Paperi ja Puu 44 (9): 439—457.
KRILOV, A. & IRONSIDE, G. E. 1973. How to make a liability into an asset by converting peeler cores to sawnwood. World Wood 14 (11): 22—23.
KÄRKKÄINEN, M. 1974. Keskusmuotoluvun perusteita tukkien ja kuitupuun mittauksessa. Summary: Foundations of middle form factor in the measurement of logs and pulpwood. Silva Fenn. 8 (1): 47—88.
—»— 1975 a. Koivu- ja haapatukkien poikkipinta-alan mittaaminen. Summary: Measurement of the cross-sectional area of birch and aspen logs. Silva Fenn. 9 (3): 212—232.
—»— 1975 b. Pohjoissuomalaisten mäntytukkien soikeus. Summary: Ovalness of pine logs in Northern Finland. Silva Fenn. 9 (4): 251—258.
LAPPI-SEPPÄLÄ, M. 1933. Faneeritukin käyttöarvoon vaikuttavista vikaisuuksista ja virheettömän faneeripuun kasvatuksesta. Suomen Puu 8 (6): 82—84.
LEHONKOSKI, N. A. 1937. Koivu faneeriteollisuuden raaka-aineena. Yksityismetsänhoitajayhdistyksen vuosikirja 10: 75—84.
LOZZI, C. 1966. Italy's plywood industry has recent growth. World Wood 7 (4): 14.
LUTZ, J. F. 1971. Wood and log characteristics affecting veneer production. U. S. For. Serv. Res. Pap. U. S. For. Prod. Lab. 150: 1—31.
—»— 1974. Techniques for peeling, slicing, and drying veneer. U. S. For. Serv. Res. Pap. U. S. For. Pro. Lab. 228: 1—63.

MERILUOTO, J. 1965. Raaka-ainetekijöiden vaikutus sorvatun koivuviilun määrään ja laatuun. Summary: The influence of raw material factors on the quantity and quality of rotary cut birch veneer. Acta For. Fenn. 80 (1): 1—155.

—»— 1968. Sorvipöllien katkaisutarkkuus. Paperi ja Puu 50 (4a): 187—190.

METTE, H. J. & BOSS, W. 1964. Zur Unrundigkeit von Buchenfurnierholz. Holzindustrie 17 (3): 83—85.

MUELLER, L. A., MARKSTROM, D. C. & LUTZ, J. F. 1968. Preliminary evaluation of small-diameter Black Hills Ponderosa pine for veneer and plywood. U. S. For. Serv. Res. Note Rocky Mt. For. Range Exp. Sta. 117: 1—11.

MUTANEN, A. 1974. Vaneritehtaan tuotannon suunnittelu. Puumies 19 (4): 107—110.

NEWALL, R. J. 1960. Bark form and veneer figure in home-grown birch. Wood 25 (5): 196—200.

NISULA, P. 1967. Tutkimuksia vaneritukkien ja sorvipölkkyjen kuutio- ja painosuhteista. Summary: Studies on the relationships between the volume and weight in veneer logs and bolts for rotary cutting. Commun. Inst. For. Fenn. 63 (1): 1—87.

OLAVINEN, O. (toim.) 1964. Vaneriteollisuus. Teoksessa: Heikinheimo, O. (toim.) Mekaaninen puuteollisuus I, s. 388—645. Joensuu. Suomen Puuteollisuusinsinöörien Yhdistys.

PALKA, L. C. 1974. Veneer cutting review inform. Rep. For. Prod. Lab., Vancouver VP-X-135: 1—54.

PETERS, C. C. 1976. Rotary cutting — a practical method for kerfless cutting of wood thicker than 1/4 inch. For. Prod. J. 26 (6): 54—56.

Proceedings of the world consultation on wood-based panels held in New Delhi, India, February 1975. 1976. 442 s. Brussels. FAO/Miller Freeman Publications.

RINNE, V. J. 1944. Puuviilun ja vanerin valmistus. Kouvola. 304 s.

—»— 1950. Vaneriteollisuutemme teknikon näkökulmasta. Paperi ja Puu 32B (4a): 11—14.

ROINE, U. 1970. Sekavaneri, uusi artikkeli vai entisen korvike. Puumies 16 (6): 187—191.

SCHROEDER, J. & CLARK, A., III. 1970. Predicting veneer grade yields for loblolly pine. For. Prod. J. 20 (2): 37—39.

TUOVINEN, O. 1954. Tutkintotehtävä aiheesta: »Vanerikoivujen arvosuhteiden määrääminen nykyisen laatuluokituksen perusteella». Konekirjoite Helsingin teknillisen korkeakoulun puunjalostusosastolla. 51 s. Julkaisematon.

Vaneriteollisuuden kehitysennuste vuoteen 1990. 1977. Julk. Kauppa- ja teollisuusministeriö. Moniste. 281 s.

Veneer species of the world. A compilation of the IUFRO working party on slicing and veneer cutting. 1973. 150 s. U. S. For. Serv. U. S. For. Prod. Lab.

WASHBURN, E. E. 1976. Reduce centering errors and increase recovery. Teoksessa: Lambert, H. G. Modern plywood techniques, vol. 3: 29—36. Miller Freeman Publications.

WOODFIN, R. O., Jr. 1973. Wood losses in plywood — four species. For. Prod. J. 23 (9): 98—106.

—»— 1974. Veneer yields by the new timber cruising grades for old-growth coast Douglas-fir. U. S. For. Serv. Res. Pap. Pacif. Nthwest. For. Range Exp. Sta. 174: 1—34.

—»— & PONG, W. Y. 1974. Veneer recovery of red and white fir — California. U. S. For. Serv. Res. Pap. Pacif. Nthwest. For. Range Exp. Sta. 171: 1—48.

YERKES, V. P. & WOODFIN, R. O., Jr. 1972. Veneer recovery from Black Hills Ponderosa pine. U. S. For. Serv. Res. Pap. Rocky Mt. For. Range Exp. Sta. 82: 1—23.

SUMMARY

In Finland the size of the raw material available for the rotary cutting of veneer is very small compared with that in many other countries. As a rule, the average diameter of birch bolts is only 21—25 cm. Therefore, great efforts are being made to find ways of avoiding waste and increasing yield. As an example, the diameter of cores from short bolts (1,3—1,6 m) is usually only 60 mm.

Some of the effects of different properties of the raw material on the yield are widely known, and these are taken into account in the mills. As an example, the longer the bolts are the more the yield is decreased by tapering of the bolts. This is the reason why highly tapering parts of the logs are cut into short veneer bolts, and cylindrical parts into longer bolts. However, these decisions are made by rule of thumb.

In order to make precise decisions a model is needed which describes the rotary cutting process. Using this model it is possible to analyze the effect of several different raw material properties on the yield and maximize the yield from a given raw material.

In this paper a theoretical model is presented. The bolt is supposed to have the form of a truncated cone, which, however, can be curved. This bolt is described by the following variables.

d_3 = diameter of the bolt at the mid-point, mm
d_6 = diameter of the core, mm
k = taper per unit length, mm/mm
L = length of the bolt, mm
L_1 = length of the veneer usable in plywood production, mm
t = veneer thickness, mm
b = bark coefficient. If 1,00, d_3 is supposed to be without bark, and the yield is calculated on a bark-free basis. Otherwise b is the ratio between the diameters without bark and with bark, and the yield is calculated as percentage of the volume with bark.
z = cross-sectional irregularity coefficient, or the ratio between the diameter at roundup and the smallest diameter of the bolt.
c = crookedness of the bolt, mm. Crookedness is defined as the distance between the bolt surface and the line connecting the butt and the top of the bolt.
r = heart rot, mm

The yield is defined as the volume of wet veneer usable in plywood production (length of it is L_1) in percent of the volume of the bolt.

The formula describing the yield as a function of these variables, with the exception of c and r, is formula (8). It is assumed that there are no correlations between different variables. However, if they exist, they can be taken into account.

Crookedness is introduced into the model if it decreases the diameter in rounding up. Slight crookedness is eliminated by the effect of taper. — Similarly, heart rot is taken into account if it increases the core diameter. Otherwise it does not affect the yield.

A desk calculator program for calculating the formula (8) is presented in the appendix. In addition, the effect of crookedness and heart rot is tested. In this case the program is for model HP-97, but the idea is not limited to this model only.

Using the theoretical model described above, several computations have been made giving useful results. It has been shown, for example, that in normal Finnish conditions an increase in bolt length decreases the yield usable in plywood production, especially if the core diameter is increased at the same time. Only for very cylindrical bolts is the opposite true, due to the fact that the proportion of waste $L—L_1$ is smaller in long bolts. — Other interesting results can be derived from the figures and the tables.

Laskimelle Hewlett Packard 97 laadittu ohjelma

1. Ohjelman toiminta

Muisteissa 0—9 sekä D ja E olevien parametrien perusteella ohjelma laskee vanerin valmistuksessa hyödynnettävissä olevan viilun saannon prosentteina pölkyn kuorellisesta tilavuudesta. Mikäli kuorikorjauskertoimen arvoksi asetetaan 1, läpimitta käsitetään kuorettomaksi ja saanto lasketaan kuorettomasta tilavuudesta. Muutoin läpimitta käsitetään kuorelliseksi.

Esimerkkiohjelma on laadittu siten, että laskin tulostaa saantoluvut läpimittaluokittain läpimitan alkuarvosta lähtien (muisti 0). Luokkaväli on muistissa 8. Yläraja, jota pienemmät läpimitat otetaan huomioon, on muistissa 9.

Käskyt 104 ja 106 muutetaan tarvittaessa. Esim. jos saantoluvut halutaan tulostaa kapenemisluokittain, kapenemisen alkuarvo tulee muistiin 4, luokkaväli muistiin 8, kapenemisen yläraja muistiin 9 ja käsky 104 muutetaan muotoon STO+4 ja käsky 106 muotoon RCL 4. Läpimitta pysyy tällöin vastaavasti vakiona, aivan kuten muutkin parametrit.

2. Muistipaikat

Muisti	Sisältö
0	Kuorellinen keskusläpimitta, mm (esimerkissä läpimitan alkuarvo)
1	Sorvipölkyn kokonaispituus, mm
2	Epäpyöreyskerroin (osoittaa pyöristetyn läpimitan ja latvaläpimitan suhteen)
3	Kuorikorjauskerroin, jota käyttäen kuorellinen keskusläpimitta saadaan kuorettomaksi
4	Kapeneminen, mm/mm
5	Purilaan läpimitta, mm
6	Viilun paksuus, mm
7	Vanerin valmistuksessa hyödynnettävän viilun syiden suuntainen pituus, mm
8	Luokkaväli
9	Yläraja
D	Lenkous, mm
E	Sydänlaho, mm

3. Suppea ohjelman selostus

Käsky	Selostus
4— 18	Lasketaan kuoreton latvaläpimitta.
19— 27	Testataan, onko sydänlaho purilasta suurempi. Jos on, purilas muutetaan sydänlahon suuruiseksi.
28— 45	Testataan, alentaako lenkous pyöristettyä läpimittaa. Jos alentaa, tämä otetaan huomioon.
46—103	Lasketaan saanto kaavalla (8) ja tulostetaan se.
104—112	Lisätään alkuarvoon luokkaväli sekä testataan, jatketaanko vielä saantojen laskentaa vai lopetetaanko.

Laskinohjelma:

1	21 11	39	21 15	76	01
2	51	40	36 00	77	02
3	21 12	41	36 03	78	—35
4	36 00	42	—35	79	—21
5	02	43	36 14	80	36 04
6	—35	44	—45	81	36 01
7	—21	45	35 46	82	—35
8	36 04	46	21 16 15	83	53
9	36 07	47	36 46	84	—55
10	—35	48	53	85	04
11	—45	49	—21	86	—24
12	02	50	36 05	87	36 01
13	—24	51	53	88	—35
14	36 03	52	—45	89	16—24
15	—35	53	36 07	90	—35
16	36 02	54	—35	91	01
17	—35	55	16—24	92	02
18	35 46	56	—35	93	—24
19	36 15	57	04	94	35 13
20	36 05	58	—24	95	36 11
21	—45	59	35 11	96	01
22	16—44	60	36 46	97	00
23	22 13	61	36 05	98	00
24	22 14	62	—55	99	—35
25	21 13	63	36 06	100	36 13
26	36 15	64	—35	101	—24
27	35 05	65	36 07	102	—14
28	21 14	66	—35	103	36 08
29	36 00	67	16—24	104	35—55 00
30	36 03	68	—35	105	36 09
31	—35	69	35 12	106	36 00
32	36 14	70	36 11	107	—45
33	—45	71	36 12	108	16—44
34	36 46	72	—45	109	22 12
35	—45	73	35 11	110	22 11
36	16—45	74	36 00	111	24
37	22 15	75	53	112	51
38	22 16 15				

MATERIALS AND ENERGY ACCOUNTING AND THE FINNISH FOREST AND TIMBER ECONOMY

ESKO JAATINEN

Seloste

MATERIAALI- JA ENERGIATILINPITO SEKÄ SUOMEN METSÄ- JA PUUTALOUS

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The present statistical information systems which use the monetary values as the only common denominator leave some of man's most fundamental dependencies on ecosystems outside the scope of the statistical description.

First, starting from the principle of the conservation of matter/energy the study defines a general materials and energy accounting framework which can offer a basis for the integrated statistical description of the economic and ecological processes and outlines some preliminary guidelines for a new complementary statistical information system.

Second, existing statistical data concerning the flow of raw materials, products, fuels and energy in the Finnish forest and timber economy are combined into the defined accounting framework. The empirical analysis gives an insight into how the Finnish forest and timber economy functions as a material system and how efficient the forest industries are, in material terms, in using wood and other physical resources.

Nykyisin käytössä olevat tilastojärjestelmät, jotka käyttävät rahassa mitattua arvoa ainoana asioiden yhteismitallistajana, jättävät eräitä ihmisen tärkeimpiä riippuvuuksia ekosysteemeistä tilastollisen kuvauksen ulkopuolelle.

Lähtien aineen ja energian häviämättömyyden periaatteesta tutkimuksessa määritellään yleinen materiaali- ja energiatilinpidon viitekehys, joka voi tarjota perustan taloudellisten ja ekologisten toimintojen integroidulle tilastolliselle kuvaukselle. Tutkimuksessa hahmotellaan alustavasti uuden, entisiä tilastojärjestelmiä täydentävän tietojärjestelmän mahdollista perusrakennetta. Tutkimuksen empiirisessä osassa Suomen metsä- ja puutalouden materiaali- ja energiavirtoja koskevaa olemassaolevaa tilastoaineistoa analysoidaan määritellyn tilinpitoviitekehyksen puitteissa. Tutkimus rakentaa kuvaa siitä, miten metsä- ja puutalous toimii materiaalisysteeminä ja miten tehokas puun ja muiden luonnonvarojen käyttäjä metsäteollisuus on fyysisin yksiköin mitattuna.

Helsinki 1978. Valtion painatuskeskus

To my son Antti Hermanni who was born on the 28th of May in 1977, at the time when the first draft of the manuscript was completed, hoping optimistically that his generation would better be able to return the harmony between man and his physical environment.

FOREWORD

»Gutta cavat lapidem non vi sed saepe cadendo». A drop gouges stone not with force but by repetition. This old Latin proverb is a part of the life philosophy of my teacher Lauri Heikinheimo. And this philosophy he used when encouraging me to undertake this study in the winter of 1975. The first roots of the study originate from 1972 when my friend and colleague James Cunningham started his three years working period at the Forest Research Institute. All the years so far spent with this study have proved very inspiring, exciting and difficult.

I am indebted to James Cunningham, Pertti Seiskari, Kyösti Pulliainen and Pentti Malaska for some basic ideas. From the many persons who read the manuscript and gave useful comments I want to mention especially Jussi-Pekka Aittola, Arnold Grayson, Kauko Hahtola, Pentti Hakkila, Lauri Heikinheimo, Veli-Pekka Järveläinen, Matti Keltikangas, Heikki Kunnas, Kullervo Kuusela, Aarno Laihonen, Pentti Malaska, Kyösti Pulliainen, Päiviö Riihinen, Olli Saastamoinen, Ashley Selby and Risto Seppälä.

Ashley Selby checked the English language. Maija Kuusijärvi did the difficult final drawing of the figures. Nora Sepulveda and Eeva-Liisa Paakkanen took care of the typing of the manuscript. In the Central Statistical Office Olli Janhunen was very helpful in taking care about the administrative routine concerning the data retrieval and processing. The computer runs were made by Tuija Sandberg.

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Kuhmoinen, July 1978

Esko Jaatinen

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1. INTRODUCTION AND STUDY OBJECTIVES

11. Man and environment

Man is a part of living nature. Nature consists of different living and nonliving parts which are linked by path-ways of chemical materials and potential energies. The networks of these material and energy flows form organized systems. Man with his cities, industries and communications is a part of the overall global system. During thousands of centuries of his existence on earth man has learned to modify and exploit both the living and nonliving parts of his natural environment to his advantage. Yet, man still cannot claim to have a full understanding — let alone control — of his environment and the systems that support his growing economy.

In general, *ecology* has been defined as a science of the structure and functioning of nature, it being understood that mankind is a part of nature (O d u m, E. 1971, p. 3). On the same level of definition, *economics* could be defined as a science of the structure and functioning of man's economy. These two concepts date back to the common Greek word »oikos», meaning »house» or »place to live». Thus, both sciences could be thought to deal respectively with the study of household management. One could easily believe ecology and economics to be related sciences on the ground that man's economy is a physically integrated part of the overall global system often called the *biosphere* where the different parts are linked into one big functional unit by the movements of energy, air, water, and other chemical materials. From this particular point of view, economics could be regarded as a subdiscipline of general ecology, concentrating on only one population among thousands of other populations living on the earth. Despite these relations ecology and economics are not usually thought of having anything in common although there have been a few individual exceptions like Alfred Marshall who has contended that economics »is a branch of biology broadly interpreted» (M a r s h a l l 1920, p. 772).

Officially, ecology has been defined as a subdiscipline of biology studying the relations between living organisms and their environment on the population, community and ecosystem levels of organization. Population is here defined as a group of individuals of the same species of organism, community as a group of all the individuals of different populations living in a given area, *ecosystem* as a community taken together with its nonliving physical environment (e. g. O d u m, E. 1971,

p. 3—6, Ehrlich et al. 1973, p. 6—7). Different *physical* measurement units such as units of energy and mass are commonly used in the ecological studies. In the economic literature, the subject-matter of economics has been defined as »the science which studies human behaviour as a relationship between ends and scarce means which have alternative uses» (Robbins 1949, p. 16) or as the science studying »the problem of choice with regard to the use of scarce, alternatively applicable means for the satisfaction of classifiable human wants» (Hueting 1975, p. 1). *Monetary* units of measurement are commonly used in the economic studies.

The mere definitions and measurement units already indicate that there is little, if any, overlap, where the two fields are commonly concerned (cf. Schultz 1967, p. 139). Both sciences have developed a technical »language» and a methodology of their own and both have their special objectives to fulfill. However, *this study aims at pointing out that both sciences would gain by recognizing and studying the areas where ecology and economics are overlapping each other.*

Economics has usually studied man's economy in isolation from the other systems of nature and if their functioning has been included in the analysis its development has been regarded as an exogen phenomenon to man's economy. Accordingly, ecology has studied the structure and functioning of nature, regarding the development of man's economy as an exogen phenomenon. The starting point and the underlying principle of this study can be stated as follows: although these two sciences have developed side by side independently from each other, the two categories of systems, that of man and nature, have always been tightly interlinked by different materials and energy flows in such a way that the former is imbedded in the latter (figure 1). (Cf. Pulliainen 1972, Malaska 1972).

The functioning of nature has clear limits with regard to material expansion. These limits are set by the definite area of the globe, by the definite and rather constant rate of insolation, by the definite and rather constant amount of earth's matter, and — based on these three — by the limited capacity of the biosphere to produce new organic matter. Because man's economy functions within these limits set by nature, using the same definite living space and part of the same matter and energy neither is man's economy capable of limitless material expansion.

Based on the fact that man, as an organism, is fully dependent on the certain basic products and services produced by nature, it has been stated that the limits to the expansion of man's economy, in material terms, are much narrower than the limits to the functioning of nature (e. g. Malaska 1972, Pulliainen 1972, Ehrlich et al. 1973). This is because man must leave enough living space for nature to produce these essential products and services like food, pure air and water, nutrient cycles of the biosphere, formation and preservation of soil, regulation of climate and the composition of the atmosphere etc., which cannot be replaced by technology now or in the foreseeable future.

Ever since his origins man has had to adapt to the natural food flows available to him. The energy source was sunlight which is not directly available as food until some of this energy has been concentrated by plants and animals. At that time man's role in nature was based on the flow of solar energy. The amount of energy available to man was too small to allow him any significant influence on the functioning of nature's systems. (Cf. Odum, H. 1971).

In modern times, man's energetic relation to his environment has changed. He has access to much more energy and it enters by different routes from various energy sources. At the moment, man's new industrialized system derives a major part of its energies from the stocks of concentrated fossil fuels. Much of this energy flow is put back into man's environmental systems so that his

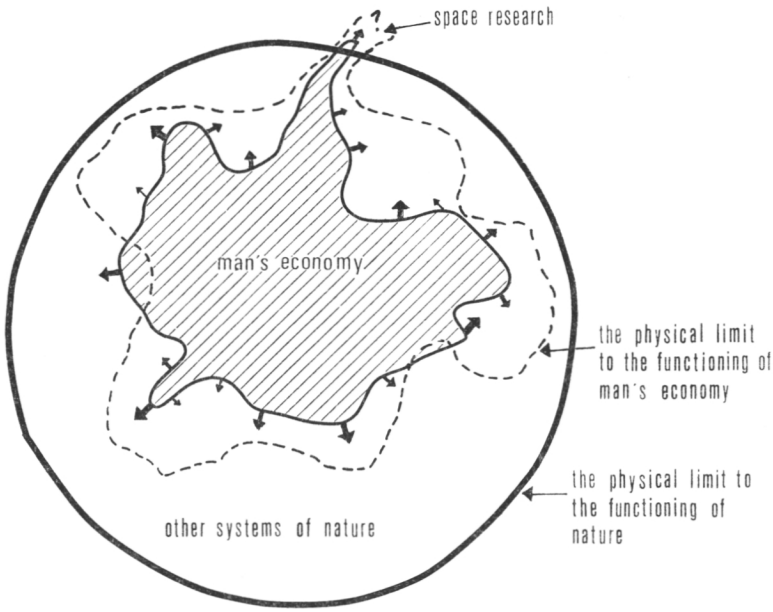


Fig. 1. Man's economy inside the other systems of nature (cf. Pulliainen 1972, Malaska 1972).

yield of food and different materials becomes greater. Although man has access to a lot of power, power itself is not control. Power can cause disorder as well as order and without the sufficient understanding of the relationships between man and his physical environment the large scale use of energy is more inclined to cause disorder than order (Cf. Odum, H. 1971).

The future development of man's economy will depend on man's capability of understanding the functioning of his growing economic systems in relation to the other systems of nature. The realization that man's economic systems are a part of — not apart from—the complex biogeochemical cycles of the earth and have increasing ability to modify these cycles to meet man's needs are becoming more and more fundamental principles both in the modern ecologic and economic thinking bringing the two »ecosciences» closer together (e.g. Boulding 1950 and 1966, Odum, H. 1971, Pulliainen 1972, Ehrlich et al. 1973, Palo & Nissilä 1976, Georgescu-Roegen 1971 and 1976, Saastamoinen 1978).

12. Statistical information systems and their objectives

A statistical information system aims at describing some part of the real world which can be studied as a system. A system has been defined as a set of elements viewed as a whole with relationships between the elements and between their states (Hall & Fagen 1956). A statistical information system aims at describing the elements, their states and the relationships among the elements and the states in

a *quantitative* way. Only a limited number of elements, states and relationships can be included in a given statistical information system. Which elements, states and relationships to include, depends on the objectives of the description and on the corresponding theories of explanation. (Cf. Laihonen 1972, p. 7—8).

The general objective in compiling statistical information is to provide man with the necessary information which he needs for the decision making concerning his different goal-seeking activities (cf. Hjerppe & Niitamo 1971, p. 1). The usefulness of a statistical information system can be evaluated by its capability to produce information which helps to attain this objective. The statistical *economic* information system, which refers here to the compilation of statistics known as the System of National Accounts (SNA) (United Nations 1968), aims at describing the economic activity of a country in such a way which produces relevant information for the economic decision making. The corresponding System of Material Product Balances (MPS) (United Nations 1971), which is used in the Socialist countries, is left outside the scope of this report.

Environmental deterioration as related to the economic activities of man has in its various forms become a topic of increased research activity and world wide interest in recent years. This term is generally defined as comprising all physical, chemical and biological changes in man's physical environment which adversely affect his physical and psychic health or which hinder satisfaction of man's material or spiritual needs (Vuoden 1970 ympäristön . . . 1970, p. 6). Environmental deterioration, such as pollution or depletion of natural resources, has been found to be basically a result of the improper functioning of man's economy compared with the functioning of ecosystems. *A hypothesis of this study is that one cause of this malfunctioning lies in the economic information systems* which are used to help in steering the production and consumption activities of man. The monetary economic information used as a basis for planning and decision making *does not take into account to a sufficient degree the prevailing ecological principles* underlying the functioning of the biosphere and its subsystems. (Cf. Palo & Nissilä 1975, p. 34).

In order to safeguard the proper functioning of the ecosystems in producing the natural resources which are essential to the quality of life man must understand the functioning of his economic systems in relation to the functioning of the ecosystems. This is not possible unless he is able to make the different ecological and economic processes commensurable with each other.

The economic processes have been usually described and analysed by using monetary values as the only common denominator. This denominator, however, is not applicable to the ecological processes. Accordingly the present statistical information systems, such as the SNA, leave some of man's most fundamental dependencies on ecosystems outside the scope of the statistical description. Therefore, there is an obvious need to consider the development of a statistical information system which would view the functioning of man's economic systems as an integrated part of the other systems of nature.

The ecological processes have been successfully described and analysed by tracing out the flows of matter and energy in the ecosystems. The economic processes are also basically material processes and as such they are physically linked with the ecological processes by the flows of matter and energy. This opens one avenue for a new statistical information system being able to identify and quantify the different physical linkages between an economic system and its physical environment by means of physical accounting of matter and energy. This kind of information system could also identify and account the flows of matter and energy within an economic system and between different economic systems thus preserving the comparability with the present economic information systems. The possible new information system would by no means replace statistical economic information systems, such as the SNA, but would rather *complement* them expanding the information base into areas which are outside the scope of present statistical information systems.

13. Structure and objectives of the study

The study is devided into two parts. The purpose of the *first part* (chapters 2 to 5) is, based on the economic and ecologic literature, to discuss some theoretical foundations for a statistical information system describing man's economic systems as an integrated part of the ecosystems. The objectives of the theoretical part are:

1. to define the theoretical framework which could offer a basis for the integrated description of the economic and ecological processes and starting from this framework to outline some preliminary guidelines for a new statistical information system,
2. based on this framework to analyse the functioning of man's economic systems and their goals, such as economic growth, from the material system point of view, and
3. to discuss some problems concerning the application of the defined framework as a basis for a statistical information system, and in general to give reasons why this kind of information system is needed.

The purpose of the *second part* (chapter 6) is to apply the defined materials and energy accounting framework in an analysis of the functioning of the Finnish forest and timber economy, comprising forestry, wood-based industries and consumption, export and import of wood and wood- based products. The forest and timber economy is one of the most important sectors of the whole Finnish economy whilst also being responsible for some major ecological impacts. The objectives of the empirical part are:

1. to study the applicability of the existing official statistics from the materials and energy accounting point of view, and
2. to obtain an insight into how the Finnish forest and timber economy functions as a material system and how efficient the forest industries are, in material terms, in using wood and other physical resources.

This is studied by combining available official statistical data into the defined accounting framework. The empirical part is exploratory in nature and no new empirical data was measured for this study.

PART I

THEORETICAL FRAME OF REFERENCE

2. NATURE AND ITS FUNCTIONING PRINCIPLES

21. Concept of ecosystem

Nature is a complicated system which consists of different living elements such as micro-organisms, plants and animals, and different nonliving elements forming the nonliving physical environment. These living and nonliving parts are joined by complex networks of different materials and energy flows forming functional units which are called *ecosystems*. The problem how to define the system boundary or which elements to include in the system and which in the system environment can and must be solved separately in each individual case. The term ecosystem has to be considered only as a conceptual tool, its main function being to emphasize the functional relationships and interdependencies between different elements. Ecosystems can vary enormously in kind and size. Any defined entity can be considered an ecosystem as long as its major components are present and operate together to achieve some sort of functional stability (cf. O d u m, E. 1971, p. 9).

22. Structure and functioning of an ecosystem

An ecosystem, to be a functional system, must have living *space* in which to function, Second, it needs *matter* for its components and third, there must be *energy* for the building and functioning of the living components. In addition to space, matter and energy, an ecosystem needs specific *control units*, which have the information for steering the flows of matter and energy.

The ecosystems get all their raw materials from the nonliving, abiotic part of nature. The necessary energy is provided mainly by the sun. The control units in the living parts of the ecosystems are made up by DNA- and RNA-molecules which contain *genetic information*. This information includes special codes which conduct the building and functioning of the living components in the ecosystems. The information steering the building and functioning of the nonliving parts of the ecosystems is still poorly understood.

The functional basis of the ecosystems is provided by the flows of energy and by the cycles of nutrients through the living components of the system. When describing the *structure* of an ecosystem, it is usually divided into the following components: 1) producers (mainly green plants), 2) consumers (herbivores, carnivores), 3) decomposers (bacteria, fungi), 4) organic compounds

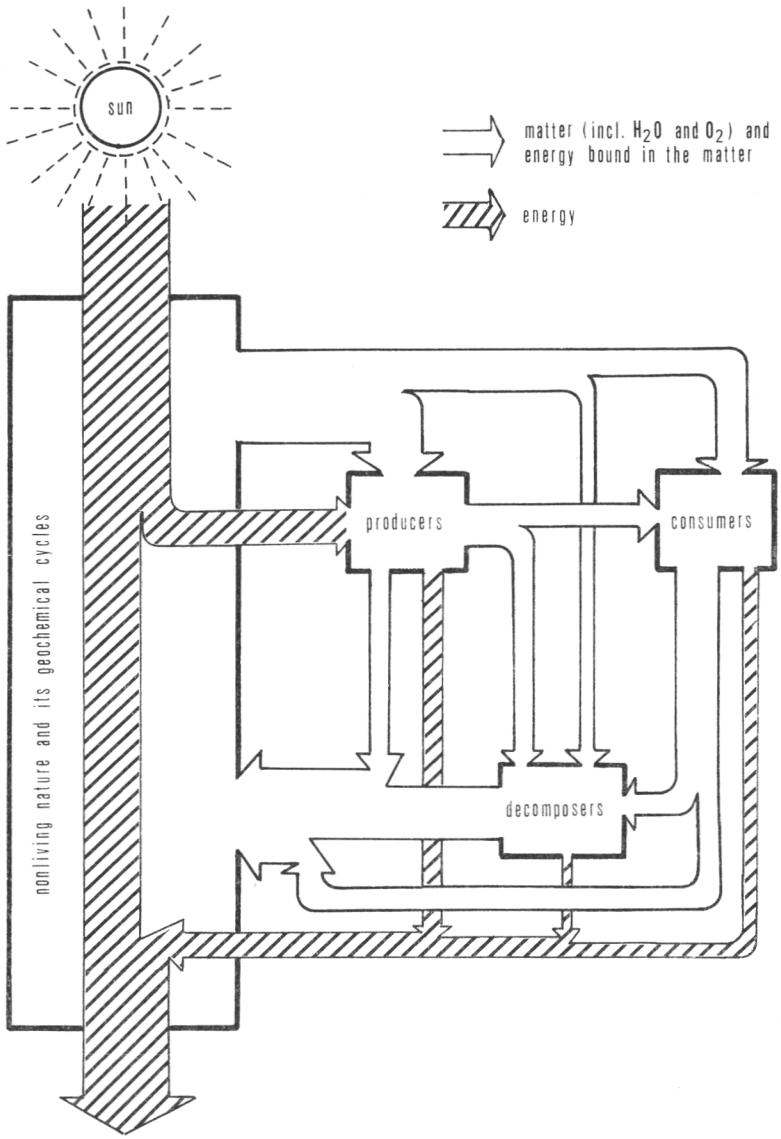


Fig. 2. An ecosystem model presenting the cyclical flow of matter and the linear flow of energy. (Modified from P u l l i a i n e n & S e i s k a r i 1972, p. 85).

(proteins, carbohydrates, etc.), 5) inorganic substances (N, CO_2, H_2O, etc.), and 6) climatic regime (temperature, etc.) (O d u m, E. 1971, p. 8). Items 1 to 4 comprise the *biotic* components of the system and their summed mass is called the *biomass*. Items 5 and 6 comprise the *abiotic* components of the system.

The *functional* description (see figure 2) of the biotic components can be given as follows (Pulliainen & Seiskari 1972, p. 84—85):

1. Producers are the components which take energy from the insolation and matter (inorganic substances or nutrients) from the abiotic part of the ecosystem, combine them into organic compounds (food) and finally give all this new organic matter and the part of energy bound in this matter to consumers and decomposers and the rest of the intaken energy as heat to the living space.
2. Consumers are the components, which take both their energy and matter from the producers and finally give all the matter and part of the intaken chemical energy to decomposers and rest of the intaken energy as heat to the living space.
3. Decomposers are the components which take both their energy and matter from the producers and consumers and finally release the major part of the matter in the form of inorganic substances (nutrients) back into the abiotic part of the ecosystem and all the energy which they have intaken is finally dissipated as heat to the living space.

23. Energy flow

Energy is usually defined as the ability to do work. The behaviour of energy can be described by the laws of thermodynamics. *The first law of thermodynamics* states simply that energy is neither created nor destroyed, although it may change form. This is the law of conservation of energy. *The second law of thermodynamics* states the principle of energy degradation saying that in any process where energy transformation occurs spontaneously some of the available potential energy must be dispersed along the process as unusable heat. This is the entropy law. (For more detailed description see e. g. Farrington & Alberty 1967, p. 3—114, Georgescu-Roegen 1971, Odum 1971, and IFIAS 1975).

Solar energy is the primary source of energy to the functioning of nature. A small fraction of solar energy falling on the earth is captured and converted to chemical energy via photosynthesis in green plants. This chemical energy is then passed on in succession to plant eaters (herbivores), eaters of herbivores (primary carnivores), eaters of primary carnivores (secondary carnivores) etc. and finally to decomposers. Each stage in this *food chain* is called a *trophic level.* At each transfer of energy from one trophic level to the next in the food chain, some energy, in accordance with the second thermodynamic law, is lost as *heat*, some is used to perform *work* and the rest is stored as *chemical energy* in the receiving organism's body. In accordance with the thermodynamic laws *all* the energy absorbed in photosynthesis is dissipated as heat while moving along the food chain. Therefore a continuous flow of new energy is needed to maintain the functioning of ecosystems.

24. Nutrient cycling

The term nutrient cycling is used to describe the movement of inorganic compounds and substances which are essential to life. These substances tend to circulate in the ecological systems through characteristic paths from the abiotic part of the system to the biotic part and back to the abiotic part. These cycles of matter are tightly connected to the flow of energy through living components and they are also powered by this energy flow. In addition to the cycles of matter between abiotic

and biotic parts of ecosystems, the solar energy also powers cycles of matter, which take place within the abiotic parts only.

Of the solar radiant energy reaching the surface of the earth on a clear day about 10 % is in the ultraviolet wavelength range, 45 % is in the visible range and 45 % in the infrared range (see e. g. Reifsnyder & Lull 1965, and Gates 1971). Photosynthesis is restricted to the visible wavelength range.

Thus, about half of the solar energy received at the earth's surface is incapable of creating photosynthesis. This part of the energy input is absorbed on the surface of the earth becoming heat. This directly absorbed heat, plus the heat released by producers, consumers, and decomposers all add together causing higher temperatures near the equator than in other regions. These temperature differences between the different zones create a giant heat engine driving the wind and water current systems of the earth. These air and water currents contribute to the primary production by bringing rain and fertilizer minerals to the sites of production; they also aid some food chains transporting organic matter to the sites of consumption. These global cycles of air and water powered by solar energy link different ecosystems into one functional unit known as the biosphere or ecosphere. (Cf. Odum, H. 1971).

All the cycles of matter in the biosphere are called *biogeochemical* cycles, »bio» referring to the cycles where living parts are involved and »geo» referring to the cycles restricted to the nonliving parts of nature.

Why then are these movements of matter called cycles and not flows as in the case of energy? The movement of matter is fundamentally different from the movement of energy in the respect that the *same* matter (same substances, atoms and molecules) can cycle continuously in the ecological systems provided that there is enough energy to maintain this movement. The cycling of matter is based on the fact that although there is a physical law of conservation of matter corresponding to the first law of thermodynamics there is — at least in principle — no law of increasing material entropy, as there is in the case of energy. The materials of the earth's crust — as known at the moment — consist of the 92 naturally occurring elements (105 elements altogether). All except a few of these elements behave in accordance with the principles of the conservation of mass and nontransmutability as formulated in classical chemistry. A few of the elements or their isotopes having abundances of only a few parts per million, are an exception to these principles in being radioactive (see Hubbert 1971). Thus it is quite possible to concentrate dispersed materials over and over again if energy inputs are allowed. This is a principle followed in the functioning of nature. The matter released by the decomposers is in such a form that the producers are able to use it as raw material for the production process.

Although the earth can be practically regarded as a closed system with respect to matter, the cycles of matter are not closed from the point of view of living components and small ecosystems. Matter flows through the living components of the system along the food chains and before leaving for the next round it often gets into the abiotic part of the nature where it can be stored for longer or shorter periods. Also the small ecosystems with arbitrarily defined boundaries are open systems with respect to matter which flows freely across the defined boundaries. Thus to understand ecosystems two kinds of processes must be studied: a) the rates of circulation within the boundary chosen and b) the rates of flows of matter and energy across the boundaries into and out of the system chosen (Odum, H. 1971, p. 59). These boundary flows describe an *environment* of the system. The magnitudes of the boundary flows depend, among other things, on the size of the system under study. In large inclusive ecosystems the boundary flows may be small compared with the internal cyclic flows. In small ecosystems the boundary flows may be very large compared with internal flows.

The functioning of similar systems having the same physical size can be different if the matter and energy flow through the systems at different rate. The functioning of the same system may also change because of changes in boundary and internal flows of matter and energy.

25. Homeostasis and ecosystem development

Ecosystems are capable of self-maintenance and self-regulation as are their component populations and organisms. *Homeostasis* is the term generally applied to the tendency of ecological systems to resist change and to remain in a state of equilibrium. The interplay of material cycles and energy flows in large ecosystems generates a self-correcting dynamic homeostasis with no outside control required. Really good homeostatic control developes only through a long period of evolutionary adjustment. (O d u m, E. 1971, p. 33—34).

Ecosystem development, often called ecological succession is a directional process of system development which involves changes in species structure and in processes of ecosystem functioning (e. g. in energy and material flows). The strategy of development has been found to be the increased control of, or homeostasis with the physical environment in order to achieve maximum protection against its perturbations. (O d u m, E. 1971, p. 25).

This strategy is followed by developing longer and more complex food chains. This usually means that the ratio of the gross primary production (P) to the amount of standing crop biomass (B) becomes smaller in the course of the succession. The ratio of the gross primary production (P) to the total community respiration (R), which is usually greater than 1 in a young ecosystem, approaches 1 along the ecosystem development. As long as P exceeds R, organic matter and biomass will accumulate in the system with the above mentioned result of a decreasing P/B-ratio. From the viewpoint of bioenergetics this development means that the amount of standing crop biomass supported by the available energy flow (E) increases when the succession goes on. Thus, the utilization of captured energy becomes more efficient in the ecosystem concerned, i. e. the *entropy*, or the amount of unavailable energy in this particular system, decreases.

The overall strategy of ecosystem development is directed toward achieving as large and diverse organic structure (good overall homeostasis) as is possible within the limits set by the available energy inputs and the prevailing physical conditions in existence (nutrients, water, climate, etc.). The succession culminates in a stabilized ecosystem where the maximum living biomass and high information content are maintained per unit of available energy flow (O d u m, E. 1971, p. 251). This stage of the ecosystem development is known as *climax*.

The P/R-, P/B- and E/B-ratios can be used to indicate the actual stage of succession in the ecosystem concerned. The ratios of gross primary production and unit of available energy flow to the total living standing crop biomass in an ecosystem can also be interpreted to measure and describe the overall *efficiency* in the functioning of the whole ecosystem (cf. P u l l i a i n e n & S e i s k a r i, 1972, p. 103). Thus, the larger the total living biomass maintained by a given amount of gross primary production, the more efficient is the ecosystem. In terms of bioenergetics this criterion of systems efficiency may be interpreted as minimization of increases in entropy in the ecosystem concerned.

The strategy of nature contained in an ecosystem developing toward a high B/P efficiency often differs from man's strategy which is usually directed toward a reverse efficiency — a high P/B ratio. E. g., the goal of intensive forestry and agriculture is to achieve high rates of production of a few harvestable products with little standing crop biomass left to accumulate on the site. These two strategies — nature trying to maximize the overall stability of the ecosystem and man trying to maximize the harvestable net production — are often found to be more or less incompatible with each other. (Cf. O d u m, E. 1971, p. 267—268).

To summarize, the functioning of nature is formed by the continuous flow of energy from outside (mainly solar radiation) and circular flows of matter inside the biosphere and its subsystems. The ecosystems of nature are capable of self-regulation and the short-term development of succession as well as a long-term evolutionary development.

3. MAN'S ECONOMY AND ITS FUNCTIONING PRINCIPLES

31. Natural resources and economic systems

Man's economy, comprising of several different economic systems, is based on the use of energy and materials (natural resources) provided by the natural ecosystems. The connexion between the concepts of ecosystem and natural resource can be defined as follows: a natural resource itself can be viewed as a complex of ecosystems, as an individual ecosystem, or as a separate component (either living or non-living) of an ecosystem. Thus it is possible to speak of natural resource ecosystems even when dealing with things like minerals, which belong to the abiotic part of the ecosystem concerned.

Natural resources are usually divided into *renewable* or *flow* and *non-renewable* or *stock* resources. The distinction between these two is not always clear.

With respect to energy, all such abiotic resources — the total amount of which is fixed within man's time horizon (although not necessarily exactly known) — are non-renewable resources (e. g. fossil fuels, uranium). This is not because they would be destroyed in use but because after use, in accordance with the second law of thermodynamics their energy is lost to civilization in the form of heat which finally leaves the planet as long-wave radiation. The only way man can influence the amount of these resources available at any given time is by changing the timing of their use. In any case, these resources which so far have been of the terrestrial origin decrease with use and the remaining stock is always smaller than the stock before use and sooner or later the total stock will be exhausted or the energy needed in mining and refining will exceed the amount of energy available in final fuel.

With respect to matter, the non-renewable resources can be defined as including all such abiotic stock resources (e. g. metals) the amount of which is fixed within the time perspective of man. They are non-renewable not because they would leave the planet (as with energy) or would be destroyed in use, but because they are (at least temporarily) lost to man when they are dispersed in concentrations too low for economical recovery under prevailing technology. There are few exceptions to this definition. Water is generally considered a renewable or flow resource, although the absolute amount of water on the earth is almost as fixed as that of metals within man's time perspective[1]. The difference is that water which has been made unusable by contamination or dispersal in use is restored to usable form as it passes through the various stages of the hydrologic cycle.

Theoretically, the metals and other minerals could be recycled after use over and over again providing that energy resources needed to concentrate dispersed substances are sufficient. Some rare valuable metals, like gold offer good practical examples: only a small amount of the extracted metal is lost and the main part remains in use.

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[1]) Small amounts of new water are released from the earth's crust during the volcanic eruptions. Water may also be formed at high altitudes by solar radiation induced chemical reactions.

Renewable resources or flow resources are based on the solar, gravitational or some other continuously functioning and long-lasting energy source. They are renewable because continuous flow of new energy makes them capable of reproduction. Renewable resources consist mainly of living biotic components of ecosystems (e. g. timber, cereal crops, game, fish, etc.), although some geochemical cycles like the above mentioned water cycle and cycles of air and the energy sources like the solar radiation or gravitational energies themselves can be considered renewable resources.

Solar radiation is a very rich source of flow energy and it reveals the difference between exoterrestrial flow and terrestrial stock resource at its clearest. Conversely, *the rate of actual use of energy does not affect the future supply of the resource at all* as in the case of non-renewable resources. Water, wind and tidal power are other examples of this kind of flow resource.

Food, fibre and other corresponding resources in living parts of the ecosystems can also reproduce themselves. These resources are special in that their reproduction is dependent on replenishment of other resources like solar radiation, water and soil as well as on the management and harvesting practices applied by man.

This classification of natural resources into fow and stock resources defines the four broad technological options open to man. The word »technology» is used here in a very broad sense to mean the way, the technique, by which the natural resources are combined in use by man. These four options are defined by cross-tabulating the natural resources as follows:

	Non-renewable matter	Renewable matter
Non-renewable energy	technology 1	technology 2
Renewable energy	technology 3	technology 4

The technologies 1 and 2 which combine the use of non-renewable energy with the use of non-renewable and/or renewable matter can continue only as long as the accessible energy resources last. Technology 3, combining the use of renewable energy and non-renewable matter, may continue much longer. It will last as long as non-renewable matter is available in form usable to man. Technology 4, based on the use of renewable energy and matter, can continue as long as their ability to renew. In practice the technologies applied at present are different mixtures of these options. (Cf. Seiskari 1976, p. 118).

For the purposes of this study *man's economic systems* are defined to consist of man's all activities using natural resources aimed at satisfying his needs. Different individuals and societies have usually defined, either explicitely or implicitely, some specific goals of economic activity which they regard as desirable. From the individual point of view these may include maximizing well-being or minimizing uncertainty (cf. Hjerppe & Niitamo 1971, p. 1). From the point of view of societies, the goals may include economic growth, maximizing national income, etc., but whatever the goals may be their achievement involves economic activity which forms a system analogous to the ecosystem. An economic system can also be divided — like an ecosystem — into production and consumption processes. Production can be defined as a process where goods are made with *tools*. Production also includes the management of ecosystems and the extraction of materials and energy needed in the process. Goods produced can be either *consumption goods* (commodities) or *capital goods* (new »tools» for the production process). Consumption can be defined as the use of these processed materials and energy for satisfying human needs.

Man's economic systems function in the same living space as the ecosystems of nature. They get all their materials and energy from the surrounding nature. The thermodynamic laws as well as the law of conservation of matter are also in force in the economic systems. Man can thus create or destroy neither materials nor energy but only change their form. All the materials abandoned by, as well as all the energy consumed in man's systems flow back into the living space and its ecosystems. The control information in man's economic system is in many ways different in nature from the DNA- and RNA-information steering the living parts of natural ecosystems. The information steering man's economic system although based on DNA/RNA-information, is for the most part generated by man himself. This information is gained through rational thinking and it is accumulating as a cumulative stock of knowledge which is stored in libraries, computer memory units, and in other such places and which is moved to the next generation not via genes but through educational processes.

32. Economic system as a market system

Because the SNA has been developed for describing the national economy of a country, it is interesting to learn how »economic system» has been defined for this statistical information system. When studing the structure of the SNA as recommended by the United Nations (1968) the conclusion is that the economic system described by the SNA can be best defined as a »market system» (cf. H j e r p p e and N i i t a m o 1971, p. 12, N i i t a m o 1970, p. 186). This term as used by economists has two meanings (F r e e m a n et. al. 1973, p. 65). First, »market system» means an actual functioning apparatus which guides the allocation of resources through pricing mechanisms in a society. These concrete market systems are formed by the set of institutional and cultural arrangements which vary from country to country. Second, the term is used to refer to the different theoretical models of the markets and their functioning as developed by economists. The theories of the model market systems have formed one of the most important cornerstones when trying to explain the functioning of the existing market economies. The development of the SNA by Richard Stone was also based on these theories as developed from the classical economics mainly by John Keynes. Therefore, it is useful to study some features of these economic theories when studing the market system as defined by the SNA.

Every economic system — whether free-market, centrally-controlled or any combination of these, i. e. mixed (see L i p s e y 1966 p. 79) — provides a framework for making choices. The choices must be made because of *scarcity*. Scarcity, which is the basic problem of economics, means the limited endowment of resources compared with human wants. The choices to be made because of scarcity are the following (e. g. L i p s e y 1966, p. 62—63):

1. What goods and services and in what quantities to produce?
2. What techniques to use in producing them?
3. How to allocate the supply of goods and services among the members who make up the economic system concerned?

Because of scarcity every economic system must have some mechanisms by which to make the choices mentioned above. The economic theories, on which the development of the SNA was based, are concerned with the functioning of the free-market economies. Such an economy is one in which the allocation of resources is for the major part the outcome of a large number of independent decisions taken by consumers and producers (L i p s e y 1966, p. 71 and 79). The mechanism through which the decisions about the allocation of scarce resources are made in a free-market economy, is the *price mechanism*. Thus, one of the most important economic theories underlying the SNA is the *theory of price*, which has many important related theories like the *theories concerning the behaviour of the producer (firm) and the consumer (household)*. These theories explain how the firms behave in supplying commodities in the markets and how the consumers behave in demanding commodities and in supplying labour. According to these theories, demand and supply will always end up at the situation where they balance each other (see e. g. N i i t a m o 1970, p. 191—192).

Other related theories include the particular *theories on production, growth, distribution, income, saving, and investment*. In addition to these, welfare theory has had its influence on the SNA. *Welfare theory* is concerned with the efficiency of production and allocation of goods and services. The economic theory has pointed out that under a given set of assumptions the free-market economy through the price mechanism automatically produces an »economically efficient» allocation of resources, which means that no other allocation would make at least one person better off without making someone else worse off. This is the principle of »Pareto-optimum» which has been a basic principle of the modern welfare theory; (for more detailed information see H j e r p p e 1975, p. 22—25).

The price mechanism plays an important role in the free-market economy when making the three choices (as listed on page 17) which originate from the scarcity of resources. The price mechanism was not consciously created. It is a control mechanism of an economic system, and it functions as a result of separate decisions taken by large number of individuals — both consumers and producers — each seeking his own private profit, but all responding to changes in prices (L i p s e y 1966, p. 161). From the point of view of the SNA, which tries to describe the functioning of the free-market economy, the key point is, that it is just the *price mechanism* that *determines which objects and phenomena are included in the national accounting* and which are left outside. Thus, in the SNA only those objects (material or nonmaterial) having the market price, i.e. being exchanged in the markets, are included when describing the functioning of the economy.

In most countries, however, some natural resources and their services (e.g. solar radiation, air, water, services by the air and water currents, waste assimilating capacity of ecosystems) are regarded as free gifts from nature without any enforceable system of property rights and they are freely available to anybody. These free gifts, known as *public goods* in economics, are not exchanged in the market and therefore no prices are attached to them and the market system using price mechanism in resource allocation cannot guide the allocation of these resources.

The price mechanism is based on *market exchange values* of different goods and services. Because of different market failures (see. F r e e m a n et. al. 1973, p. 71—79) the actual *»economic values»* (G e o r g e s c u - R o e g e n 1971, p. 276—291) or *»use values»* (N i i t a m o 1970, p. 184, A h m a v a a r a 1969, p. 196) of goods and services may differ from their market exchange values (prices) or there may be a high »economic value» without any price at all as in the case of above mentioned public

goods. Georgescu-Roegen (1971, p. 287) defined his »economic value» by saying that »everything which supports life enjoyment directly or indirectly belongs to the category of economic value». The corresponding definition of the concept of »use value» can be found from Ahmavaara (1969, p. 196): »everything which satisfies some biological need or which can be used as a tool for attaining the need satisfaction, has use value».

The standard economic theory concerning the functioning of market economy is in practice concerned with services. Material objects are merely the means to obtain these services. Yet we persist in referring to the »final consumption» of goods — indicating the failure to recognize the fact that the fundamental law of the conservation of mass and energy also holds true in man's production and consumption processes. This failure can also be seen in the structure of the SNA, which describes the functioning of the market economy as a *wholly circular* (i.e. closed) *process* between the production and the consumption (cf. Georgescu-Roegen 1976, p. 4).

The scope of the SNA is thus limited. In the SNA the resources, goods and services are seen only in their market context. The SNA is not interested in the origin of the natural resources in use or in the destination of goods and materials which have lost their market exchange value. Accordingly, this statistical information system omits some of man's most fundamental dependencies on nature. The main deficiencies of the SNA, with respect to the use of natural resources, can be summarized as follows (cf. Niitamo 1970, p. 184):

1. Natural resources, goods and services which have no market price are excluded from the SNA.
2. The SNA does not, in its accounting formula, take into account environmental deterioration (see p. 8) which results from man's production and consumption activities.

From the market system point of view, environmental deterioration in its various forms seems to be — at least partly — due to the »incorrect» prices created by different market failures as well as to the fact that some of the phenomena belonging to the field of the economic activity are outside the functioning of the price mechanism. Therefore many economists are of the opinion that the deterioration can be cured by improving the functioning of the price mechanism in the present market systems. This could be done by correcting the »incorrect» prices by various economic means such as taxation and expanding in one way or another the price mechanism to include those economic phenomena which so far have been outside this mechanism, that is, by »internalizing the environmental costs» (see Dahmén 1970, Kneese et al 1970, p. 74—107, Hueting 1975, p. 4—14).

On the other hand there are economists who think that the problems concerning environmental deterioration cannot be solved through the price mechanism. Georgescu-Roegen has studied this alternative and ended at conclusions best expressed in his own words (1976, p. xix, 10, 11, and 30): »Only economists still put the cart before horse by claiming that the growing turmoil of mankind can

be eliminated if prices are right. The truth is that only if our values are right will prices also be so . . . the market mechanism by itself can never heal a wrong. Prices are only parochial elements of the economic struggle of the human species . . . they cannot reflect the needs of future generations for the simple reason that those generations cannot bid on the present day market . . . Each generation can use as many terrestrial resources and produce as much pollution as its own bidding alone decides . . . It is a myth that the price mechanism can offset any shortages, whether land, energy or materials.»

There are practical examples which seem to indicate that the market mechanism can cure environmental deterioration, the cases of London air and the River Thames being good examples. But even in these cases it is difficult to point out whether the improving situation is due to the functioning of the market system alone or to the actions based on the information independent on the actual market system.

Be this as it may, also the economic activities aiming at improving the functioning of the price mechanism in the present market systems must be based on the *physical* information describing the relationships between economic and ecologic systems. Reliance purely on the price information can be misleading and dangerous because the economic feed-back usually functions after a much longer time lag than the feed-back based directly on the physical information. Because of the nature of many environmental injuries, a long time lag may make the reparation unnecessarily costly or some damage may even turn out to be irreparable within man's time horizon.

Actual market systems function and economic decisions are made within market mechanisms controlled in variable degrees by a governmental framework of different requirements and restrictions. Whatever the differences in the institutional systems may be, the scope and quality of economic decision making cannot exceed the scope and quality of the information available to decision makers. If man wants to understand the functioning of his economic systems as a part of complex ecosystems of the earth he will need a statistical information system wherein the functioning and interaction of these systems has been made *commensurable*. In this respect any statistical system using only one common denominator has its natural limitations. These limitations are, among other things based on the following reasons (N i i t a m o 1970, p. 194):

1. It is not possible to quantify *all* the relevant experience.
2. Although it is possible to quantify a part of the relevant experience, it may be impossible to make this experience commensurable.
3. Although a part of the relevant experience can be quantified and made operationally commensurable a detailed examination may reveal the applied quantification and evaluation technique to be unsatisfactory.

One way to develop the present statistical economic information systems further is to develop and apply different alternative quantification and evaluation techniques by which to make different phenomena commensurable.

Concerning the statistical data on the use of natural resources, it seems hard to expand the present economic accounting systems which use market price as the only common denominator to include the functioning of different ecosystems. Conversely, it seems possible — at least in principle — to expand the materials and energy accounting systems used in quantitative ecology to include the functioning of man's economic systems. A lot of useful physical information has been already collected together with the monetary based economic data although this information is fragmentary and difficult to make commensurable. The existence of physical statistical data and of some partial material accounting systems like the wood consumption and forest balance statistics in Finland indicates that the physical, nonmonetary-based information has already been found to be necessary in some areas of economic activity It is thus suggested that there is plenty of room for improvement in this respect and both the scope and usefulness of the statistical economic data could be significantly augmented by applying the ecological material and energy accounting techniques in a more systematic way than carried out so far (cf. C u n n i n g h a m 1974, p. 7).

33. Economic system as a material system

The analysis of a material process, both in the natural sciences and also in economics, cannot be sound without a comprehensive analytical description of such a process. The description must define the *boundary* which separates the process from its »environment». Usually the boundary must be defined more or less artificially, and it does not exist in the real world process under study. It is also necessary to define the *duration* of the material process concerned. The process can then be described analytically by the complete time schedule of all inputs and outputs. Where to draw the abstract boundary, what duration to consider and how to classify the elements of the process, depend on the particular purpose of the analysis. (Cf. G e o r g e s c u - R o e g e n 1976, p. 6.)

In the following, the functioning of man's economic system is considered by defining the rather arbitrary boundary as seen in figure 3, between man's system and its »environment» formed by different ecosystems. When analysing the functioning of man's economic system as a material system, we must study the flows of energy and matter across the defined boundary into and out of the economic system, i.e. the physical inputs and outputs as well as their circulation within the economic system in order to understand the functioning of this system and its relationships with the ecosystems (»environment»).

These boundary fluxes and internal circulations of materials and energy can be described by a simplified materials balance system model which is a modified version of the model as presented by K n e e s e et al. (1970, pp. 7—13) (figure 3). In this figure the economic system is schematically divided into four main compartments: production, use or consumption, materials recovery, and rejection.

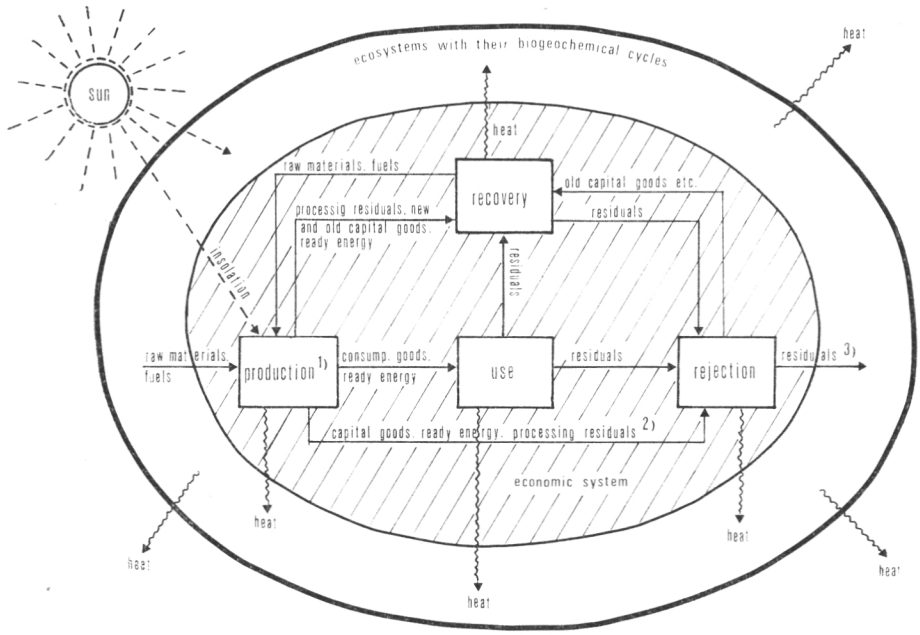


Fig. 3. Materials balance model linking the economic system with the ecosystems.
1) incl. human reproduction
2) this arrow incl. human corpses
3) this arrow incl. the material components of corpses

The production compartment includes all the activities engaged in the extraction of different natural resources from the ecosystems, their processing and refinement into capital goods, marketable consumption goods, ready fuels and ready energy (electricity, heat, etc.) and their transportation and distribution to the place of use. Use compartment includes all the activities engaged in the use of consumption goods.

The rejection compartment includes all the activities concerning the transportation, treatment and disposal of nonrecovered waste materials and waste energy produced by the economic system. The materials recovery compartment includes all the activities related to the transportation and processing of waste materials into usable raw materials and fuels.

In this simplified model it is assumed that the economic system has no material exchange with other economic systems, that is, there are no imports or exports. The global economic system as a whole is a good example of this kind of system. The physical input flow to the economic system includes different natural resources such as food, organic and inorganic raw materials, fossil and nuclear fuels, electricity from water power, heat from the sun, etc. In the production compartment these inputs — considered from the material point of view — are partly converted into products which include prosessed fuels, ready energy, consumption and capital goods. The rest of the material inputs, not incorporated into the products, are here called *residuals*. Capital goods are new »tools»

needed in the production, transportation, rejection and recovery processes. The consumption goods are then used or »consumed» in the use compartment and after they have worn out or become obsolete they become residuals which flow either to the rejection or recovery compartments. The capital goods used in the production, recovery and rejection compartment wear out as well and they must be replaced by new ones. The materials in the old capital goods become residuals and get into the rejection or recovery compartment. The recovery compartment converts the incoming residuals partly into raw materials or fuels usable in the production compartment, and partly into residuals flowing into rejection compartment. The rejection compartment disposes of all the residuals from the economic system into the ecosystems, either in the same form as the materials had when entering the rejection compartment or after having altered their form and composition. The rejection compartment itself generates residual materials like worn-out capital goods and residuals from fuel combustion and energy use in general.

The total amount of materials in the economic system at any moment (the summed mass of materials in the production, use, rejection, and recovery compartments) has been called »technomass» by Pulliainen & Seiskari (1972), who have used this concept in analogous way to the concept of biomass in the ecosystem. The material and energy flows obey the basic law of physics concerning the conservation of matter/energy. The principle of material balance based on this law can be formulated in many different ways including the following:

Total amount of technomass at the end of the accounting period = total amount of technomass at the beginning of the accounting period+the amount of new matter extracted from ecosystems during the accounting period — the amount of technomass rejected from the economic system during the accounting period.

This principle of material balance must hold true except for the economic system as a whole also for each compartment or sector of the economic system taken separately.

According to the thermodynamic laws (see p. 12) *all* the energy used in the economic system is finally lost as dissipated heat to space. Therefore the continuous flow of materials through the four different compartments of the economic system cannot be maintained without the continuous new inputs of energy. Accordingly, energy balances can be drawn up to account for the division of energy production among useful work, noise, and waste heat being dissipated into the air and water.

Based on the materials balance model, man's economic system as a material system can be regarded as an open dynamic system taking inputs such as raw materials, food and fuels, etc. from the open dynamic ecosystems and giving outputs like waste materials, products which have worn out, heat from the energy use, etc. back into the ecosystems. While being in the economic system, these inputs form and maintain the structure of this system. Combined with each other these two types of systems form one unique system which is globally in practice closed with respect to matter and open with respect to energy.

34. Evaluating the performance of economic systems

Welfare and economic growth

On the national level, the general overall economic goal which has been sought, and which will probably remain as a principal goal in the future, is the increase of overall *welfare* or maximized welfare under the different prevailing restrictions existing at any moment.

The content of the term »welfare» being very complex and having many different — even contradictory — aspects, no elaborate discussion is carried out in this study. It is simply stated that welfare refers to the degree of satisfaction of different existing human needs which may be both tangible and intangible, and whilst this study is restricted to the tangible it must be remembered that many intangible benefits (e.g. recreational, amenity and esthetic factors of a landscape) are also based on the physical structures created by different material and energy flows.

The analysis in this study is restricted to the material basis of welfare as it is included and measured in the System of National Accounts describing the functioning of the market economies. The SNA produces different social indicators like gross national product or national income which are commonly interpreted to describe the *performance* of the economic system with respect to the different goals which — either implicitely or explicitely — have been set to the functioning of the economic system concerned. The problem how well these indicators describe the attainment of the overall societal goals like economic growth and increasing welfare is beyond the scope of this study. The critique which has been presented on these indicators in this respect is very well summarized e.g. by H u e t i n g (1975, p. 22—30). This chapter tries to analyze the nature of some most commonly used »performance indicators» from the material system point of view. The analysis is also restricted to the quantitative aspects of welfare rather than to the qualitative ones. This does not mean that the qualitative aspects are not important but that their inclusion would expand the scope of the study too wide to be handled in a single report.

Since the Keynesian influence on economic theory in the 1930's and 1940's, the goal of increasing welfare has been sought by means of a phenomenon generally known as *economic growth*, which itself has become an explicit main goal for the economic system in many countries. The performance of these economic systems is thus evaluated by means of different indicators measuring how much and how steadily these economic systems are growing during a given period (usually a year).

The System of National Accounts produces many indicators for economic activity. This activity is measured in various ways, e.g. by the monetary value of the commodities (goods and services) produced during a year, the annual production and consumption of some important materials (like steel, paper and water), or annual consumption of energy. The summed monetary value of the commodities produced and exchanged through the market during a year is called the gross national product (GNP) which is the indicator most commonly used to measure the economic activity.

The present ideology to measure economic growth in the SNA can be summarized as follows: if more commodities (measured either in monetary or in physical terms) are produced this year than in the previous year the economy has grown and welfare increased (cf. B o u l d i n g 1966, P u l l i a i n e n 1972, P a l o & N i s s i l ä 1975).

In economic growth we can separate *physical growth* from growth as measured with the GNP. Physical growth occurs if the physical amount of goods (consumption, capital and export goods) produced during a year has increased from the previous year. The situation where the economic growth is measured in monetary terms is more complex and the GNP value can change without any change in the amount of material production. This may happen if the monetary values of the produced commodities change or because, without any change in the values, the production of the nonmaterial services changes. The more the GNP is based on the production of goods than on the production of services the better it is as an actual indicator of the physical growth. Of course the production of goods must have some kind of correlation with the production of services and the increase in the production of some special services like education may influence on the future production of goods in one way or another.

Regardless of the kind of measurement unit employed, the performance of the economic system is generally evaluated with the amount of commodities produced during a certain time period. This ideology is based on (and explicitely includes) the hypothesis that welfare is dependent on the production flow of new commodities. This leads to the difficult basic problem of whether human welfare is to be regarded as a *stock* or a *flow* (cf. B o u l d i n g 1966, p. 10).

Considering only material welfare, the economists agree that it consists of the services by the material commodities which can be used to satisfy different human wants (cf. K n e e s e et. al. 1970, P u l l i a i n e n 1972). But there exist many insolved problems concerning the question of whether the degree of the need satisfaction based on the amount of these services (the amount of material welfare) depends on the *stock* of the material commodities in use or on the *flow* (production) of new material commodities.

Most material commodities (like consumer durables and capital goods) can give their services many times before they finally break down. In this case, the stock of these commodities in use could be a better indicator of welfare than is their production flow. E. g. the amount of dwellings or the number of automobiles or refrigerators (per capita) in existence in an economic system is probably a better measure of material welfare than the annual production or sales of these goods. Of course the distribution of welfare among the members of an economic system is important in this connection.

Some goods are by their very nature necessarily flow goods because they can give their services only once (not repeatedly). This is true with all the materials which are in use converted into energy (e. g. food and fuels). Some goods staying as goods in use are also by their nature flow goods the services of which become quickly useless or obsolete (e. g. daily newspapers, let alone disposable goods). The flow-stock dilemma is also nearly related to the length of the time period under study. Almost all resources and goods, which during some limited time periods can soundly be regarded as stocks, turn out to be flows, if the considered time period is extended long enough.

On the other hand it is possible to argue that it is more important to be well fed than to carry out the eating activity itself. In other words we eat primarily to restore bodily homeostasis in the

same way as we burn oil or wood to restore the heat losses through the walls and windows during space heating. Stock concept could therefore be regarded as more fundamental than the flow concept, but there are still difficulties. It may be claimed that the flow itself, with the activity needed to sustain it (such as production and consumption, producing food and eating it) has a certain importance or inherent value. Furthermore, the existence of a demand for variety based on the changes in the preferences (tastes) and human wants underlying these preferences emphasizes the flow rather than the stock aspects of material welfare. (Cf. Boulding 1966).

Some aspects of both the stock and flow elements seem to be involved in human welfare and there have been very few studies aimed at identifying these two dimensions of human satisfaction. Therefore the following two hypothetical cases are considered separately when analyzing physical economic growth in detail within the materials balance framework:

case 1: Material welfare depends only on the total stock of material commodities available.

case 2: Material welfare depends only on the flow (production) of new material commodities.

These two hypothetical cases describe the two theoretical extremes. In reality material welfare probably depends *both on the stock and the flow* of material commodities, these two aspects having a varying proportion from case to case. Although these two hypothetical cases can be regarded as a theoretical simplification, they may help to understand some problems concerning the growth of man's economy as a material system.

Physical economic growth in the materials balance framework

Starting from these two hypothetical cases the material balance framework can be used for defining and analysing different alternative ways to create, maintain and increase a desired level of material welfare.

Redrawing the material balance flow chart on page 22 (figure 3) by presenting the materials and energy *flows* with arrows and the *stock* of produced material commodities with a box symbol the framework of materials balance can be presented in a very simplified manner (figure 4). (Cf. Pulliainen 1972, p. 114).

Based on the conservation of matter the amount of material commodities in use is controlled by two material flows: production and disposal (both measured with the same units as the stock of commodities).

We start the analysis making the following basic assumptions:

1. The population in the economic system is constant.
2. Material level of living (affluence) is to be kept constant.
3. The density of material in need satisfaction is constant: the amount of material commodities needed to reach the same given level of need satistaction over time is constant (Malaska 1972).

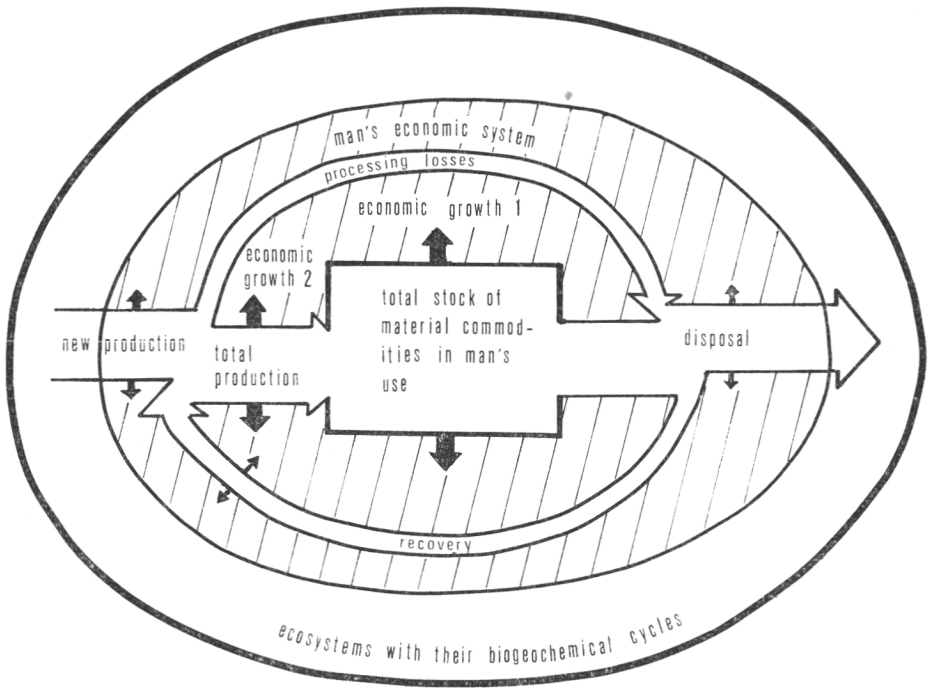


Fig. 4. Economic growth in the materials balance framework. Economic growth 1 = growth is measured by the increase of the total stock (volume or value) of material commodities. Economic growth 2 = growth is measured by the increase of the total production (volume or value) of material commodities.

We first consider *case 1*, in which material welfare depends only on the stock of commodities.

The total stock of material commodities in man's use (affluence) *is constant as long as the rate of new production* (the new matter entering the stock of material commodities) *equals the rate of disposal* (the matter leaving the stock of material commodities) (see figure 4).

Affluence remains constant as long as production equals disposal *independently from the actual rate of these flows*. This statement also holds true in the case where both the production and disposal flows are zero, i.e. there are no flows at all. This case is theoretical and the second thermodynamic law makes it impossible in practice. Thus, *there exists always a minimum flow which is needed to maintain a stock of a given size*.

How can we decide which level of through-put to choose when maintaining a given level of material well-being? In hypothetical case 1, material well-being depends only on the stock of commodities and there is thus very little desirability in production itself. The less production needed to maintain a desired amount of material commodities, the better off we are. This suggests that the best policy to follow in these circumstances would be to try to minimize the production and disposal flows required to maintain the given level of affluence.

The ratio of material commodity stock to through-put can be broken down as follows:

$$\frac{\text{stock}}{\text{through-put}} = \frac{\text{stock}}{\text{welfare}} + \frac{\text{welfare}}{\text{through-put}}$$

In a steady state economic system the affluence/through-put-ratio (efficiency) can be improved either by using a given (constant) affluence in a way which increases the total welfare or by maintaining a given (constant) welfare with smaller through-put. (See P u l l i a i n e n 1975).

The assumptions on page 26 are the assumptions of a steady state economic system; a situation of *zero physical economic growth*. In hypothetical case 1, the *physical economic growth can be defined as an increase in the stock* (amount) *of material commodities in use*. Economic growth is necessary if, for example,

1. population grows and the affluence per capita is to be unchanged or increased
2. while population is constant, affluence is to be increased
3. the density of material in need satisfaction increases.

Physical economic growth or the increase in the stock of material commodities can be created in the following ways:

1. increasing the new production flow while keeping the disposal flow constant
2. increasing the new production flow while decreasing the disposal flow
3. increasing the new production flow more than the disposal flow
4. decreasing the disposal flow while keeping the new production flow constant
5. decreasing the disposal flow more than the new production flow.

Which of these alternatives for physical economic growth to choose is a problem that depends on the conditions set up by the availability of different natural resources including the waste assimilative capacity of the ecosystems.

We then start to analyse the economic growth from the point of view of *hypothetical case 2*, in which material welfare depends only on the flow (production) of new commodities. Making the same assumptions as on page 26 it can be stated that *affluence is constant as long as the flow* (production volume) *of new commodities is constant*, independent on how these new commodities are used (do they accumulate in the economic system or do they just flow through the system?).

Physical economic growth in this kind of system then *means an increase in the production volume*. This is how physical economic growth is commonly measured in the different Western and Eastern economies at present. It matters very little if the new commodities are just replacing the commodities discarded from the system or if they are adding to the stock of material commodities in use.

The System of National Accounts allows an exception from this »rule». With respect to capital goods, the depreciation of the capital goods already in use is taken into account to some degree although this depreciation is more »allowable» than »real». But no corresponding subtraction is made with respect to the consumption goods.

A given volume of production flow can be maintained by taking *new* materials from the ecosystems (»new production» in figure 4) and also partly by *recycling* the materials already in the economic system. Physical economic growth or an increase in the production volume can be created by taking *more new materials* from the ecosystems and also partly by *recycling the materials faster* from the use (consumption) compartment to the production compartment, that is, increasing the internal rate of recycling in the economic system.

The material performance of the economic system, in this case, is measured solely by the production volume of new commodities making no difference between the production based on *recycled* materials and the production based on intake of *new* natural resources.

In the economic system where no recycling of materials exists, this evaluation technique *measures purely the capacity of the system to extract new materials and energy* (natural resources) *from the ecosystems*. In the economic system where recycling *does* exist this evaluation technique tells only the actual production rate giving no information about the materials and energy basis of the production process. It should be possible, however, to distinguish that part of the GNP which is derived from the recycled materials (used either as raw materials or fuels) and that which is derived from the new inputs of materials and energy from outside the economic system.

What combination of new materials and recovered materials to choose in the production process is a problem that depends on the availability of different natural resources and the capacity of the surrounding ecosystems to tolerate the different disturbances caused by the functioning of the economic system concerned.

Principles with which to measure and improve the material performance of an economic system

The principle with which to measure the performance of the economic systems with the increase of the production and consumption of the materials, energy and commodities suggests, that the original idea was probably to measure the capacity of the economic system to produce new commodities. As long as the production of new goods is based on the »virgin» raw materials and energy rather than on recycled materials this criterion also measures the capacity of the economic system to extract and use different natural resources. The criterion of increasing production and consumption was understandable measure of the system performance in the frontier economy where compared with the population natural resources were abundantly available and where the cycles of the ecosystems were able to cope with the disposal flows. But in the world of growing population and *limited resources as available to man under prevailing technology during a given time period* this is certainly not a rational way to evaluate the performance of the economic system.

The efficiency of any process or system is usually measured with an output/input ratio. The bigger this ratio the more efficient is the system in question. The amount of the output itself, produced during a given time period, does not tell anything about the efficiency of the process or system. The output/input ratio is usually called the productivity of the input concerned. The principles of the productivity analysis should be applied to the functioning of the whole economic system.

If we suppose that from the human point of view the goal of the economic system is to produce welfare, the general principle of the system efficiency in the use of natural resources is very simple: the higher the welfare (independent of how it is measured) maintained with a certain limited amount of natural resources available to man under the prevailing technology during a given time period, the more successful the economic system. Starting from a desired welfare this principle can also be stated as follows: the smaller the amount of new natural resources (as indicated by the arrow of new production in figure 4, p. 27) needed to maintain the welfare on a given desired level the more successful the economic system.

This principle for calculating the material performance of the economic system can be applied regardless of the output measurement technique. E.g., if the output in the functioning of the economic system is measured in terms of GNP, this output should be divided by the amount of the new natural resources (raw materials and energy) needed to produce that output. The ratio so produced would be a much better indicator of the system performance in material terms than the GNP itself.

From the point of view of natural resource use there are several ways to improve the material performance of the economic system.

Concerning the use of *matter*, the material basis of a given level of welfare can be maintained with a smaller intake of new matter if the matter once taken into the economic system is retained there for a longer time. This principle can be followed by extending the lifetime of the material commodities and by recycling the matter inside the economic system. This includes activities which aim at re-educating people to get rid of unnecessary changes of fashion (cf. Pulliainen & Seiskari 1972, Georgescu-Roegen 1976) and manufacturing goods to be more durable (cf. Pulliainen 1972, Malaska 1972, Ehrlich et al. 1973, Palo & Nissilä 1975) and making durable goods still more durable by designing them so as to be reparable (cf. Georgescu-Roegen 1976). This kind of development would decrease the one-way flow of matter through the economic system and increase the internal circular flows of matter. Both the input and output boundary flows of the economic system would thus decrease with respect to matter, leaving the available material basis quantitatively unaffected. A further way to decrease the boundary fluxes of the matter would be to improve the physical raw material/product ratios, increasing the utilization of the raw materials in the product, thus decreasing the amount of waste materials. Figure 5 presents the diagrams of a materially efficient and inefficient economic system in the case where the accessible natural resources are scarce.

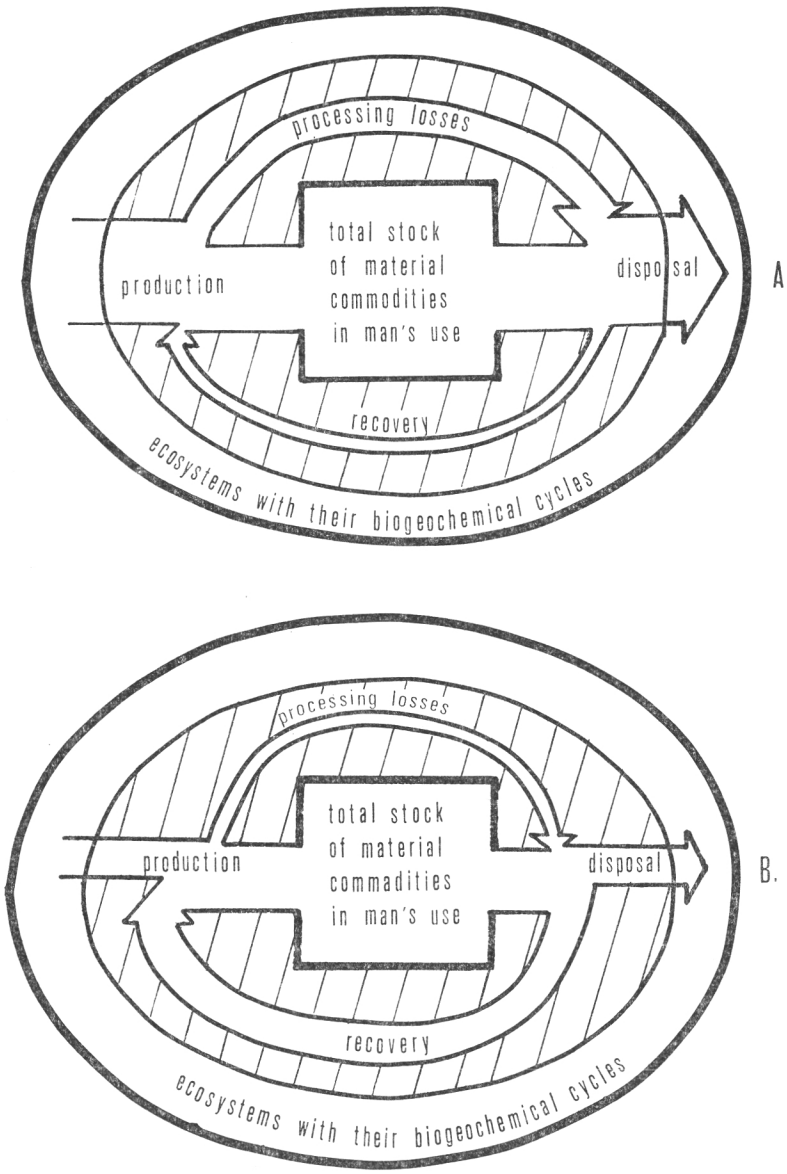


Fig. 5. Materially inefficient (A) and efficient (B) economic systems having equal stocks of material commodities in use.

There is certainly potential for production based on recycled materials. It has been pointed out many times that the technology available for handling and recycling residuals is poorly developed compared with the present technology geared to the use of virgin natural resources (e.g. K n e e s e, A y r e s & D ' a r g e 1970).

Energy which is vital for creating and maintaining all the materials flows cannot be recycled. According to the second thermodynamic law all the energy used to perform work is finally dissipated as heat and this loss can be compensated only by taking new energy from the natural resources. Some energy is also expended in this extraction process. The continual need for new energy inputs means that it is *impossible to maintain the economic system as a closed system*, no matter how efficient the re-use of inert materials.

The closed recycling of matter within the economic system would be very costly in energy terms, e.g. the concentration of all the dispersed materials would demand huge amounts of energy. The amount of energy available under existing technology sets one ultimate limit to the functioning of the economic system. The other limit, which is often met earlier than the previous one, is set by the impacts of energy extraction, refinement and use on the ecosystems. These impacts will be discussed in more detail in chapter 4.

The more effective use of energy is one of the primary means of making the whole economic system function more efficiently. If energy is scarce, for example the energy costs of material recycling must be compared with the energy costs of extracting the corresponding amount of virgin material. The environmental impacts of these two alternatives should also be compared. Much potential capacity exists for increasing the efficiency of the economic system with respect to energy use, such as by increasing the technological efficiencies of different processes and by recycling some energy containing residuals as fuel.

4. INTEGRATED ECONOMIC-ECOLOGIC SYSTEMS

41. Concept of carrying capacity

So far, the analysis has concentrated on flows and stocks of materials which are mainly internal to economic systems or to ecosystems. The analysis is now continued by paying special attention to the boundary flows between these two types of systems.

An economic system, as we have seen, is an open system which changes materials and energy with its environment (ecosystems). The overall global system formed by the interaction of ecologic and economic systems, however, is practically *closed with respect to matter*. In a closed system, the outputs of all parts of the system are linked to the inputs of other parts (cf. B o u l d i n g, 1966, p. 4). There are no inputs from outside (excluding the almost negligible amount of matter of incoming meteorites) and no outputs to the outside (excluding the negligible amount of matter in the form of small particles, spaceships and satellites which succeed in escaping from the earth's gravitational system). It also seems unlikely that additional physical resources will be obtainable from outside the planet in the near future.

From the point of view of *energy*, all the systems on the earth are open systems. The earth bathes in the continuous flow of solar radiation and is a part of the universal gravitational system. The earth also gives off energy in a less accessible form (heat) which flows out of the global system. The interplay of these input and output flows maintains a delicate thermodynamic equilibrium between the globe and outer space at a propitious temperature (for more detailed information see D y s o n 1971). But although this system is an open system the inputs of energy and energy containing materials to the economic systems are outputs from the functioning of the ecosystems and the outputs of waste heat (and energy containing materials) become inputs to the ecosystems before the heat has radiated into space.

Considering the boundary flows into and out of the economic system, an open system of this kind can persist indefinitely, if it has the capacity to draw upon the necessary inputs of materials and energy and to get rid of unavoidable residuals or wastes after use.

The capacity of ecosystems (surrounding the economic systems) on the ecologically sustainable basis to offer the input resources to the economic systems and to absorb the material and energy outputs of these systems can be defined as a *carrying capacity* of the ecological systems for the economic systems.

The concept of carrying capacity can also be defined in the following way. When using and managing the natural resource ecosystems — either in order to obtain inputs of materials and energy or in order to get rid of outputs like waste materials and energy — man and his economic systems are linked to the ecosystems and are subject to the same restrictions as any other factor in the ecosystems. Any action man takes in the ecosystem can be viewed as an additional input or output of energy and matter which has some effect on the functioning of the ecosystem concerned. In making large energy and matter exchanges man disturbs the dynamic equilibrium of natural ecosystems. Sometimes such disturbances result in changes which are deliberate and beneficial to economic system i.e. the carrying capacity of the ecological system for the economic system increases, as in some cases of agriculture and forestry. Nevertheless, individual ecosystems and ecological regions vary a great deal in their capacity to tolerate and recover from disturbances caused by the functioning of the economic system. This capacity of tolerance of the ecosystems is their carrying capacity for the economic systems as defined above.

If disturbances caused by the economic system result in adverse changes in the structure and functioning of an ecosystem and these changes are nonreversible within the time perspective of man, we can say that the carrying capacity of the ecosystem concerned has been exceeded. Premature extinction of species, disappearance of forest cover, erosion of productive soil and other such permanent changes can be mentioned as examples of exceeding the carrying capacity of natural resource ecosystems through mismanagement.

42. Principles with which to increase and measure carrying capacities

Measurements of the gross and net primary production in different ecosystems can provide estimates for the theoretical carrying capacities in production of biotic resources (O d u m, H. 1971, p. 120). According to Odum man can increase his share of the useful production in the ecosystem in two different ways:

1. In the ecological regions where different limiting factors such as water or nutrient shortages are a problem, a natural ecosystem which has existed for a long time period has developed mechanisms to overcome the limiting factors within its budget of available energy. However, if some limiting factors have remained beyond the resources available to the ecosystem concerned, relatively small subsidies of energy from outside the system (e. g. fossil fuels through man's activities) can be directed to overcome these factors. In this case the whole carrying capacity of the ecosystem concerned may increase.

2. In the ecological regions with few limiting factors the ecosystems may have overcome these except the factor set by the limited light. In such systems the energy subsidies from outside cannot overcome limiting factors but they can be substituted for the energy being used for the internal work processes in the ecosystem concerned. If an increasing amount of energy from outside the system is substituted for necessary internal work of the system, the net production may be increased toward

the gross production, that is, the ratio of net primary production to gross primary production increases. Genetic breeding in some of its forms is an example of this kind of development. One branch of the genetic breeding tries to eliminate all the special energy-using abilities of plants and animals involved in the breeding. This means that after a successful breeding their food can go into a bigger net growth than before the breeding. As a result we have plants and animals with so few protective survival mechanisms that these species are not able to survive in the competition with the wild species without the power-rich management of man. (For further information see Odum, H. 1971).

The concept of carrying capacity, being concerned with the boundary fluxes of materials and energy into and out of the economic system, can be applied to the use of natural resource ecosystems in the following three different contexts:

1. when extracting different natural resources from the cycles of ecosystems and when using the ecosystems to satisfy the needs for intangible benefits (e. g. recreation and landscape benefits)
2. when managing ecosystems to stimulate the production of useful natural resources
3. when discarding materials and energy flows from the economic system back to the ecosystems.

To make the concept of carrying capacity operational, it must be defined separately in each of these cases. Because of varying tolerance of individual ecosystems, the carrying capacity of each has to be defined separately. On the operational level, therefore, there must be plenty of empirical work of considerable refinement concerning the measurement of carrying capacities. Furthermore, knowing the carrying capacity of a certain ecosystem is not enough to control the situation. We must also know the *magnitude and development of the actual stress or disturbance* caused by the economic system upon the ecosystem concerned. Quantification of the carrying capacities and measurement of the level of actual disturbances raise difficult problems which still remain unanswered. Measuring and accounting the flows of materials and energy across the boundary of the economic system as defined in the materials balance framework (figure 3, p. 22) can offer a good starting point and basis for understanding and empirical research in this respect.

43. Carrying capacity and the use of natural resources

There are many reasons why the carrying capacities of different ecosystems have been lowered and in some cases exceeded through the activities of man in the course of history. Only some potential reasons concerned with point 3 above are briefly discussed here.

The locations of natural resource extraction sites are usually different from residual rejection sites (see Pulliainen & Seiskari 1972, p. 91—96, Seiskari 1976, p. 54—59). This kind of practice may cause nutrient shortages in the extraction sites while often causing nutrient surplusses in the rejection sites. Materials are usually transformed both physically and chemically whilst in the economic system. On the basis of the nature of the transformation process, the material residuals can be divided into two broad categories, which in practice are by no means mutually exclusive:

1. *Biodegradable residuals* are materials which naturally exist in nature and usually are easily degraded by natural processes.

2. *Nondegradable residuals* are such forms of materials which do not naturally exist in nature and natural processes are not able to decompose them or the degradation takes a very long time. (For further information see O d u m, E. 1971, pp. 432—450).

If the material residuals are rejected from the economic system in the »right» place, if they have the »right» composition, and if the »dosage» is »right», harmful effects will not occur. On the contrary, natural cycles are supported in a beneficial way. A right rejection site combined with wrong residual composition or dosage, as well as a wrong rejection site, may overload the geochemical cycles (such as air and water cycles) in the physical environment of the economic system.

The extra-somatic energy use always changes the nature of different biogeochemical cycles in a defined ecosystem in one way or another by changing the magnitude of the energy flow powering these cycles. From the point of view of man these changes can be deliberate and beneficial or accidental and harmful. The potential energy sources available to man can be divided into solar-based and nonsolar-based sources. The former sources include direct solar energy as such or in the form of different chemical fuels concentrated through micro-organisms, plants and animals, as well as in the form of wind-and hydropower. Nonsolar-based sources include nuclear sources, tidal energy from the gravitational system of the earth, the moon, the sun and the planets, the heat from the earth's interior based on the original gravitational condensation of the earth about four billion years ago supplemented by a modest energy input from natural radioactivity. From the nuclear sources of energy, uranium has already been harnessed. Furthermore man is optimistic that he will learn how to burn hydrogen isotopes existing in the oceans in a controllable way.

From all the potential energy sources known so far only the use of *direct* solar energy as such or in the form of wind- or hydropower and the terrestrial energy based on gravitation are as energy absolutely *pollution-free*. This is based on the fact that whether this energy is utilized or not, its amount remains the same and its final destination is to become the dissipated heat which maintains the thermodynamic balance between the earth and the space. Of course, if the energy is released in another place as was originally collected or the collected energy is concentrated into one place, there may appear some local climatical disturbances. This is true also for large differences in time between collection and release. The indirectly solar-based fossil fuels offer an example of solar energy bearing this kind of time difference.

The use of other energy sources except those two mentioned above, produces some residuals, whether thermal, radioactive or material, which are capable to cause pollution. For example, thermal residuals from the wide scale use of all types of nuclear energy may be capable of altering the present delicate thermodynamic equilibrium of the globe. The sensitivity or »carrying capacity» of this equilibrium is not known at the moment. For further information see D y s o n 1971, H u b b e r t 1971, G e o r g e s c u - R o e g e n 1976.

5. GUIDELINES FOR THE INFORMATION SYSTEM

51. Basic principles

The usefulness of a statistical information system depends on its ability to help man in his planning, decision-making and research concerning his different activities. In this case we are interested in a system which would produce information concerning the use of natural resources. Because man's economic systems are a part of the global biogeochemical cycles we need an information system which would approach the functioning of the economic systems from this viewpoint. Some basic issues concerning the development of the new complementary statistical information system are briefly discussed in this chapter. A few persons have dealt with this field in their research, e.g. P e s k i n (1972) and L a i h o n e n (1972). P e s k i n has approached the problem from the point of view of the SNA and L a i h o n e n from the point of view of the existing statistical information systems in general. Some international organizations like OECD and United Nations have activities going on in this field. In a working document, OECD presents guidelines how to expand the SNA to better take into accout some environmental problems in monetary terms (OECD 1971). In a working document of the UN, the basic guidelines for a special Materials/ Energy Balance Statistical Sub-System (MEBSS) are presented as a preliminary description. Physical units of measurement are planned to be used in this statistical system (for further information, see United Nations 1976).

The underlying principle for designing the proposed information system should be based on the physical law of conservation of materials and energy. The general materials balance framework as defined in figure 3 (page 22) could be used as a starting point for the planning of this kind of system. The production of statistical data should be carried out in physical units by means of materials and energy accounting.

Materials accounting should produce information describing the extraction of materials from ecosystems, import of materials from other economic systems, flows of these input materials within the economic system, export of materials to other economic systems and outputs of materials (e.g. fertilizers and other chemicals, waste materials) from the economic system to ecosystems. Energy accounting should produce information describing the production and use, imports and exports of energy in energetic units of measurement.

In addition to the regular *flow* information, materials and energy accounting should produce data describing the corresponding *stocks* of materials and energy both in the economic system (e.g. inventories of different materials, stocks of capital goods and consumption goods in use) and in the ecosystems (e.g. stocks or reserves of raw materials and fuels). Stock accounting identifies and quantifies the stocks of materials and energy at the beginning and end of the accounting period; flow accounting — e.g. in the form of the input-output tables — describes the changes in the stocks during the accounting period.

The most important problem to be solved when developing an information system is to agree on the measurement units and different classifications to be used in applying the system in practice. The usefulness of the whole information system will mostly depend on the disaggregation of the data into different classes of materials, energy, and economic activities. Because it would be useful if the new information system were at some level of disaggregation comparable with the System of National Accounts, the classifications of the SNA could be used as a starting point for the proposed *System of Materials and Energy Accounts*.

52. Measurement units

With respect to material flows and stocks we need measurement units which will make the different raw materials, products and waste materials commensurable with each other.

Materials usually go through different physical and chemical transformations when they are extracted and processed. Therefore almost the only way to ensure that the materials balance principles are followed in the accounting is to measure the materials in units of mass. Volumetric measures are useful in materials accounting only as long as no chemical or physical transformations occur. The comparability of different statistics on mass presupposes that the measurements of mass have been made according to unified principles, such as the water content (dry mass versus fresh mass) of materials. In principle, the comparability of statistics between different countries and regions presupposes that the differences in weight of objects having the same mass are taken into account. In practice the differences are usually negligible.

Some generally accepted measurement units of energy (e.g. joule) are used in energy accounting which follows the principles defined by the laws of thermodynamics. Energy accounting is restricted to energy provided by different nonrenewable or renewable fuels or by renewable sources such as solar, wind or hydro power generation. Because the fuels are materials they are also included in the materials accounting using mass units of measurement.

One way to make all the flows of materials and energy commensurable would be to measure everything in energy units. Thermodynamics determines that *all* materials

have a potential for furnishing energy. This is also true of the materials which are not usually considered to be fuels. This thermodynamic potential of materials is often called *free energy* which can be generally defined as »the surplus energy we can obtain for final use after deducting the energy required to transport substances and transform them into the desired form» (C u n n i n g h a m 1975, p. 3). Because of the difficulties in measuring these thermodynamic potentials in practice, this kind of energy accounting can hardly be included in the suggested information system. The »conventional» materials and energy accounting — if carried out with sufficient accuracy produces the basic data needed to make such an *energy analysis*. The objectives, techniques and underlying philosophy of energy analysis are studied in detail in the reports of the International Federation of Institutes for Advanced Study (IFIAS 1974 and 1975).

53. Classification of materials and energy

The classification of materials applied in the SNA is based on standard lists of materials and commodities, such as the Brussels Nomenclature. Such standard lists usually include only those materials and commodities which have a market price. To be useful for the system of materials and energy accounts these lists should be expanded to include all non-market inputs of materials and energy into and out of the economic system.

At the moment, there exists no standard list of non-market inputs and outputs. The development of this kind of standard list and its classification scheme is a difficult task. First, the basic accounting unit has to be decided upon. A detailed list of all possible non-market inputs and outputs can easily become so large that it may expand the size of the accounting system beyond that which can be conveniently handled. Second, the appropriate classification criteria have to be found. Because the measurement of materials' mass does not permit the comparison of different residuals according to the nature of their environmental effects, this aspect should be taken into account when classifying the residuals. A fundamental problem is that a residual, which is a combination of other residuals may have properties which in no way represent the properties of these component residuals. The properties of an »aggregated» residual, in terms of its harmful effects or in terms of its further processing, are a function of the amounts of the components and their physical and chemical properties. This »function» may be difficult to calculate and often it is completely unknown. (Cf. P e s k i n 1972, pp. 27—29).

Considering the classification of materials and energy in general, it would be useful to separate the *renewable* and *nonrenewable* forms from each other. From the environmental point of view one useful basic classification of materials could be the division into *biodegradable* and *nondegradable* residuals (see p. 36). Another possible

classification principle for both material and energy residuals would be to divide them according to the nature of the receiving environmental media e.g. into airborne, waterborne and solid residuals. Special attention should be payed to the nutrients; in the accounting they could be separated into a group of their own. The aspects of recycling could form a useful classification criterion. The general principle to be followed when solving the difficult materials classification problem is to base the classification on the physical and chemical properties of the materials, fuels and energy. This principle implies that all the materials, fuels and energy belonging to the same group should have properties which make them similar, such as with respect to their environmental impacts or recycling potentials. The energy should further be classified according to the source e.g. into the solar-based and nonsolar-based energy and into their sub-classes (cf. p. 36).

54. Sector definition

Decisions on sector definitions both in the economic and ecologic systems can be based on convenience, historical accident, or different more specific criteria set by analytical or policy objectives. Although the criteria set by these two types of objectives often differ from each other, the sector definition in the accounting system should meet one basic criterion: the sectors regardless of their degree of aggregation should be distinguished by how they transform physical inputs into physical outputs (where inputs and outputs also include those physical entities which have not conventional market value). This criterion implies that if a sector is aggregate its components should have both *process* homogeneity and *product* or output homogeneity. (Cf. P e s k i n 1972, p. 24).

These objectives are very difficult to attain in practice. In the economic system, the *establishment* which is usually the basic reporting unit when compiling data for the SNA often produces several products with several processes under the same roof. Thus it seems unrealistic to expect to attain the ideal goal of homogeneity in both process and product, and consequently a choice must be made between them when defining sectors. For example from the viewpoint of pollution problems the best choice could be to distinguish sectors by process within products rather than by products alone. Thus, instead of a pulp sector there would be pulp made by sulphite process, pulp made by sulphate process, etc. (Cf. P e s k i n 1972, p. 25).

In the »ideal» accounting system production, consumption, recovery and disposal activities can be separated from each other so that one can study the role of each of the sectors as a producer of waste materials or as a consumer of energy, or whatever. In practice this kind of sectoring presents problems because production, recovery and disposal activities often take place within the same establishment and it may be impossible to separate these jointly-performed processes from each other.

There is no doubt that different geographical considerations must be taken into account when building the materials and energy accounting system. These considerations include important questions concerning the location of natural resources, location of harvesting and mining activities, location of different pollution sources (e.g. industries, and densely populated areas), location and characteristics of the ecosystems which are the primary recipients of the non-recovered residuals, and so on.

The classification of economic activities into different sectors as applied in the SNA is rather comprehensive — this is especially true with respect to production processes — and they can be used as a starting point for the proposed materials and energy accounting system thus preserving the comparability between these two types of information systems.

55. Conclusions and recommendations

The proposed System of Materials and Energy Accounts describing the functioning of economic systems by means of materials and energy accounting, could greatly expand the scope of the overall statistical information base offered by the present economic accounting systems. The data produced by this kind of system would help to measure and improve the material and energetic efficiency in the use of the scarce physical resources. It would also help to understand the important connections between the size and composition of industrial activity and residual generation as well as the relationships between alternative industrial processes and the generation of residuals, the total effects of different residual treatment activities, etc.

Furthermore, this kind of accounting would identify and quantify the dynamic physical linkages between the economic system (or any part of it) and ecosystems. It would quantify the intake of different kinds of materials into the economic system and how much and in which form is returned to the ecosystems. Of course this kind of information is not sufficient as such. It is not enough to know the inflows and outflows but we must also know how the ecosystems *respond* to these physical material and energy exchanges. The suggested information system is *not* able to quantify the response or ecological impact itself, but it is able to help to attain this objective by providing the necessary data base for such kinds of evaluations.

Finally, there is the question of costs when considering the design and maintenance (including data collection, storing, and publishing the summary tables) of the proposed System of Materials and Energy Accounts. A careful analysis of costs as well as of benefits should be carried out when planning this kind of statistical information system. While it is beyond the scope of this paper to carry out such an analysis, it is easy to see that the analysis of costs would be much easier than the analysis of benefits. This is due to the fact that the costs are more easily measurable than the benefits

which involve different quantification problems. Furthermore, the costs can be easily related to a given time period while the benefits may occur after a varying time lag and their relation with time is not easily measurable.

In most countries, there are ready statistical organizations which regularly collect, store and publish statistical data. The collection and assembly of data needed for the proposed System of Materials and Energy Accounts, could probably be carried at low marginal costs when combined with compiling of the present statistics. Plenty of useful physical data concerning the intersectoral flows of materials and energy is already being collected. It would probably not involve large additional costs to make this collection more comprehensive and systematical by means of a common materials balance framework as suggested in this paper.

The development of the complementary statistical information system based on the physical accounting of materials and energy can be started on the basis of the formal accounting framework of the SNA. The first task is to expand the material and commodity lists to include *all* the physical input and output flows of materials and energy, and to agree on the physical measurement units and measurement techniques. In the beginning, it would probably be wise to use an unambitious classification of materials and energy including only relatively few aggregate classes. This would limit both the size and compiling costs of the statistical system. Later on, first aggregate classification can be changed and broken down little by little according to the needs which arise when the information system is used in practice. It is not possible to develop a complete information system all at once. As the development of the SNA has proved, an efficient and useful information system can be developed only through the experiences gained during a long practical experiment period.

PART II

EMPIRICAL CASE STUDY

6. FOREST AND TIMBER ECONOMY AS A CASE STUDY

61. Forest and timber economy in the Finnish economic system

This case study, concerning the Finnish forest and timber economy, tries to test the usefulness and describing power of the statistical information based on the physical accounting of materials and energy as suggested in the theoretical part of the study. The purpose is also to test the applicability of the available official statistics from the materials and energy accounting point of view. The functioning of the forest and timber economy as a material system will be illustrated and the physical efficiency of this system in using different natural resources empirically analysed. The forest and timber economy is generally considered to comprise that part of the Finnish economic system which deals with the production and consumption of forest resource-based commodities. This economic sector can be divided into two parts on the basis of the commodities produced: production and consumption of wood and wood-based goods, and production and consumption of non-wood commodities. (Cf. Seppälä & Valtanen 1975).

For the purpose of this study, the forest and timber economy is considered to comprise only the production and consumption of wood and wood-based products. More precisely, this sector includes all the activities of forestry (i.e. silviculture and harvesting), manufacture of the wood-based products (primary and secondary forest industries), and the final consumption, export and import of wood and wood-based products.

In Finland there are good reasons to concentrate on the utilization of timber resources when studying the relationships between economic systems and ecosystems. The forests are the country's most important natural resource, covering about 87 %

of the total land area. A major part of the whole economic system of the country is based on the use of only one renewable natural resource — wood biomass. Forestry and forest industries accounted for 20 to 25 % of the GNP-value of the material production, 12 to 14 % of the total gross national product, and over 50 % of the value of the exports in the beginning of the 1970's. In economic terms, these sectors have been even more important in the 1950's and 1960's and the forest industries have played a major role in the economic growth of the Finnish economy.

In addition to its economic importance the forest and timber economy is also responsible for some major ecological impacts in exchanging materials and energy with the forest and water ecosystems — the two dominating ecosystems in Finland. For example, the forest industries contributed to the total waste water load as follows in 1970 (Yearbook of Environmental Statistics of Finland, 1972):

BOD_5 (kg/day)	84 %
the runoff of waste water (m^3/day)	73 %
nitrogen (kg/day)	24 %
phosphorus (kg/day)	22 %

The consumption of the domestic roundwood was since the 1950's up to the early 1970's, more or less on the same level as the roundwood production capacity of the forests. The limited amount of the domestic roundwood has generated several ambitious forestry programmes for expanding the domestic roundwood base through intensified forest management practices. It has also created research and development programmes for new technologies which would be able to utilize — either for industrial raw material or for domestic fuel — other parts of the wood biomass in addition to normal stemwood. These developments in the forestry mean that man's impacts on the forest ecosystems will continue to increase both in kind and intensity.

In addition to the scarcity of raw materials which was one limiting factor to the desired futher expansion of the forest industries in the 1960's, there is also another problem which has become relevant during recent years. This is the increasing price of imported fossil fuels. The present forestry and forest industry technology is heavily based on the use of these fuels. It seems possible that at some time in the future there may be difficulties in securing the required fossil fuels at prices which would keep the energy costs of the forest industries within the tolerable limits.

Such problems — the limited amount of the domestic roundwood, increasing price of the imported fossil fuels and the ecological impacts of the whole forest and timber economy — have created an increasing need for information which describes the amount and regeneration of raw materials, the flow of different materials through the processes of the forest industries, the flow of wood-based products through the consumption-stage, re-use of materials, generation of waste materials and their flow into the ecosystems as well as the sources and flows of energy needed to maintain the material flows.

62. Forest and timber economy as a material system

Materials balance model

Considering only the production and consumption of wood and wood-based products the forest and timber economy as a material system can be schematically divided into the following compartments (cf. the general model on page 22):

1. forestry, including silvicultural and harvesting activities
2. wood processing, including industrial manufacturing and non-industrial processing of wood into goods
3. consumption, including the final use of the wood-based products
4. materials recovery, including the collection and processing of residuals into raw materials or fuels
5. treatment of residuals, including treatment and transportation of residuals to be disposed to the ecosystems
6. energy conversion, which provides the energy needed in other parts of the system (for transportation, industrial processing, residual treatment, etc.).

Energy conversion is artificially identified as an independent part in this schematical description in order to emphasize its overall importance (see K n e e s e et al. 1970, p. 9). In practice energy conversion is usually an inseparable part of the different forestry, wood processing and residual treatment activities. Also, the treatment of residuals, as well as the recovery of materials, often takes place as an integrated part of the industrial manufacturing process.

The interlinking flows of materials and energy combine these compartments into a system. As an open system, the forest and timber economy exchanges materials and energy with other systems. These boundary flows can be classified as follows:

1. inflows from the ecosystems and outflows into the ecosystems
2. inflows from other sectors of the Finnish economy and outflows into these sectors
3. inflows from foreign economies (imports) and outflows into these economies (exports).

The schematical description of the forest and timber economy as a material system is presented in figure 6. This figure is based on the general materials balance model as presented on page 22. The different compartments of the system can be further divided into smaller parts. Forestry for example, can be divided into silviculture and harvesting, processing can be broken down according to the industrial types, residual treatment can be divided on the basis of the treatment methods, etc. The forest and timber economy as a whole and any part of it regardless of the degree of disaggregation must, in their functioning, obey the basic law of the conservation of matter/energy and the entropy law.

Flow of wood

The basic structure of the forest and timber economy can be revealed by mapping the flows of wood. The material system as a whole is formed by the flows of materials

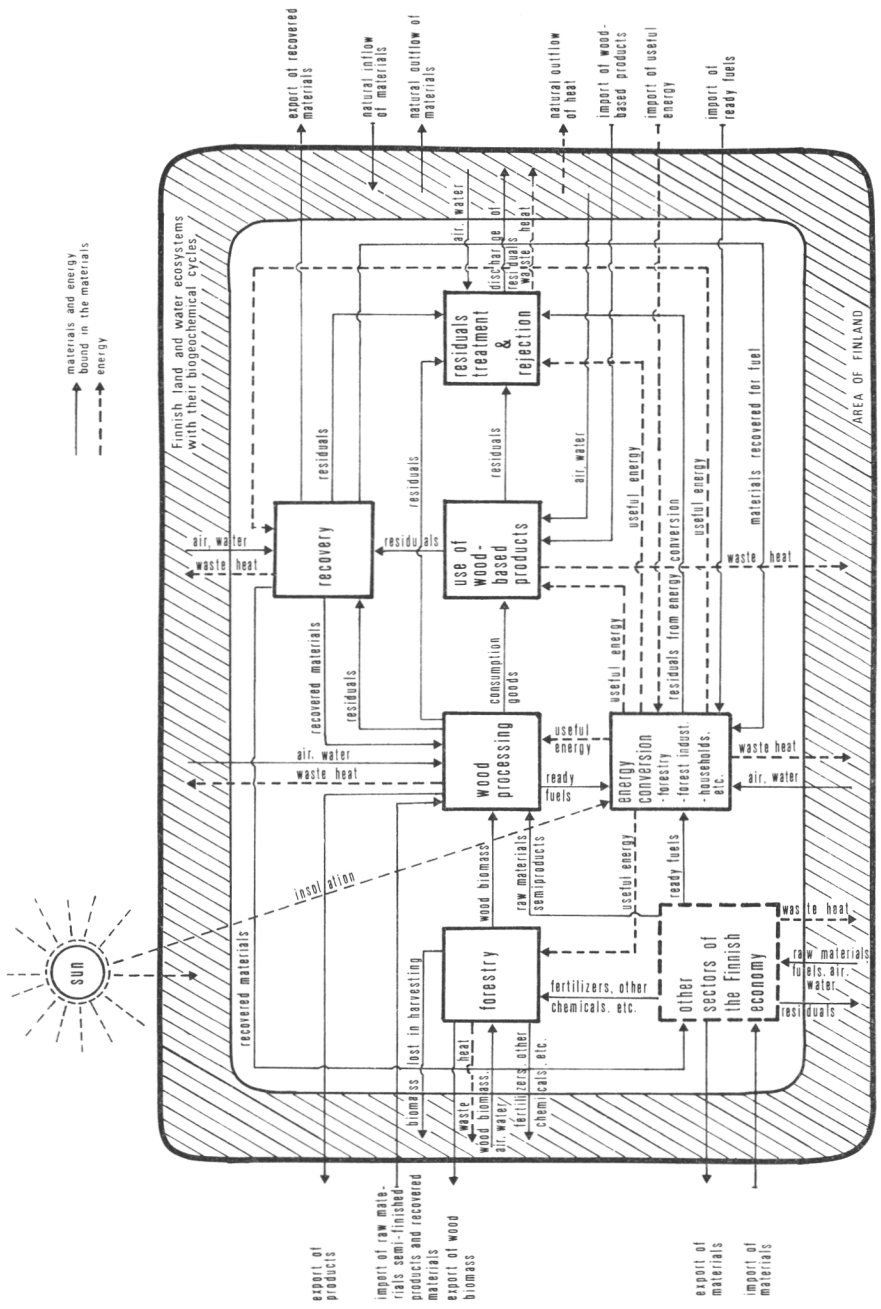


Fig. 6. Schematical flow chart of materials and energy in the Finnish forest and timber economy.

and energy which are necessary to create and maintain the flows of wood during a given time period. These flows include other raw materials and semi-products used by forest industries, non-wood fuels and other energy used in silviculture and harvesting, in industrial processing, materials recovery, and waste treatment.

In the broadest sense, the forest and timber economy as a material system includes all the machines and other capital equipment of forestry and forest industries, as well as the materials and energy needed to make this capital equipment. This part of the material system is outside the scope of this study.

The flow chart of wood and wood-based products in the Finnish forest and timber economy is presented schematically in figure 7. This chart follows the principles of the materials balance model, identifying the flows of wood material within and across the defined system boundary.

Figure 8 presents cross-sectional data concerning the flows of wood material in 1972. The purpose of this figure is to give an unified overall picture of the flows and use of wood material during a year. The year 1972 was selected for this study because at the time this study was started it was the latest year for which the official statistical information was fully available.

The circular symbols in figure 8 — as well as in figure 7 — can be thought to describe different inventories of wood, wood-based products and wood residuals. The rectangular symbols describe the different forest industries which have been divided into primary and secondary industries. The hexagonal symbols describe the final consumption of wood and wood-based products. Materials balance principles are followed at every step of the figure, i.e. the inputs and outputs of the wood material in every industry correspond with each other and the wood material flowing into an inventory or for consumption is either flowing out or stored there.

The basic data were taken from the Industrial Statistics (1972) and from the statistics prepared at the Finnish Forest Research Institute (H u t t u n e n 1974 a and b, Yearbook of Forest Statistics 1972). In order to make the different flows commensurable, all figures were converted into metric tons of dry matter. Roundwood and wood residuals which are measured in cubic metres (incl. bark) in the statistics were converted into units of mass using the following average conversion factors (H a k k i l a & H e i s k a n e n 1971):

	kg/m³ (solid volume) wood	bark
pine *(Pinus sylvestris)*		
logs	385	30
pulpwood	360	30
spruce *(Picea abies)*		
logs	345	40
pulpwood	345	40
birch *(Betula pendula & pubescens)*		
logs	444	66
pulpwood	435	65
other *(Alnus* sp, *Populus* sp, etc.)	317	43
chips and particles (sawmills)	160 kg/m³ (piled volume)	
chips and particles (plywood mills)	175	»
sawdust	140	»
bark residuals	130	»
other residuals	400 kg/m³ (solid volume)	

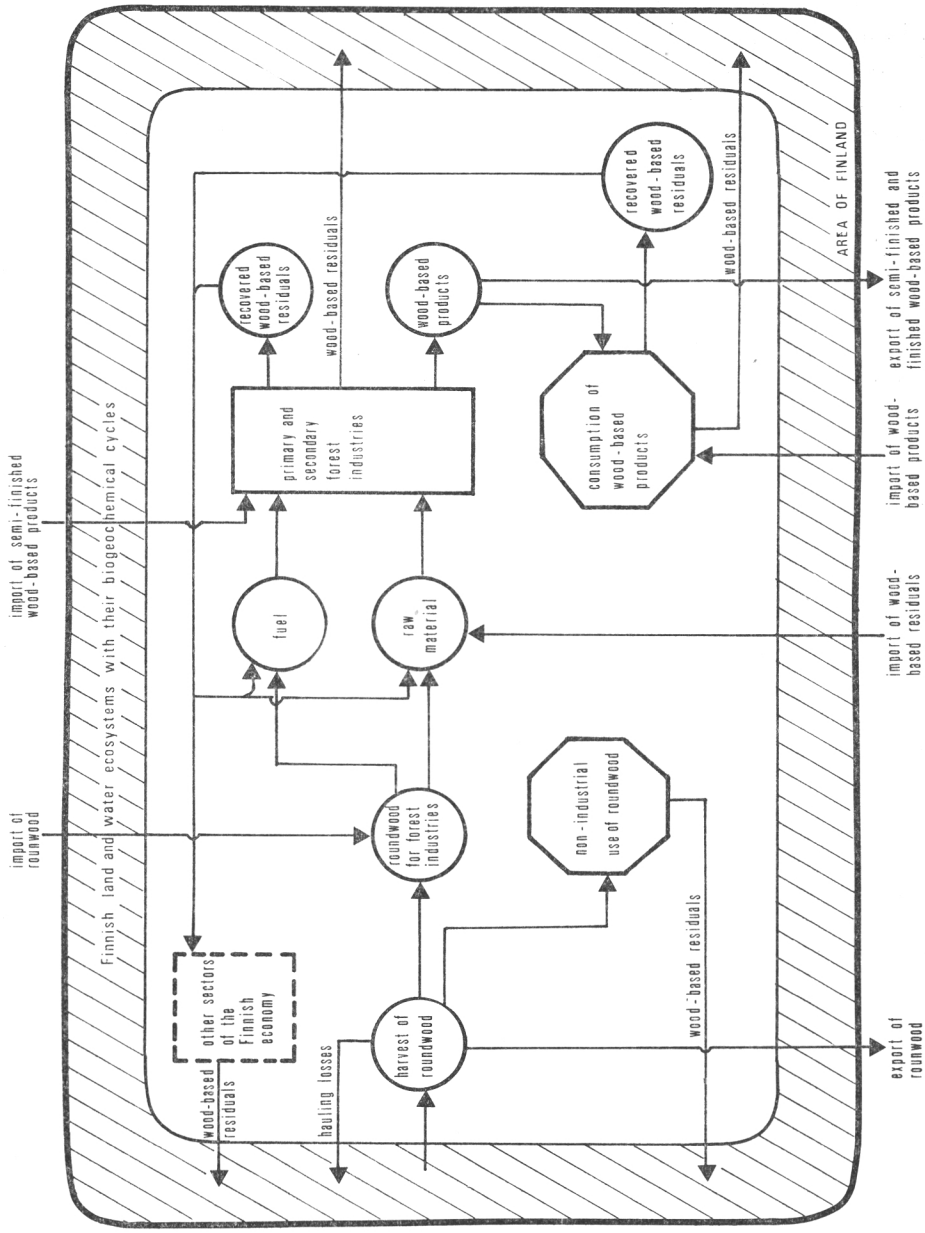
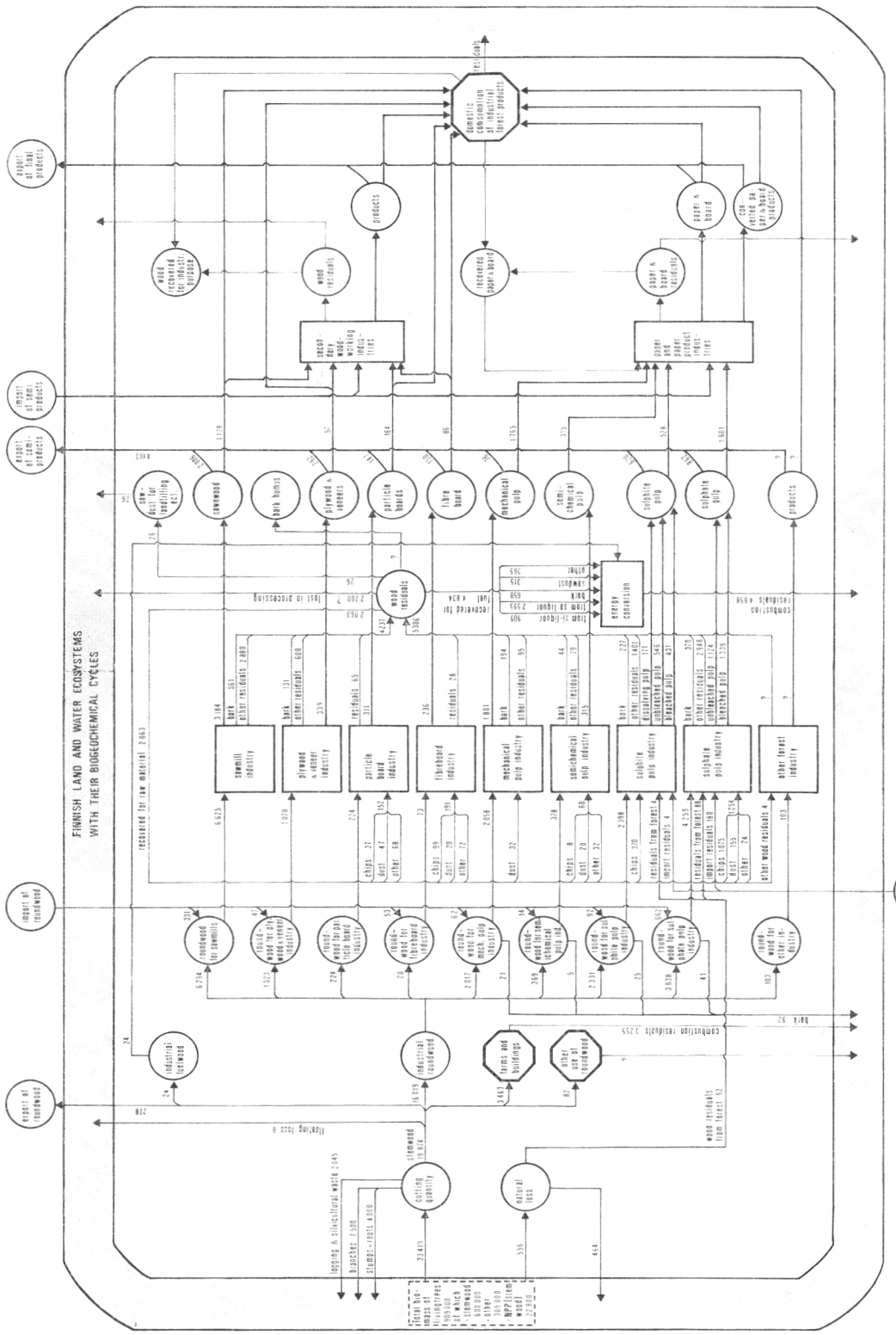


Fig. 7. Schematical flow chart of wood material in the Finnish forest and timber economy.


FINNISH LAND AND WATER ECOSYSTEMS
WITH THEIR BIOGEOCHEMICAL CYCLES
import of roundwood
export of roundwood
import of semi-products
export of semi-products
import of final products
export of final products
import of industrial wood residues
domestic consumption of industrial forest products
products
paper & board
wood recovered for industry purposes
wood residuals
recovered paper & board
paper & board residuals
secondary wood-working industries
paper and paper product industries
sawdust for textiling etc.
sawnwood
bark humus
plywood & veneers
particle boards
fibre board
mechanical pulp
semi-chemical pulp
sulphite pulp
sulphate pulp
products
wood residuals
energy conversion
sawmill industry
plywood & veneer industry
particle board industry
fibreboard industry
mechanical pulp industry
semichemical pulp industry
sulphite pulp industry
sulphate pulp industry
other forest industry
roundwood for sawmills
round-wood for ply-wood & veneers industry
round-wood for particle board industry
round-wood for fibreboard industry
round-wood for mech. pulp industry
round-wood for semi-chemical pulp ind.
round-wood for sulphite pulp industry
round-wood for sulphate pulp industry
round-wood for other in-dustry
industrial roundwood
fuel-wood
farms and buildings
other use of roundwood
felling quantity
natural loss
logging & silvicultural waste 2445
branches 7300
stumps+roots 4000
total biomass of living trees
of which
sawlogs
pulpwood
other
NPP(stem wood)
NPP(total wood)
recovered for raw material 2463
lost in processing
recovered for fuel 4834
combustion residuals 4858
combustion residuals 3255
bark 92
flowing loss a
wood residuals from forest 32
chips 37
dust 47
other 68
chips 99
dust 29
other 72
chips 8
dust 20
other 32
chips 310
residuals from forest 4
import residuals 4
residuals from forest 168
import residuals 168
chips 1075
dust 155
other 74
other wood residuals 4
from sulphite liquor 2595
from sulphate liquor 909
bark 650
sawdust 315
other 765
bark 561
other residuals 2889
bark 131
other residuals 660
residuals 65
311
residuals 28
236
bark 194
other residuals 95
bark 44
other residuals 19
315
bark 222
other residuals 1401
discharging pulp 177
unbleached pulp 545
bleached pulp 437
bark 370
other residuals 2945
unbleached pulp 1124
bleached pulp 1139
3 184
6 625
1 078
224
152
72
191
2 068
328
60
2 398
4 235
254
103
6 734
1 078
224
20
2 817
21
369
5
2 331
25
3 638
41
103
24
24
16 019
3 463
82
226
2 445
32 814
324 473
556
464
4 000
7 300
385 000
2 400
4 600
2 200
2 063
4 237
5 986
1 378
57
164
85
1 765
315
1 681
558
?
?
?

These conversion factors are here regarded as the approximate average conversion factors and are considered sufficiently reliable for the purposes of this illustrative case study concerning the whole country. The density of the wood material or the amount of dry matter per volumetric unit varies on the basis of many different factors. The density varies inside of each individual part of a tree. The variations between the different trees are based on the endogenic genetical factors on the one hand and on different exogenic factors such as the factors influencing on the growth rate on the other hand. Also, the age differences cause variations between individual trees. The same factors also cause variations between individual wood stands. Different geographical variations also play an important role. The Scots pine has the largest variations in density of the wood material in this respect. (Hakkila & Heiskanen 1971, p. 446).

Sawnwood, plywood and veneer, which are measured in cubic metres, were converted into units of mass assuming that the mass of the product per cubic metre is the same as the corresponding mass of roundwood (without bark) used in these industries in 1972. In the particle board industry, it was assumed that the mass of the product per cubic metre is the same as the corresponding mass of all wood raw material used in this industry in 1972. The mass of the pulp, as reported in the statistics, was assumed to include, on average, 9 % of water and the figures were adjusted accordingly (Teollisuuden jäteinventaari 1972).

The total cutting quantity of the wood biomass was about 33,4 million tons in 1972. From this amount only the stemwood or approximately 59 % was actually harvested from the forests. A small amount of the harvested biomass was lost into the water courses during floating. About 10 % of the harvested pulpwood was assumed to be barked in the forest (accidental losses of bark during harvesting and transportation were not taken into account). The roundwood flowing to non-industrial domestic consumption was mainly used as fuelwood, which for the most part returned to the ecosystems as various combustion residuals. The major part (about 80 %) of the harvested wood biomass entered the industrial process.

Comparing forest industries' input and output flows we can calculate the percentage of the wood raw material (incl. bark) used by the industry consumed by the main products. These estimated conversion efficiencies by primary forest industries were, in 1972 as follows:

fibre board industry	89 %
mechanical pulp industry	86 %
particle board industry	83 %
semichemical pulp industry	72 %
sawmill industry	48 %
sulphate pulp industry	43 %
sulphite pulp industry	41 %
plywood and veneer industry	32 %

In the primary forest industries as a whole about 56 % (9,8 mill. tons) of the primary wood raw material (17,4 mill. tons) used went into the main products. The amount of residuals by industry groups, i.e. the wood material which was not incorporated in the main products, was estimated by subtracting the mass of the products from the mass of the used wood raw material.

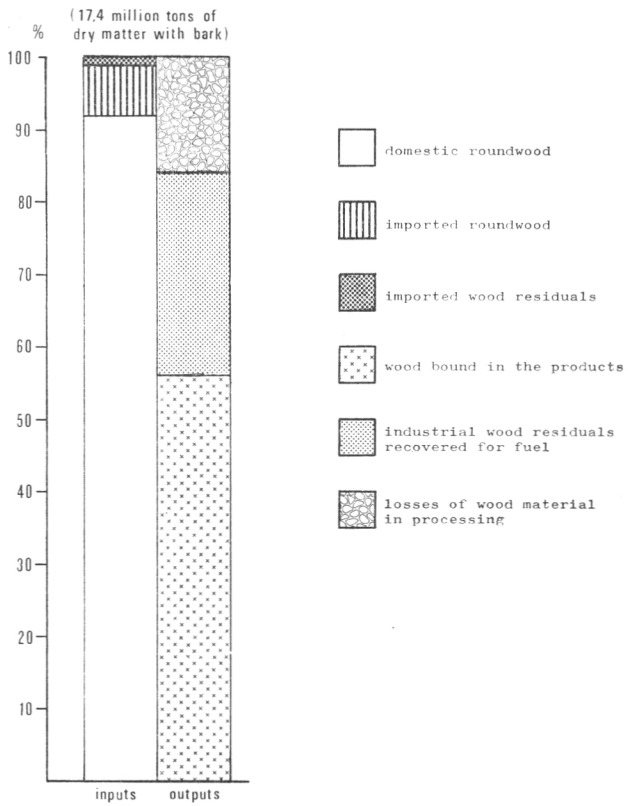


Fig. 9. Estimated wood material balance in the primary forest industries in 1972.

The total amount of wood residuals produced by the primary forest industries was estimated to be 9,6 million tons in 1972. During the same year some 2,1 million tons of wood residuals were used as raw material by the primary forest industries (H u t t u n e n 1974 b). This amount was about 22 % of the total amount of residuals produced in 1972.

Furthermore some 4,8 million tons of different industrial wood residuals (including the wood material recovered from the cooking liquors of the pulp industry) were burned as fuel in different sectors of the Finnish economy in 1972. This amount was about 50 % of the total amount of the industrial wood residuals produced during that year. The recovery of dissolved wood residuals from the sulphite and sulphate liquor was estimated on the basis of a study concerning the dissolved waste materials from the pulp industries in 1969 (Teollisuuden jäteinventaari 1972). This calculation assumes that the recovery rates in different pulp processes were the same in 1972 as in 1969. The amount of other industrial wood residuals used as fuel in 1972 was calculated from the Industrial Statistics.

Assuming that there was no significant accumulation of wood residuals in the inventories, i.e. the amount of residuals produced in 1972 approximately corresponded to the amount of residuals either used during the same year or lost from the economic system, it can be calculated that some 2,7 million tons (about 28 %) of the wood residuals produced by the primary forest industries were lost during processing in 1972.

Comparing the amount of products produced by primary forest industries with the amount of these products exported in 1972, we can estimate that about 42 % of the wood material which was incorporated in the products of primary forest industries was exported. This amount was about 24 % of the total amount of wood raw material used by these industries in 1972.

The estimated total material balance of the wood in primary forest industries in 1972 is presented in figure 9. This figure is based on the assumption that the amount of industrial wood residuals recovered in 1972 roughly corresponded to the amount of these residuals actually used during the same year.

It is very difficult to follow the wood material flow any further, because in the secondary forest industries the ingredients of wood become so mixed with different non-wood ingredients that it would demand a special analysis to identify the fractions of wood-based materials. Therefore the analysis is continued by taking into account the most important flows of the non-wood materials. Also the rest of the wood material flow chart is left schematical in figure 8.

Material balances in the pulp and paper industries

The analysis concerning the total flows of materials in the forest industries is restricted to the pulp and paper industries because their input and output flows of materials are measured either directly in mass units or in units which are easily convertible to mass units. With respect to the other primary forest industries, such as plywood, veneer, particle board industries, and also the sawmill industry, the output flows of the products are measured in volumetric units which are difficult to be converted into units of mass because in addition to wood material these products include various amounts of different nonwood materials (e.g. glues and different protective chemicals).

Similarly, in the secondary forest industries, except the paper and board industries, present raw material and product statistics use a variety of measurement units (e.g. m^2, m, unit number, etc.) which cannot be made commensurable because the conversion factors are not known.

The basic data for this material balance analysis was taken from the Industrial Statistics of Finland. Based on the principle of materials conservation the mass of

all input materials to a process should be equal to the mass of all output materials from that process. In the following, the mass of all raw materials identified in the Industrial Statistics is compared with the corresponding mass of products. The comparison is made by forest industry groups for six different years (1968—1973) which are comparable relatively well with respect to the statistical data base. The classification of pulp and paper industries, as reported in the Industrial Statistics during the study period, corresponds to the International Standard Industrial Classification (ISIC).

The raw materials identified in the statistics include the materials and semi-products which have a market value. The output materials from the different industry groups, as identified in the statistics, include all the primary and secondary products and also the most important recovered waste materials. Because no process is 100 per cent efficient the mass of the raw materials should be greater than the mass of the products and recovered materials in all industrial groups, the difference between these two indicating the amount of materials lost during processing.

There are several uncertainties which must be kept in mind when considering the results of this analysis. The *first* uncertainty concerns the reliability of the conversion factors. The amounts of roundwood and wood residuals measured in cubic metres in the statistics were converted into tons of dry matter using the average conversion factors calculated by forest industry groups for 1972. When applying these conversion factors (calculated separately for roundwood and wood residuals) to other years we assume that the distribution of roundwood and wood residuals by tree species and residual groups remained unchanged during the study period. This assumption does not hold true. But for the purpose of this study these conversion factors are considered sufficiently reliable.

Second, the statistics probably do not identify all the materials which have been recovered. This may be especially true regarding materials which have been recovered for use within the originating plant. Furthermore, the mass of the pulp and paper as reported in the statistics includes a small water content. The statistics probably include also a small amount of double counting with respect to some material. These uncertainties may, in fact, cancel each other to some degree.

Third, there is a varying amount of missing information in the statistical data concerning the physical quantities of identified raw materials, products and recovered residuals, which are thus reported only in monetary terms. Finally, there is the question of the overall reliability of the quantity figures as reported in the Industrial Statistics. Comparisons made between the physical quantities and corresponding monetary values revealed a good consistency, except in a few cases. In practice it is almost impossible to evaluate the overall reliability of these statistics without special studies.

The results of the material balance analysis in the different pulp and paper industry groups and in the fibreboard industry are presented in figures 10 to 13. In these figures the mass of the identified outputs is presented as the percentage of the mass of the inputs so that the difference between the raw material and production histograms immediately indicates the percentage of the mass of the raw materials lost in the industrial process in question. The figures also present the proportions of the most important groups of the domestic and imported raw materials, products and recovered residuals.

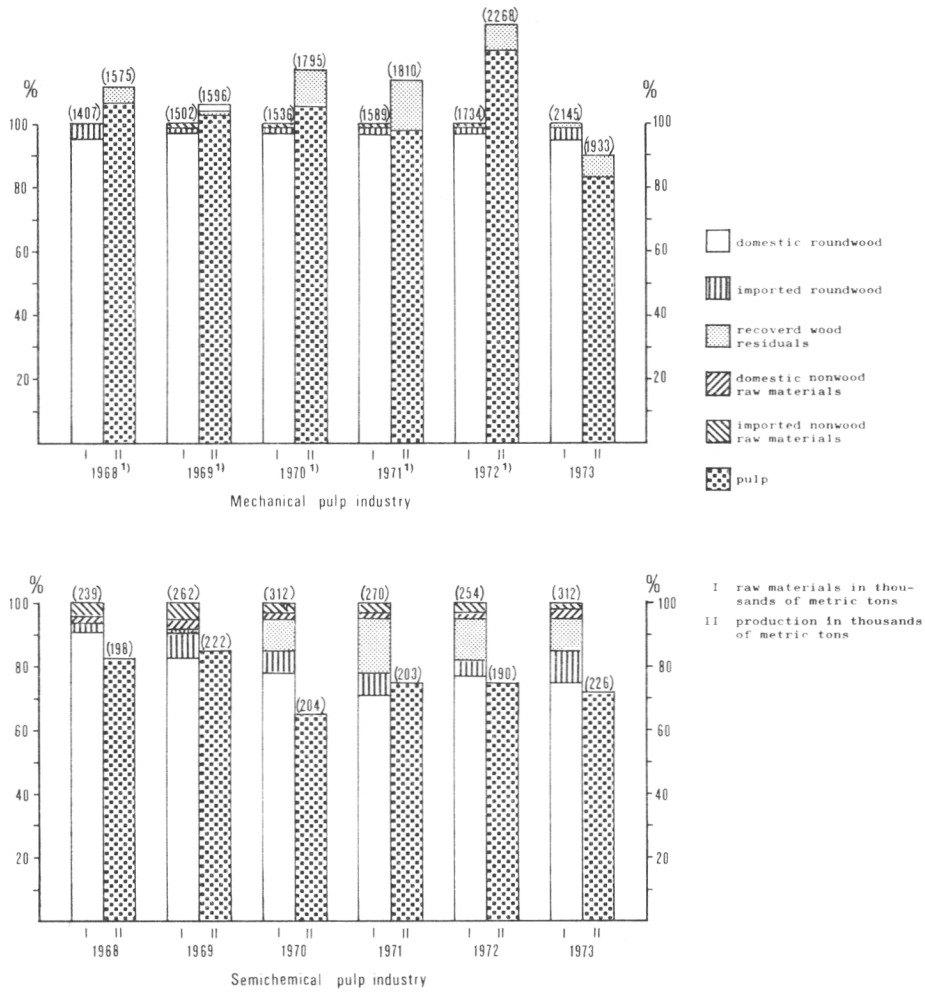


Fig. 10. Material balances in the mechanical and semichemical pulp industries, 1968—1973. (Roundwood in dry matter weight with bark, wood residuals in dry matter weight, fraction of bark unknown; other materials as measured in the Industrial Statistics.)

1) The reason for the production being larger than the raw materials is due to some unidentified errors in the statistical data base.

In the mechanical pulp industry, the results systematically show the mass of the production to be larger than the mass of the raw materials for all years except 1973. There are, therefore, some unidentified errors in the statistics for this industry group.

In the other pulp industry groups, the proportion of the non-wood inputs, such as chemicals, of the total mass of the raw materials has been greatest (about 15 %) in the sulphite pulp industry and smallest (about 5 %) in the semichemical pulp industry. The sulphite and sulphate pulp industries have also produced a considerable

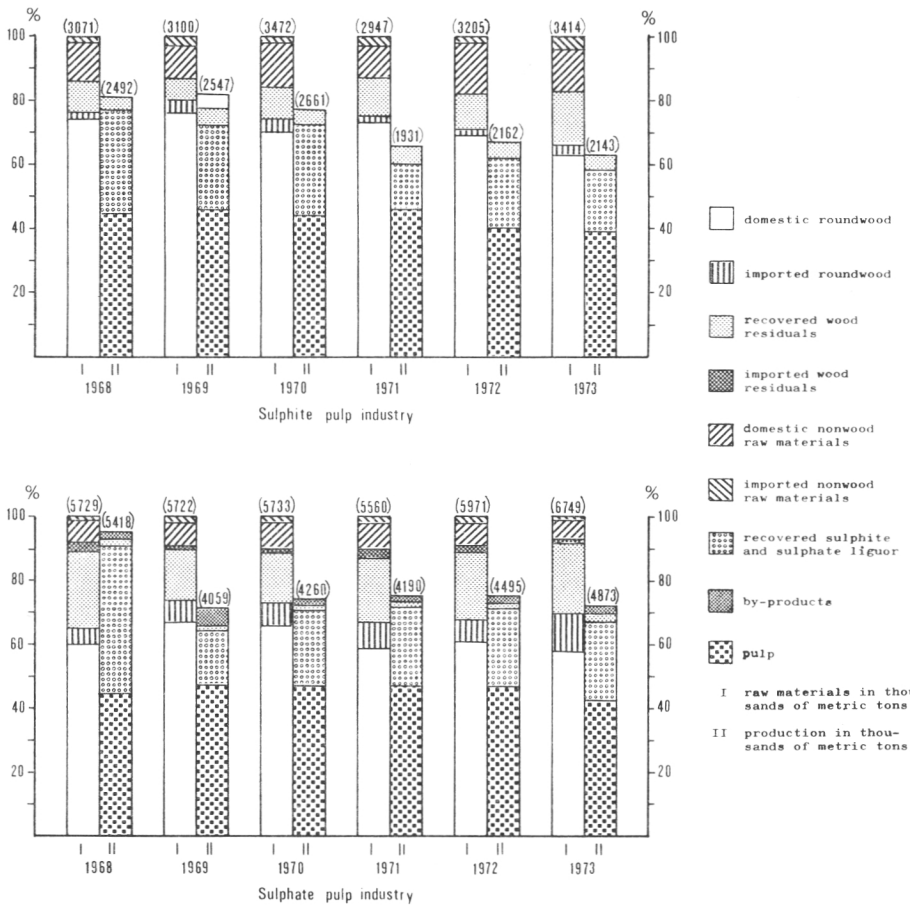


Fig. 11. Material balances in the sulphite and sulphate pulp industries, 1968—1973. (Roundwood in dry matter weight with bark; wood residuals in dry matter weight, fraction of bark unknown; other materials as measured in the Industrial Statistics.)

amount of recovered waste materials and secondary products which mainly include recovered waste liquors and wood residuals. These materials account for about 40 % of the total production.

In the paper industry group, the nonfibre inputs account for about 10 % of the total mass of the raw materials. In the paperboard industry group, the corresponding fraction is under 10 %.

The comparison between the total mass of the raw materials and the total mass of the production reveals considerable unidentified material losses in all industry groups. In the paper and paperboard industries the material losses are found to be considerably smaller than in the pulp industries. Rather large year-to-year variations in the proportional share of the material losses were found in most industrial groups.

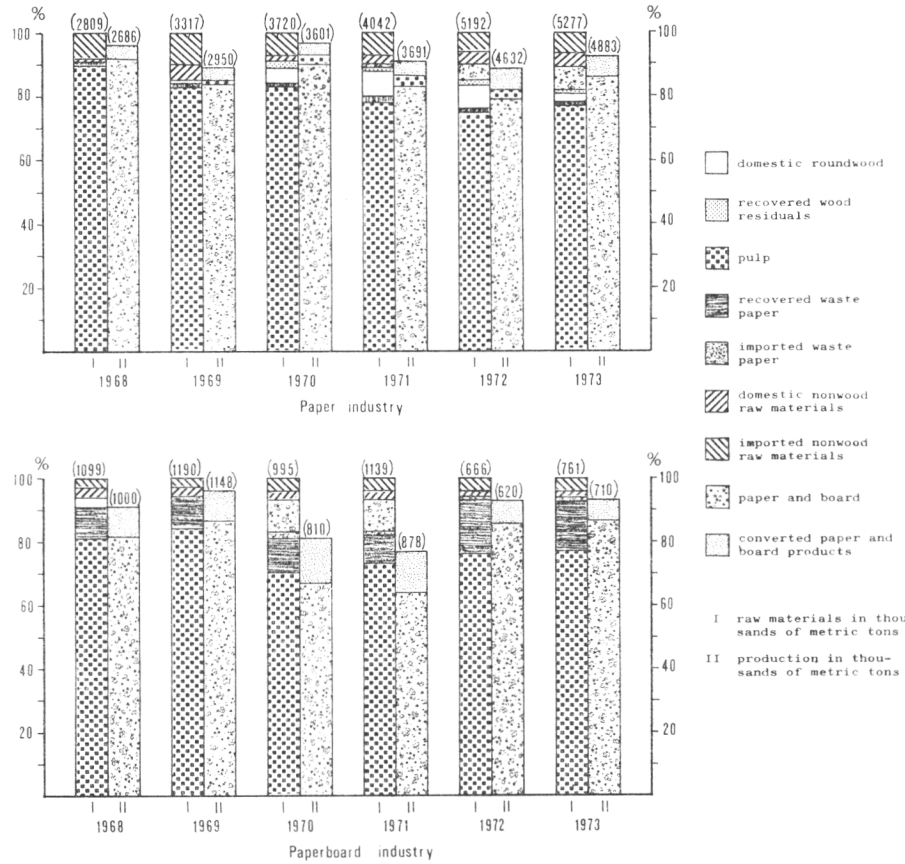


Fig. 12. Material balances in the paper and paperboard industries, 1968—1973. (Roundwood in dry matter weight with bark; wood residuals in dry matter weight, fraction of bark unknown; other materials as measured in the Industrial Statistics.)

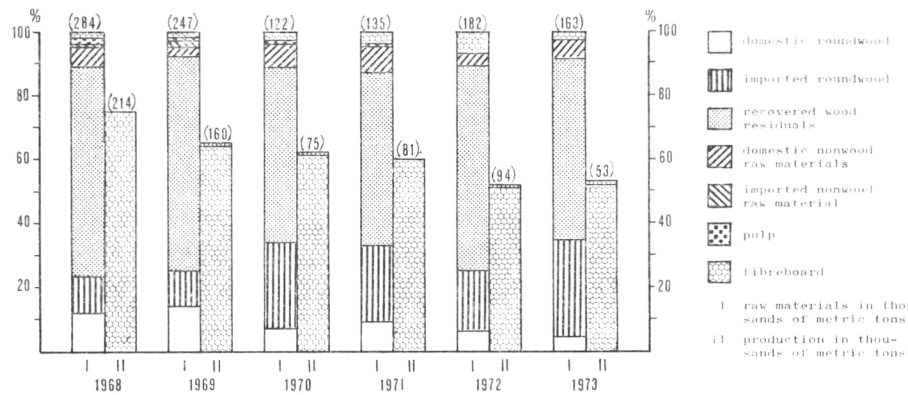


Fig. 13. Material balances in the fibreboard industry, 1968—1973. (Rounwood in dry matter weight with bark; wood residuals in dry matter weight, fraction of bark unknown; other materials as measured in the Industrial Statistics).

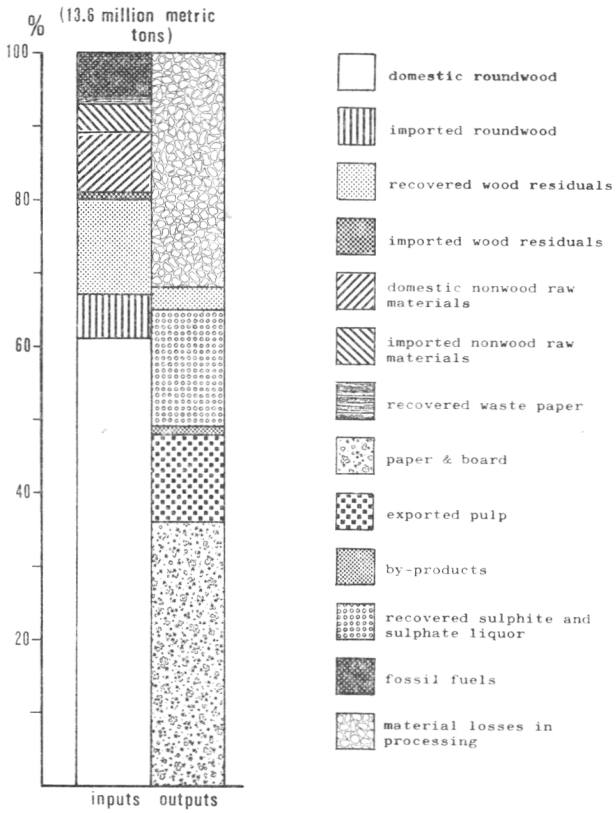


Fig. 14. Estimated material balance in the pulp and paper industries in 1972. (Roundwood in dry matter weight with bark; wood residuals in dry matter weight, fraction of bark unknown; other materials as measured in the Industrial Statistics.)

How much of these variations is based on the real variations in the industrial processes and how much is based on the deficiencies of the statistical data is an open question which cannot be studied here.

On average, the estimated material losses during processing have been as follows during the study period: 24 % in the semipulp industry, 28 % in the sulphite pulp industry, 23 % in the sulphate pulp industry, 8 % in the paper industry, and 13 % in the paperboard industry.

The fuels which were bought and consumed by the pulp and paper industries in 1972 belong to the total material balance of these industry groups. The pulp and paper industries consumed the following amounts of fossil fuels in 1972 (Industrial Statistics 1972):

mechanical pulp industry	4 000 tons
sulphite pulp industry	21 000 tons
sulphate pulp industry	418 000 tons
paper industry	266 000 tons
board industry	30 000 tons
Altogether	739 000 tons

These figures are probably underestimates of the actual consumption figures. This is because in same cases, where the pulp and/or paper mill or the whole industry complex has a power plant of its own, the fuel consumption of this power plant for producing energy for different establishments is not included in the fuel consumption figures of these establishments as recorded in the Industrial Statistics. This missing fuel consumption in the different industry groups cannot be quantified without special studies.

The estimated total material balance (including the fuels) in the pulp and paper industries in 1972 is presented in figure 14. This figure is based on the assumption that the amount of pulp which was used for domestic paper and board production in 1972 roughly corresponded to the amount of pulp which was produced for this purpose during the same year.

Energy and fuel consumption in the forest industries

The extension of the material balance analysis to energy balances and energy residuals is straightforward in concept but would involve substantial data problems in application, and is therefore left outside the scope of this report. This illustrative case study is restricted to the analysis of the consumption of energy and fuels in the industrial part of the forest and timber economy.

In the forest industries there is a unique relationship between the principal raw material and the power needed to process it: the same renewable wood material can be used both as a raw material and as a fuel. The supply of non-renewable fossil fuels at cheap prices has discouraged the use of wood as a fuel, whilst increasing power requirements have created the technology for generating power from recovered processing residuals. The recent price increases of imported fossil fuels have initiated studies which take a fresh look at the potential wood resources as a source of energy (e.g. K u u s e l a 1974 and 1977). Should prices of fossil fuels increase markedly relative to the prices of wood and wood products the use of wood for fuel purposes becomes economically more feasible.

From the materials balance point of view, the generation of useful energy from fuels generates different residuals formed by the material components of the fuel in question. In the total material balances of the forest industries any substitution of industrial wood material for fossil fuels means a reduction in the total amount of

Table 1. Total production and consumption of energy in Finland in 1973, by source and sector (Suomen energiahuolto . . . 1974, p. 37). Mtoe = million equivalent oil tons

	Production of energy					
	Hydro power	Wood, waste liqours	Peat	Coal	Oil	Import of electricity
	Mtoe					
Forest industry	—	2,00	0,05	0,35	2,11	—
Other industries	—	0,15	—	0,59	1,84	—
Other sectors of the economy	2,56	1,84	0,02	1,15	8,84	1,08
Altogether	2,56	3,99	0,07	2,09	12,79	1,08

	Use of energy sources				Altogether including the use of electricity and the share of oil refining industry	
	Altogether		For production of electricity	For production of heat		
	Mtoe	%	Mtoe		Mtoe	%
Forest industry	4,51	20	0,61	3,90	6,73	30
Other industries	2,58	11	0,08	2,50	4,27	19
Other sectors of the economy	15,49	69	5,50	9,99	11,58	51
Altogether	22,58	100	6,19	16,39	22,58	100

material throughput and generation of residuals in these industries. Furthermore, the residuals generated from the combustion of wood are environmentally less harmful than the corresponding residuals from the combustion of fossil fuels. Finally, wood combustion residuals include different nutrients which can be returned to the forests as fertilizers.

Table 1 presents the total production and consumption of energy in the Finnish economy in 1973 by energy sources and sectors, as estimated by Energiapolitiikan neuvottelukunta (Suomen energiahuolto . . . 1974). In this table the final column presents the estimated direct and indirect energy consumption by sectors, calculated by dividing the fuels used for electricity production among sectors in proportion to their consumption of electricity and the oil consumption of oil refineries in proportion to the use of oil in different sectors. According to these estimates, the forest industries consumed about 30 % of the total energy produced in Finland in 1973. The most important fuel sources inside the forest industry group were oil (47 %) and wood and different wood derivatives including sulphite and sulphate waste liquors (44 %).

Table 2 presents figures of the direct consumption of energy, in the form of electricity, steam and hot water, by forest industry groups in 1968 and 1972. The fuel energy used in the forest industries, by industrial ISIC-groups, is presented in table 3. In this table, the different fuels are made commensurable according to their combustion values by converting them into joules employing general conversion

Table 2. Consumption of energy in the forest industry in 1968 and 1972, by industry group (Industrial Statistics 1968 and 1972). TJ = 10^{12}J.

Industry Group	Electricity				Steam & hot water				Altogether			
	1968		1972		1968		1972		1968		1972	
	TJ	%	TJ	%	TJ	%	TJ	%	TJ	%	TJ	%
Manufacture of wood and wood products	1 499	6	2 596	7	7 700	8	11 280	11	9 199	8	13 876	9
— Sawmills & planing mills	687	3	984	3	2 257	2	3 856	4	2 944	3	4 840	3
— Plywood & veneer mills	448	2	616	2	4 384	5	4 422	4	4 832	4	5 038	4
— Particle board mills	163	1	381	1	620	1	1 047	1	783	1	1 428	1
— Manufacture of furniture	151	0	159	0	305	0	268	0	456	0	427	0
— Other	50	0	456	1	134	0	1 687	2	184	0	2 143	1
Manufacture of pulp, paper and paper products	25 260	94	34 384	93	83 979	92	95 786	89	109 239	92	130 170	91
— Mechanical pulp mills	6 352	24	8 332	22	235	0	264	0	6 587	6	8 596	6
— Semichemical pulp mills	260	1	281	1	745	1	754	1	1 005	1	1 035	1
— Sulphite pulp mills	2 989	11	2 839	8	15 722	17	14 499	13	18 711	16	17 338	12
— Sulphate pulp mills	5 221	20	6 574	18	31 629	35	35 422	33	36 850	31	41 996	29
— Paper mills	6 779	25	14 223	38	21 144	23	38 646	36	27 923	24	52 869	37
— Paperboard mills	3 027	11	1 532	4	11 828	13	4 480	4	14 855	12	6 012	4
— Fibreboard mills	532	2	314	1	2 144	2	1 093	1	2 676	2	1 407	1
— Other	100	0	289	1	532	1	628	1	632	0	917	1
Forest industry altogether	26 759	100	36 980	100	91 679	100	107 066	100	118 438	100	144 046	100
Factory industry altogether	40 317		57 810		136 191		145 490		176 508		203 300	

Table 3. Consumption of fuels in the forest industry in 1968 and 1972, by industry group (Industrial Statistics 1968 and 1972). TJ = 10^{12}J.

Industry group	Consumption of fuels			
	1968		1972	
	TJ	%	TJ	%
Manufacture of wood and wood products	4 605	14	7 465	13
— Sawmills & planing mills	2 102	6	2 567	5
— Plywood & veneer mills	1 390	4	2 759	5
— Particle board mills	205	1	812	1
— Manufacture of furniture	720	2	666	1
— Other	188	1	661	1
Manufacture of pulp, paper and paper products	28 532	86	48 634	87
— Mechanical pulp mills	167	0	238	0
— Semichemical pulp mills	4	0	356	1
— Sulphite pulp mills	4 229	13	5 024	9
— Sulphate pulp mills	20 930	63	31 574	56
— Paper mills	1 842	6	9 324	17
— Paperboard mills	992	3	1 231	2
— Fibreboard mills	8	0	385	1
— Other	360	1	502	1
Forest industry altogether	33 137	100	56 099	100
Factory industry altogether	106 676		148 639	

factors (Industrial Statistics 1972, volume 1, p. 21). The fuel consumption figures as recorded in the Industrial Statistics are understimates because of the reason explained above (see p. 58).

In figure 15, the fuel consumption figures from 1968 to 1973, have been broken down by fuel type and industrial group. The forest industries presented in this figure cover over 95 % of the direct consumption of fuels in the whole forest industry sector. Although the absolute consumption figures are probably underestimates in some industry groups, this does not necessarily significantly alter the percentage proportions of different fuel types. The mechanical pulp industry, the sawmill and planing as well as the plywood and veneer industries have covered a considerable part of their fuel requirements with wood and wood residuals. The sulphate and sulphite industries have covered the major part of their fuel requirements by using recovered cooking liquors.

Figure 16 presents the energy use in the forest industries as a whole in 1973, as estimated by EKONO, the Association for Power and Fuel Economy (H u l t i n & K i r v e l ä 1975). According to this estimate, the energy generated from the different processing residuals represented approximately 30 % of the total energy consumption of the forest industry in 1973.

A more detailed analysis of energy use in the forest industries — let alone energy balances and energy residuals — would require data which is not readily available

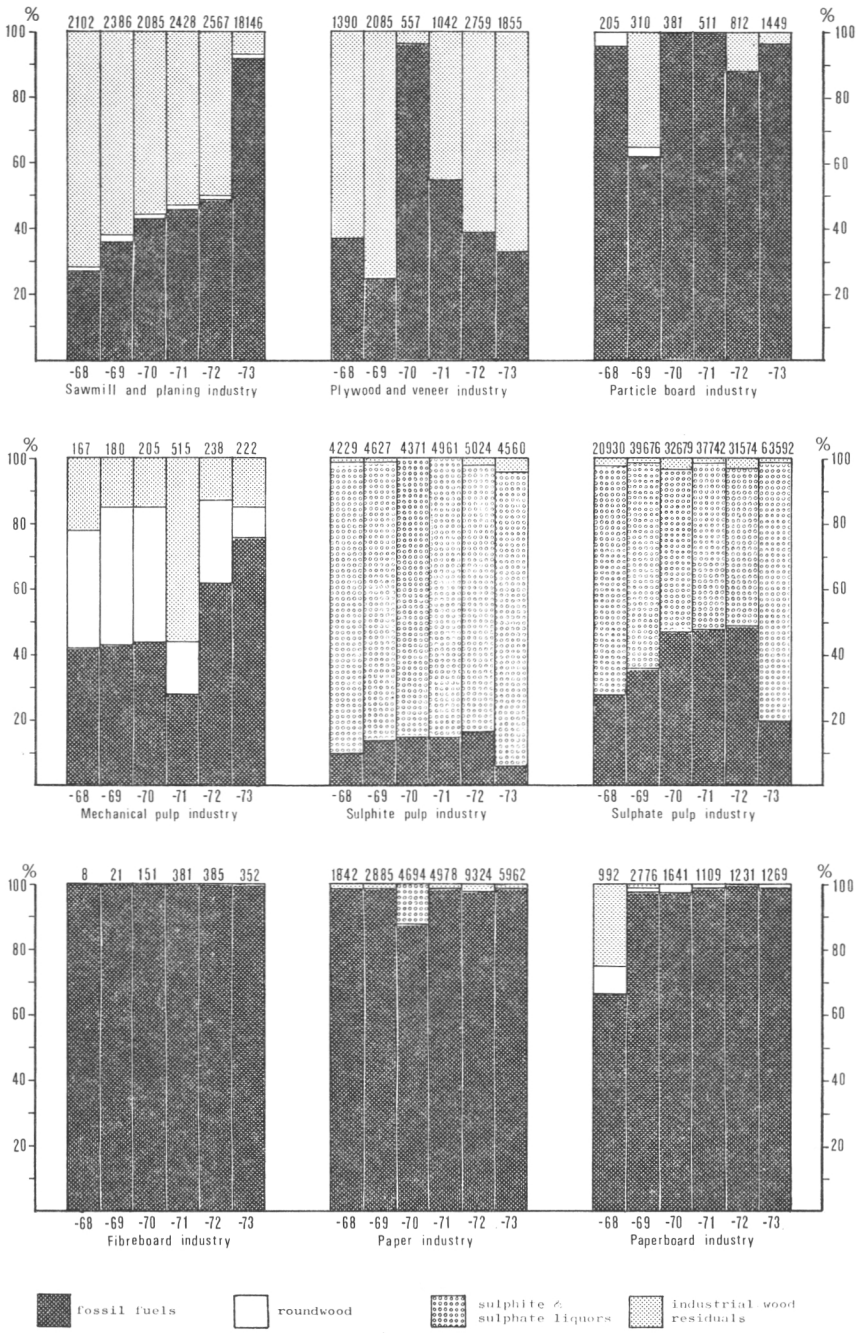


Fig. 15. Fuel consumption (TJ = 10^{12}J) in some forest industry groups, 1968—1973, by fuel type.

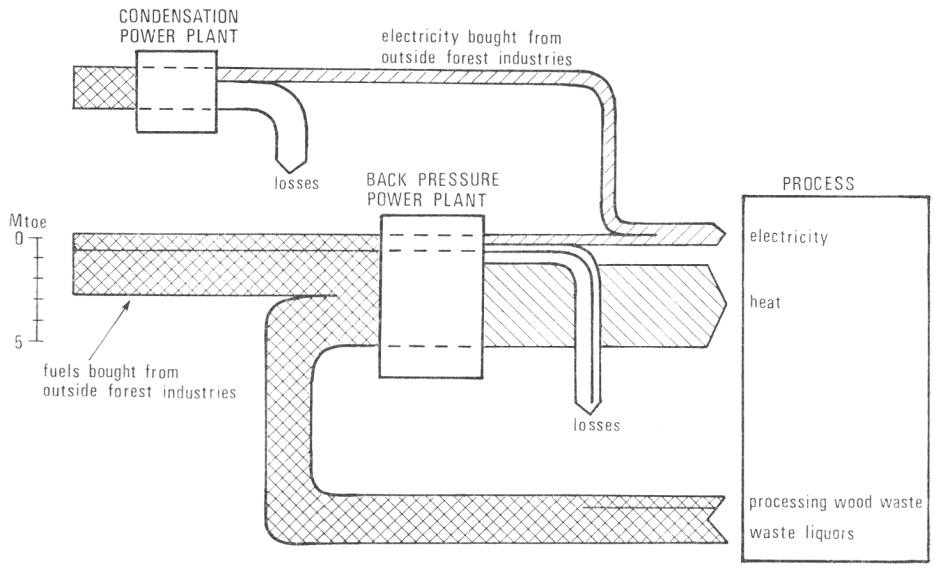


Fig. 16. Estimated energy balance in the forest industries in 1973 (H u l t i n & K i r v e l ä 1975). Mtoe = million equivalent oil tons.

in the present statistics. A more comprehensive study would, for example, require measures of efficiency of conversion of one form of energy to another, and of efficiency of applying energy to perform useful work. The description of the system relationships would also require data concerning intersectoral or interindustrial energy transfers. Such information would provide measures of total energy consumption in different sectors or industries, by adding indirect energy use to the direct one which is already recorded in the statistics for the most part. (Cf. C u n n i n g h a m 1974).

Material efficiency of the forest industries

Forest ecosystems produce a certain amount of wood biomass annually. Starting from the amount of wood biomass which is available on the ecologically sustained yield basis the material efficiency of the forest industries is the better the smaller the amount of biomass lost during the processing. This kind of physical efficiency depends on the product and on the processing technology used in manufacturing it.

Different physical input/output ratios were studied earlier. To further study the level and development of engineering efficiency in the forest industries, some general wood raw material/product ratios for the most important groups of the primary forest industries from 1955 to 1973 have been calculated. These ratios are presented

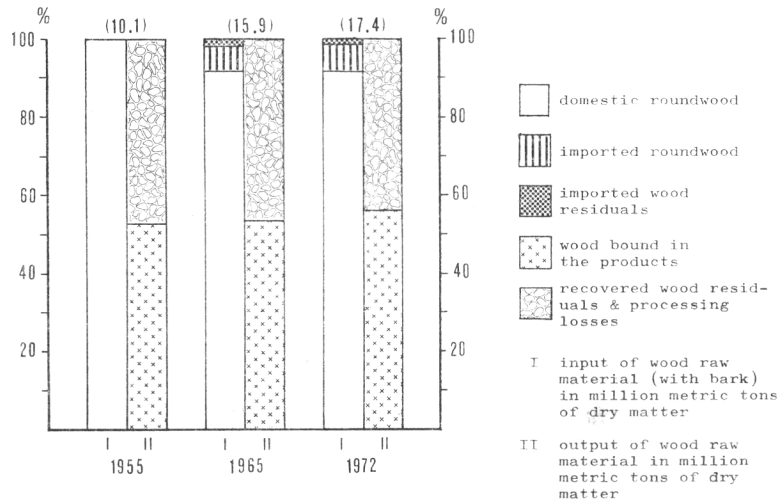


Fig. 17. Estimated wood material balances (excl. fuelwood) in the primary forest industries in 1955, 1965 and 1972.

in table 4 and they are based on the raw material and production statistics as given by the Yearbook of Forest Statistics. According to these approximate »wood consumption» figures the efficiency of the utilization of wood raw material has clearly improved in the particle board and fibreboard industries and remained rather constant in all the other primary forest industries. Although the material efficiency has stayed rather constant in most industry groups when studied separately, the efficiency of the whole primary forest industry may have improved because of the better integration of these industries in the use of wood raw material.

To obtain an idea of the efficiency of wood raw material utilization in the primary forest industries the proportion of wood raw material bound in the final products of these industries as a whole in 1955, 1965 and 1972 has been calculated. For this calculation, the wood raw material and wood product figures were converted into tons of dry matter according to the principles explained on pages 47 and 50. The results of the calculation are presented in figure 17. The slight increase in the proportion of wood raw material which was bound in the products during the study period is due to the increasing efficiency in using the processing residuals of wood inside this industrial group.

The use of energy is concerned with engineering efficiency. In any process the smaller the amount of energy needed to produce a given output the more efficient is that process with respect to the use of energy. Some energy consumption ratios calculated per unit of raw material used and per unit of final product produced by the different forest industry groups in 1968, 1970 and 1972 are presented in table 5.

Table 4. Wood raw material/product ratios and the percentages of industrial wood residuals from the wood raw material, 1955—1975, by industry group.

Industry group	Measurement units[1]	1955		1960		1965		1970		1971		1972		1973	
			Resid. %		Resid. %		Resid. %		Resid. %		Resid. %		Resid. %		Resid. %
Sawmills	m^3/m^3	2,0	—	2,0	—	2,2	—	2,3	—	2,3	—	2,2	—	2,2	—
Particle board mills	m^3/m^3	—	—	2,1	26	1,7	20	1,6	35	1,4	41	1,2	44	1,3	50
Plywood and veneer mills	m^3/m^3	4,0	—	2,8	—	3,2	—	3,2	—	3,3	—	3,2	—	2,9	—
Fibreboard mills	m^3/t	3,4	63	3,2	61	3,3	62	2,6	73	2,5	69	2,5	72	2,7	75
Pulp mills altogether	m^3/t	4,7	9	4,5	12	4,5	16	4,5	17	4,4	19	4,4	18	4,4	19
— mechanical pulp mills	m^3/t							2,8	—	2 8	—	2,8	1	2,8	2
— semichemical pulp mills	m^3/t							2,9	11	2,9	13	2,9	16	2,5	8
— sulphite pulp mills	m^3/t							5,7	10	5,5	12	5,5	13	5,5	16
— sulphate pulp mills	m^3/t							5,2	25	5,1	29	5,1	27	5,3	27

[1]) Roundwood solid volume with bark; wood residuals solid volume, proportion of bark unknown.

Table 5. Ratios of energy consumption to raw materials and main products in some forest industry groups in 1968, 1970 and 1972. TJ = 10^{12}J.

Industry group	1968		1970		1972	
	TJ/thousands of tons of raw materials	TJ/thousands of tons of products	TJ/thousands of tons of raw materials	TJ/thousands of tons of products	TJ/thousands of tons of raw materials	TJ/thousands of tons of products
Sawmills and planing mills	0,6	1,3	0,6	1,3	0,8	1,7
Plywood and veneer mills	5,2	15,8	4,4	15,6	3,7	14,7
Particle board mills	3,6	6,1	3,3	6,2	3,2	5,4
Fibreboard mills	9,4	12,5	9,4	15,2	7,7	15,2
Mechanical pulp mills	4,7	4,4 [1])	4,8	4,6 [1])	4,9	4,0 [1])
Semichemical pulp mills	4,2	5,1	3,5	5,3	4,1	5,4
Sulphite pulp mills	6,1	13,5	5,7	13,1	5,4	13,2
Sulphate pulp mills	6,4	14,3	7,4	15,7	7,0	15,0
Paper mills	9,9	10,3	10,0	10,4	10,2	11,4
Paperboard mills	13,5	14,8	11,4	14,0	9,0	9,7

[1]) The reason for the energy consumption per products being smaller than the energy consumption per raw materials is due to some unidentified errors in the statistical data base (cf. page 54).

Energy consumption here includes only the direct use of energy in the form of electricity and the use of steam and hot water. The raw materials include all the materials identified in the Industrial Statistics. The final products, from the same source, include the principal products produced by the industry group in question.

Because of technological variations from one industry to another, the energy consumption figures do not show the actual energy use efficiency. This kind of information is useful, however, when planning the internal structure of the forest industry; the more energy intensive the process the more sensitive it is to any disturbances in energy supply. Many industrial processes use energy which is generated from processing residuals. Therefore, for planning purposes it is important to know how much imported energy is required and what are the trade-offs between different potential energy sources (cf. pp. 58—63).

From the materials utilization standpoint, the efficiency of the forest industries can be improved by increasing the efficiency of material use in producing the main products, by recovering additional by-products, and by substituting processing residuals for imported fuels.

In the economic accounting system the output of different forest industries is measured in monetary terms as *value added*, which indicates the contribution of the industry in question to the GNP-value of the whole economy. Measuring the outputs in monetary units and inputs in physical units we can analyse the efficiency of the different industries and industry groups in the following way. In manufacturing, some wood-based products involve larger quantities of material and energy throughputs per unit of value added than do others. The efficiency of the different industrial processes can then be evaluated as follows: the smaller the quantity of raw materials and energy needed to produce a unit of value added, the more efficient the process. Table 6 presents some preliminary value added/raw material and value added/energy consumption ratios for different forest industry groups in 1968, 1970 and 1972. Raw materials include all the input materials identified in the Industrial Statistics. Energy consumption includes only the direct use of energy (electricity, steam and hot water) in different industry groups.

In principle, the efficiency of forest industries as a whole can be improved if their structural composition is changed so that the industries involving small material and energy throughputs per unit of value added increase their production while the industries involving large throughputs decrease their production. This means that either the same GNP-value can be produced with a smaller amount of material and energy inputs or the bigger GNP-value may be achieved with the same amount of these inputs. Correspondingly, the manufacturing of some wood-based products generates larger quantities of polluting residuals per unit of value added than does the manufacturing of others. Thus the overall load of these polluting residuals can be reduced without necessarily affecting the total GNP-value if the internal structure of the forest industries is altered in a suitable way.

Table 6. Ratios of output to raw materials and energy in some forest industry groups in 1968, 1970 and 1972. TJ = 10^{12} J.

Industry group	Value added[1])/raw material consumption			Value added[1])/energy consumption		
	1000 Fmk/1000 tons			1000 Fmk/TJ		
	1968	1970	1972	1968	1970	1972
Sawmills and planing mills	58	66	70	97	116	90
Plywood and veneer mills	189	186	202	36	43	54
Particle board mills	131	136	114	37	42	36
Fibreboard mills	137	207	195	15	22	25
Mechanical pulp mills	28	32	33	6	6	7
Semichemical pulp mills	18	11	15	4	3	4
Sulphite pulp mills	51	86	61	8	15	11
Sulphate pulp mills	53	92	78	8	12	11
Paper mills	174	193	149	18	19	15
Paperboard mills	193	136	214	14	12	24

[1]) Value added at current prices

It is not easy to carry out this kind of reorganization in practice. There are various restrictions set by the physical characteristics of the wood raw material, e.g. small-size pulpwood cannot be used as a raw material in producing certain qualities of sawnwood. The more efficient use of raw material inputs may conflict with the more efficient use of energy inputs. Structural changes of industry take a very long time and variations in raw material, product and energy prices may change the GNP/physical input ratios, thus changing the ranking of industries. Furthermore, the prevailing market structures set their own limitations.

The above mentioned ways of improving the material efficiency of forest industries and the whole economic system simultaneously are related to the internal material flows of these industries. In addition to more effective utilization of raw materials, fuels and energy, internal recovery of processing residuals, and internal structural changes of the forest industries, the recycling of materials from the consumption stage back to the industrial process offers a powerful way for improving the material efficiency of the forest and timber economy and the whole economic system. In the forest and timber economy, paper products offer the best possibilities for this kind of recycling. In Finland, such recycling possibilities are limited by the fact that the major part of the produced paper is exported.

Palo & Nissilä (1975) carried out a comprehensive study on the waste paper recycling and its economic and ecological prospects. Table 7, which is based on their study, presents the past development in the consumption and recovery of paper and board in Finland. Palo & Nissilä (1975, p. 91) used the estimate that a ton of waste paper equals 2,7—5,6 m^3 of pulpwood (solid volume, with bark) according to which the potential theoretical secondary raw material base offered by waste paper in 1972 equaled 1,6—3,2 million m^3 of pulpwood. This amount was

Table 7. Consumption and recovery of paper and board in Finland, 1950—1973 (Palo & Nissilä 1975, p. 75).

	A. Consumption of paper and board	B. Recyclable fraction (0.85·A)	C. Waste paper recovery	D. Recovery rate (100 · C/A)
	1 000 metric tons			%
1950	167	142	14	8
1955	256	218	38	15
1960	311	264	78	25
1965	435	370	106	24
1970	548	466	140	26
1971	596	507	135	23
1972	676	575	130	19
1973	762	648	149	20

8—15 % of the total amount of domestic roundwood consumed by the pulp industry in the same year. From the potential amount of the theoretically recyclable waste paper only 22,6 % or 0,4—0,7 million equivalent m^3 of pulpwood was actually recovered in 1972. There is thus room for considerable improvement in the use of this potential raw material. The potential recovery possibilities are expanded further by the fact that the same fibres can be recycled many times. According to some estimates, the number of successful repulpings could be six or even higher depending on the process (Palo & Nissilä 1975, p. 87).

The increase in waste paper recovery reduces the need for the virgin wood raw material (when producing a given amount of paper) and thus reduces the stress placed on the forest ecosystems by wood production activities. Recycling also reduces the amount of municipal solid wastes and in this way reduces the costs of waste disposal. Furthermore, calculated per ton of pulp produced, the energy consumption in waste paper recovery and processing has been found to be considerably lower compared with the energy consumption in harvesting and processing virgin pulpwood. According to Berry & Makino (1974) the energy costs per ton of paperboard pulp produced from waste paper were about 50 % lower than the corresponding energy requirements for pulp produced from virgin pulpwood.

However, the effects of waste paper recycling on the residual flows are usually more complex than is apparent at first sight, as waste paper includes only some 60 to 75 per cent by mass of usable pulp. The remainder consists of coatings, fillers, ink, and colour. In reprocessing, the usable pulp is separated from these other materials. In the repulping processes mostly used at present, these other materials usually emerge as solid wastes suspended in the water which has passed through the pulping process. This suspended load may be up to ten times greater than the suspended solids generated by pulping using new pulpwood. Paper recycling therefore involves a combination of reducing one flow of residuals (the pulp component of waste paper) whilst relocating other residual flows. (Freeman et al. 1973, p. 27).

Although the final result may be a positive reduction in the total flow of materials through the economic system, it is useful to remember that almost every action has multiple effects. It is neither easy to trace these effects nor to find out whether their net effect is negative or positive. The material balance approach based on the accounting of physical flows of materials and energy offers a good framework for these kinds of evaluations by preventing one from taking views which are too narrow and partial for analysing the complex relationships between ecosystems and economic systems.

7. DISCUSSION

The study suggests that it would be useful to consider a new complementary statistical information system where the functioning and interactions of economic and ecologic systems can be made *commensurable*. It seems difficult to expand the present economic accounting based on monetary units of measurement to include the functioning of ecosystems; on the other hand it seems possible to expand the ecological materials and energy accounting based on physical units of measurement to include the functionings of both economic and ecologic systems. *The System of Materials and Energy Accounts*, as preliminary outlined in this study, is *not* able to quantify the ecological impacts of economic activity as such, but it is able to help to attain this objective by providing the necessary data base — missing so far — for these kinds of calculations.

The empirical part of the study is a very modest attempt to implement some of the ideas discussed theoretically and to demonstrate how the accounting of physical material flows can be used as a tool for describing and analysing the structure and functioning of an economic system. Whilst numerous empirical results are presented, these must be understood to be primarily of illustrative value. This is because all relate to national aggregates rather than to the regions in which the actual planning and operations concerning the management and use of natural resources as well as natural resource ecosystems would have to be concentrated. The results give also a static, cross-sectional picture about the process the very nature of which is fully dynamic.

Furthermore, a part of the basic statistical data used in this study has been compiled as a by-product of compiling traditional economic data for the economic information system. The quality of such data is not always as good as the quality of the principal economic information. Even so, these exploratory results do yield some useful insights into how an economic system — in this case the forest and timber economy — functions as a material system, how it is linked with ecosystems and why it is important to understand and quantify these linkages.

The empirical work met many problems concerning the availability and quality of basic empirical data. A lot of useful physical data has already been compiled, along with the economic data, but it does *not* offer a sufficient basis for making comprehensive and reliable material and energy balance and flow analyses. The principles of materials and energy conservation are not followed when compiling the present statistics and in consequence the measurement units are inconsistent and material and energy flows which have no market value are not usually recorded at all.

The philosophy of materials accounting implies that the basic data is compiled in units of mass or at least in such measurement units that are easily convertible into mass units. With respect to the production and consumption of wood-based commodities there is a severe lack of this kind of data, e.g. for the goods used in the consumption stage. Therefore it is almost impossible to develop material balance estimates for this part of the forest and timber economy.

With respect to the industrial part of the Finnish economic system, the generation of physical data can be improved by developing the present Industrial Statistics which are prepared by the Central Statistical Office of Finland. This can be done by modifying the basic questionnaire so that the raw material and production data, as reported by each establishment, includes all the physical inputs and outputs. The reporting must, of course, follow the principles of materials conservation, that is, the total mass of the inputs equals the total mass of the outputs. Furthermore, if the origin of input materials and the destination of products and residuals are reported with sufficient accuracy, the material flows can be presented in the form of input-output tables, for example, which include both different ecosystems or their parts and different parts of the economic systems. The data concerning the physical energy flows can be compiled according to the same principles taking into account also the energy degradations as defined by the entropy law.

However, data generation solely through the questionnaire technique can create a serious quality control problem. Even in their present form, the industrial statistics only *assume* a reasonably high level of data quality, as the current procedures for checking quality are rather weak. So far, the checking has been based on temporal consistency tests comparing an establishment's response to the response of earlier years. The Central Statistical Office has also applied some logic tests. As long as the reporting establishments are reasonably honest and careful, these temporal consistency checks may be sufficient as such.

The problems of quality control will probably become more severe if the industrial questionnaire is expanded to the total material balances with a rather detailed description of all input and output flows. First, establishments are being asked to report on items that are normally remote from the information which is needed for every day business operations. Many managers may not have sufficient knowledge of the residuals produced and they may be unable to provide the desired data. Second, the reporting establishments may not be very willing to reveal their process information even under the strictest confidentiality safeguards. Laws and social pressure may force firms to fill out the forms, but these incentives can not assure accurate responses. (Cf. P e s k i n 1972, p. 33).

The data on the physical inputs and outputs of materials and energy as reported by the establishments can be checked only by qualified specialists who have knowledge of the industrial processes concerned. Of course it would become too expensive and time consuming for the Central Statistical Office to have every questionnaire analysed by an engineer. However, this kind of checking might be possible on a sample basis.

Industrial specialists could also develop typical physical input-output ratios for different types of processes and the responses could be compared to these ratios. In cases where the reported ratios differ considerably from the typical ones, the response should be checked by contacting the reporting establishment in question. (Peskin 1972, p. 33).

Finally, the statistical data concerning the physical flows and stocks of materials and energy, and that of the economy should be collected by the same agency. A large official agency such as the Central Statistical Office is experienced in preserving confidentiality and it has the capacity for efficient processing, storing and retrieving large amounts of data. The annual collection of both the physical and economic data should be carried out effectively at one time so that the firms and other reporting units do not become tired of a continuous stream of separate questionnaires and inquiries.

SUMMARY

Man with his cities, industries and communications is a part of the overall global system. After thousands of centuries of his existence on the earth man still cannot claim to have full understanding — let alone control — of his environment and the systems that support his growing economy. Environmental deterioration has been found to be basically a result of the improper functioning of man's economic systems compared with the functioning of the ecosystems.

In order to safeguard the proper functioning of the ecosystems in producing the natural resources which are essential to the quality of life man must understand the functioning of his economic systems in relation to the functioning of the ecosystems. This is not possible unless he is able to make the different ecological and economic processes commensurable with each other.

The economic processes have been usually described and analysed by using monetary values as the only common denominator. This denominator, however, is not applicable to the ecological processes. Accordingly, the present statistical information systems, such as the System of National Accounts, leave some of man's most fundamental dependencies on ecosystems outside the scope of the statistical description. Therefore, there is an obvious need to consider the development of a statistical information system which would view the functioning of man's economic systems as an integrated part of the other systems of nature.

The study was devided into two parts. The purpose of the first part was to define the theoretical framework which could offer a basis for the integrated description of the economic and ecologic processes and starting from this framework to outline some preliminary guidelines for a new statistical information system.

The ecologic processes have been successfully described and analysed by tracing out the flows of matter and energy in the ecosystems. The economic processes are also basically material processes and as such, they are physically linked with the ecological processes by the flows of matter and energy. Although the functioning of the economic system is in many ways different from the functioning of the ecosystem, man's production and consumption activities do also obey the basic physical laws of entropy and the conservation of matter/energy. Based on these laws any economic system can be studied as a material system by means of materials and energy accounting. This opens one way to study the economic and ecologic processes on a commensurable basis by tracing out the matter and energy flows within and between these two types of processes.

Systematic materials and energy accounting could produce information which would help to measure and improve the material and energetic efficiency in the use of the scarce physical resources. Furthermore, this kind of accounting could help to identify and quantify the dynamic physical linkages between the economic systems and ecosystems. It could also help to understand the dependence of these physical inflows and outflows on the different technologies applied in the economic processes.

Preliminary guidelines for a new System of Materials and Energy Accounts were briefly outlined as concerned with basic principles, measurements units, classification of materials and energy, and sector definition. The suggested new information system is not able to quantify the ecological impacts of the economic activity as such, but it is able to help to attain this objective by providing the necessary data base for such kinds of evaluations.

In the empirical part of the study, a material balance model for the Finnish forest and timber economy was developed and existing empirical statistical data was analysed within this model.

From the total cutting quantity of the wood (33,4 million tons of dry matter) in 1972, only the stemwood or approximately 59 % of the wood biomass was actually harvested from the forests. The major part or about 80 % of the harvested wood entered the industrial process. The rest of the wood was for the most part used as fuel wood outside the forest industries. Comparing forest industries' input and output flows one can calculate the percentage of the wood material (incl. bark) which was bound in the main products in different industries. These estimated conversion efficiencies by primary forest industry groups were, in 1972, as follows:

fibre board industry	89 %
mechanical pulp industry	86 %
particle board industry	83 %
semichemical pulp industry	72 %
sawmill industry	48 %
sulphate pulp industry	43 %
sulphite pulp industry	41 %
plywood and veneer industry	32 %

According to the estimated total material balance of the wood in the primary forest industries as a whole in 1972 about 56 % of the used primary wood raw material (incl. bark) was bound into the main products, 28 % was recovered for fuel, and 16 % was lost in the industrial process.

When studying the total material balances (incl. also the nonwood raw materials) in the pulp and paper industries by industrial ISIC-classes it was estimated that on average the annual total material processing losses from 1968 to 1973 were as follows: 24 % in the semichemical pulp industry, 28 % in the sulphite pulp industry, 23 % in the sulphate pulp industry, 8 % in the paper industry and 13 % in the paperboard industry. The estimated total material balance in these industries in 1972 showed that about 49 % of the used raw material was bound in the products, 19 % was recovered in various forms and 32 % was lost in processing.

The forest industries were estimated to have consumed directly and indirectly about 30 % of the energy produced in Finland in 1973. The most important fuel sources inside this industry group were oil (47 %) and wood and different wood derivatives including sulphite and sulphate liquors (44 %).

According to an estimate, the energy generated from the different processing residuals represented approximately 30 % of the total energy consumption of the forest industries in 1973.

The material efficiency of the forest industries can be improved by internal measures related to the more effective utilization of raw materials, fuels and energy, internal recovery of processing residuals, and internal structural changes of the industries. The efficiency can also be considerably improved by external measures, i.e. by recycling the materials from the consumption stage back to the industrial process.

The empirical study pointed out that whilst much useful physical data has been compiled along with the monetary-based data, the present statistics do not offer a sufficient basis for making comprehensive and reliable material and energy balance and flow analyses. From the materials and energy accounting point of view the main drawback is that the principles of materials and energy conservation are not followed when compiling the statistics. Consequently, the physical measurement units are inconsistent and material and energy flows which have no market value are not usually recorded.

REFERENCES

AHMAVAARA, Y. 1969. Yhteiskuntatieteen kyberneettinen metodologia. Helsinki. 301 p. Kustannusosakeyhtiö Tammi.

BERRY, S. R. & MAKINO, H. 1974. Energy Thrift in Packaging and Marketing. Technology Review. February 1974:33—43.

BOULDING, K. E. 1950. A Reconstruction of Economics. John Wiley and Sons, Inc. USA, 311 p.

—»— 1966. The Economics of the Coming Spaceship Earth. In: *Environmental Quality in a Growing Economy*. Ed. by Henry Jarret. Resources for the Future Inc. Baltimore. The John Hopkins Press. p. 3—14.

CUNNINGHAM, J. P. 1974. An Energetic Model Linking Forest Industry and Ecosystems. Seloste: Metsäteollisuuden ja ekosysteemien välisen vuorovaikutuksen energiamalli. Commun. Inst. For. Fenn. 79. 3: 1—51.

—»— 1975. Energy Conservation, Environmental Protection and Forest Policy. In: Symposium of Forests and Wood: Their Role in the Environment. Interlaken (Switzerland) 22—26 September 1975. ECE, FAO. TIM/SEM 4/R. 15. 15 p. Mimeograph.

DAHMÉN, E. 1970. Elintilamme hinta (Alkuperäisteos: Sätt pris på miljön) Sininen Kirja Oy. Tapiola. Oy Weilin+Göös Ab. 2. painos, 110 p.

DYSON, F. J. 1971. Energy in the Universe. In: *Energy and Power*. A Scientific American Book. San Francisco. W. H. Freeman and Company. pp. 17—27.

EHRLICH, P. R., EHRLICH A. H. & HOLDREN J. P. 1973. Human Ecology, Problems and Solutions. San Francisco. W. H. Freeman and Company. 304 p.

FARRINGTON, D. & ALBERTY R. A. 1967. Physical Chemistry. Third edition, second printing. Wiley International Edition. New York. John Wiley and Sons, Inc., 767 p.

FREEMAN III, M. A., HAVEMAN R. H. & KNEESE A. V. 1973. The Economics of Environmental Policy. New York. John Wiley & Sons Inc.

GATES, D. M. 1971. The Flow of Energy in the Biosphere. In: *Energy and Power*. A Scientific American Book. San Francisco. W. H. Freeman and Company. p. 41—52.

GEORGESCU-ROEGEN, N. 1971. The Entropy Law and the Economic Process. Cambridge, Mass.: Harvard University Press. 457 p.

—»— 1976. Energy and Economic Myths. Institutional and Analytical Economic Essays. New York. Pergamon Press Inc. 380 p.

HAKKILA, P. & HEISKANEN V. 1971. Puu teollisuuden raaka-aineena. Puun ja puutavaran ominaisuuksia. *Tapion taskukirja*. Metsä ja puutalousmiesten sekä metsänomistajien käsikirja. 16., uudistettu painos. Keskusmetsälautakunta Tapion julkaisuja. Helsinki. Kirjayhtymä. p. 440—485.

HALL, A. D. & FAGEN, R. E. 1956. Definition of System. Yearbook, Society for the Advancement of General Systems Theory. Vol. 1: 18—28.

HJERPPE, R. 1975. Tutkimus tehokkaan ja optimaalisen allokaation käsitteestä ja tuotannontekijöiden allokaatiosta Suomen kansantaloudessa 1965—1970. Summary: A Study on the Concept of Efficient and Optimal Allocation and the Allocation of Resources in the Finnish Economy 1965—1970. Kansantaloudellisia tutkimuksia XXXIV. Julkaissut Kansantaloudellinen Yhdistys. Economic Studies. Published by the Finnish Economic Association. Helsinki. 214 p.

HJERPPE, R. & NIITAMO O. E. 1971. Uuden SNA:n mukaisen kansantalouden tilinpidon perusrakenne. Tilastokeskus. Tutkimuksia No. 15. Elokuu 1971. 197 p.

HUBBERT, M. K. 1971. The Energy Resources of the Earth. In: *Energy and Power*. A Scientific American Book. San Francisco. W. H. Freeman and Company. p. 29—40.

HUETING, R. 1975. Environmental deterioration, economic growth and national income. Paper prepared for the fourteenth general conference of the international association for research in income and wealth at Aulanko (Finland), August 18—23, 1975. Netherlands Central Bureau of Statistics. Voorburg. 56 p. Mimeograph.

HULTIN, S. O. & KIRVELÄ, K. 1975. Teollisuuden energiatalouden kehitysnäkymät. Alustus the Finnish Pugwash Committeen energiaseminaarissa Helsingissä 5. 5. 1975. Mimeograph. 5 p.

HUTTUNEN, T. 1974a. Suomen sahateollisuus vuonna 1972. Summary: The sawmill industry in Finland in 1972. Folia For. 193: 1—35.

—»— 1974b. Suomen puunkäyttö, poistuma ja metsätase vuosina 1972—74. Summary: Wood consumption, total drain and forest balance in Finland in 1972—74. Folia For. 219: 1—49.

IFIAS 1974. Energy Analysis. Workshop report. Report No. 6. Stockholm. 89 p.

—»— 1975. Workshop on Energy Analysis and Economics. Workshop report. International Federation of Institutes for Advanced Study. Lidingö, Sweden. June 22—27, 1975. Stockholm. 103 p.

Industrial Statistics. Official Statistics of Finland XVIII A: 93. (Teollisuustilasto. Suomen virallinen tilasto XVIII A: 93). Central Statistical Office of Finland (Tilastokeskus). Helsinki. Various years.

KNEESE, A. V., AYRES R. U. & D'ARGE R. C. 1970. Economics and the Environment. A Materials Balance Approach. Resources for the Future Inc. Baltimore. The John Hopkins Press. 120 p.

KUUSELA, K. 1974. Metsäpolitiikan energiapoliittinen tausta. Kansallis-Osake-Pankki. Taloudellinen katsaus 3: 3—8.

—»— 1977. Puun asema muuttuvassa raaka-aine- ja energiastrategiassa. Kansallis-Osake-Pankki. Taloudellinen katsaus 3: 14—19.

LAIHONEN, A. 1972. Ympäristötilastollisen tietojärjestelmän kehikko. Tilastokeskus. Tutkimuksia No. 20. Joulukuu 1972. 120 p.

LIPSEY, R. G. 1966. An Introduction to Positive Economics. Second Edition. London. Weidenfeld and Nicolson. 874 p.

MALASKA, P. 1972. Towards Engineering Conclusions in Human Problems of Environment. Turun Kauppakorkeakoulun Julkaisuja. Sarja B I 1972 (2): 1—20.

MARSHALL, A. 1920. Principles of Economics. Ninth (variorum) Edition with annotations by C. W. Guillebaud. Volume I. Text. London. Macmillan and Co Limited 1961. 858 p.

NIITAMO, O. E. 1970. SNA:n rakenteeseen liittyvistä ongelmista ja puutteista. Kansantaloudellinen Aikakauskirja (The Finnish Economic Journal) 3: 181—197. Helsinki. Kansantaloudellinen Yhdistys.

ODUM, E. P. 1971. Fundamentals of Ecology. Third edition. Philadelphia. W. B. Saunders Company. 574 p.

ODUM, H. T. 1971. Environment, Power, and Society. Wiley- Interscience. New York. A Division of John Wiley & Sons Inc. 331 p.

OECD. Economics and Statistics Department 1971. Environment and Growth in National Accounts. DES/NI/70.3 (Rev.) Paris 22. 4. 1971. Working document. Mimeograph.

PALO, M. & NISSILÄ O. 1975. Waste Paper Recycling: Economic and Ecological Prospects. Seloste: Keräyspaperin käytön ekonomiset ja ekologiset perusteet ja mahdollisuudet. Commun. Inst. For. Fenn. 82. 5: 1—112.

PESKIN, H. M. 1972. National Accounting and the Environment. Statistisk Sentralbyrå. Artikler 50: 1—60. Oslo H. Aschehough & Co.

PULLIAINEN, K. 1972. Taloudellisen kasvun ekologinen kritiikki. Summary: An Ecological Critique of Economic Growth. Kansantaloudellinen Aikakauskirja (The Finnish Economic Journal) 2: 111—123. Helsinki. Kansantaloudellinen Yhdistys.

—»— 1975. Nollakasvu vai tasapainotalous. Summary: Zero-Growth or a Stationary-State Economy. Kansantaloudellinen Aikakauskirja (The Finnish Economic Journal) 3: 229—239. Helsinki. Kansantaloudellinen Yhdistys.

—»— & SEISKARI P. 1972. Ympäristömme systeemit. Forum-kirjasto. Helsinki. Kustannusosakeyhtiö Tammi. 148 p.

REIFSNYDER, W. E. & LULL H. W. 1965. Radiant Energy in Relation to Forests. Tech. Bull. 1344: 1—111. U. S. Dept. Agriculture, Forest Service.

ROBBINS, L. 1949. An Essey on the Nature & Significance of Economic Science. 2nd edn. London. MacMillan and Co., Limited. 160 p.

SAASTAMOINEN, O. 1978. Luonnonsuojelu ja talousteoria. Summary: Conservation and economic theory. Helsingin Yliopiston maankäytön ekonomian laitos. University of Helsinki. Dept. of Land Use Economics. Julkaisuja. Research Reports 4: 1—89.

SEISKARI, P. 1976. Ihmisen ekologia. Luonnonvaramme ja niiden käyttö. Helsinki. Weilin+Göös. 188 p.

SEPPÄLÄ, R. & VALTANEN H. 1975. Mietteitä metsäsektorista. Metsäntutkimuslaitos. Metsäekonomian tutkimusosasto. Helmikuu 1975. 29 p. Mimeograph.

SCHULTZ, A. M. 1967. The Ecosystem as a Conceptual Tool in the Management of Natural Resources. In: *Ciriacy-Wantrup S. V.&J. J. Parsons (editors). Natural Resources. Quality and Quantity*. Papers presented before a faculty seminar at the University of California, Berkeley, 1961—1965. University of California Press. Berkeley and Los Angeles. p. 139—161.

Suomen energiahuolto vuosina 1975—1985. Energiapolitiikan neuvottelukunnan väliraportti. Komiteanmietintö 1974: 112. Helsinki 1974. 107 p. Mimeograph.

Teollisuuden jäteinventaari. SITRAN tutkimus No. 4008 TA. Loppuraportti 375. 148 p. Mimeograph.

United Nations 1968. A System of National Accounts and Supporting Tables. Studies in Methods Series F, No. 2. Rev. 3. Department of the Economic and Social Affairs, Statistical Office of the United Nations.

United Nations 1971. Basic Principles of the System of Balances of the National Economy. Studies in Methods Series F, No. 17.

United Nations. Economic and Social Council. 1976. Environment Statistics. Draft quidelines for statistics on materials/energy balances. Statistical Commission. Nineteenth session. New Delhi, 8—9 November 1976. E/CN.3/492. 29 March 1976. 33 p. & Annex.

Vuoden 1970 ympäristönsuojelutoimikunnan mietintö I, 1970. Komiteanmietintö 1970: B 25. Helsinki. 72 p. Mimeograph.

Yearbook of Environmental Statistics of Finland 1972. Ympäristötilastollinen vuosikirja 1972. Tilastollisia tiedonantoja, julkaissut Tilastokeskus. 50. Helsinki 1972. 78 p.

Yearbook of forest statistics 1974. Metsätilastollinen vuosikirja 1974. Official statistics of Finland (Suomen virallinen tilasto) XVII A: 7. Metsäntutkimuslaitos. Folia For. 255: 1—214.

SELOSTE

Ihminen kaupunkeineen, teollisuuslaitoksineen ja liikenneyhteyksineen on maapallon kokonaisjärjestelmän osa. Vaikka ihminen on elänyt maapallolla satojatuhansia vuosia, hän ei vieläkään voi väittää ymmärtävänsä täysin ympäristöään ja siihen kuuluvia järjestelmiä, jotka ylläpitävät ihmisen kasvavaa taloutta. Ympäristön pilaantumisen on havaittu olevan pohjimmiltaan ihmisen talouden ekosysteemien lainalaisuuksiin verrattuna virheellisen toiminnan tulos.

Turvatakseen sellaisten ekosysteemien toiminnan, joiden luonnonvarat ovat elämisen laadun kannalta välttämättömiä, ihmisen on ymmärrettävä taloudellisten järjestelmiensä toiminnan yhteydet luonnon muiden järjestelmien toimintaan. Tämä on mahdollista vain jos ekologiset ja taloudelliset toiminnat voidaan yhteismitallistaa.

Taloudellisia toimintoja on tavallisesti kuvattu ja analysoitu käyttäen rahassa mitattua arvoa ainoana yhteismitallistajana. Tätä yhteismitallistajaa ei voida kuitenkaan soveltaa ekologisten toimintojen kuvaamiseen. Niinpä nykyisin käytössä olevat tilastojärjestelmät, kuten kansantalouden tilinpito, jättävät eräitä ihmisen tärkeimpiä riippuvuuksia ekosysteemeistä tilastollisen kuvauksen ulkopuolelle. Siksi on ilmeinen tarve harkita uuden, entisiä tilastojärjestelmiä täydentävän tietojärjestelmän kehittämistä, jossa tarkasteltaisiin ihmisen taloudellisten järjestelmien toimintaa luonnon muiden järjestelmien osana.

Tutkimus jaettiin kahteen osaan. Ensimmäisen osan tarkoituksena oli määritellä sellainen teoreettinen viitekehys, joka tarjoaisi perustan taloudellisten ja ekologisten toimintojen integroidulle tilastolliselle kuvaukselle, sekä hahmotella alustavasti uuden tilastojärjestelmän mahdollista perusrakennetta.

Ekologisia toimintoja on onnistuneesti kuvattu ja analysoitu ekosysteemien aine- ja energiavirtojen avulla. Taloudelliset toiminnat ovat myös pohjimmiltaan materiaalitoimintoja, ja sellaisina ne kytkeytyvät fyysisesti ekologisiin toimintoihin aine- ja energiavirtojen välityksellä. Materiaalitoimintoina ihmisen taloudelliset toiminnat ovat sidottuja noudattamaan aineen ja energian käyttäytymistä määritteleviä fysiikan peruslakeja.

Näitä ovat aineen ja energian häviämättömyyden laki sekä entropian laki. Näihin lakeihin perustuen kaikkia aineen ja energian liikutteluun ja muuntamiseen toimintansa perustavia systeemejä voidaan tutkia materiaalisysteemeinä materiaali- ja energiatilinpidon avulla. Tämä avaa myös erään mahdollisuuden taloudellisten ja ekologisten toimintojen yhteismitalliseen kuvaamiseen.

Systemaattinen materiaali- ja energiatilinpito voisi tuottaa informaatiota, joka auttaisi mittaamaan ja parantamaan niukkojen luonnonvarojen käytön tehokkuutta. Edelleen tällainen tilinpito voisi auttaa määrittämään ja mittaamaan taloudellisten toimintojen ja niiden fyysisen ympäristön välisiä yhteyksiä sekä näiden yhteyksien riippuvuutta taloudellisessa toiminnassa sovellettavista teknologioista.

Uutta, entisiä tilastojärjestelmiä täydentävää materiaali- ja energiatilinpitoon perustuvaa tilastojärjestelmää hahmoteltiin alustavasti sen perusperiaatteiden, mittayksiköiden, aineen ja energian luokittelujen sekä toimintojen määrittelyn osalta. Ehdotetun kaltainen uusi tilastojärjestelmä ei pysty määrittelemään ja mittaamaan taloudellisen toiminnan ekologisia vaikutuksia sinänsä, mutta se pystyy auttamaan tämän päämäärän saavuttamisessa tarjoamalla ajan mittaan tällaisten arviointien suorittamisessa välttämättömän tietoperustan.

Tutkimuksen empiirisessä osassa määriteltiin Suomen metsä- ja puutalouden materiaali- ja energiatilinpidon malli ja nykyisten tilastojärjestelmien tuottamaa empiiristä aineistoa analysoitiin mallin tarjoaman viitekehyksen puitteissa.

Puubiomassan kokonaishakkuumäärä kuorineen oli noin 33,4 miljoonaa kuiva-ainetonnia vuonna 1972. Tästä määrästä vain runkopuu eli noin 59 % korjattiin pois metsästä. Korjatusta puusta noin 80 % meni teollisuuden raaka-aineeksi. Vertaamalla metsäteollisuuden fyysisiä panos- ja tuotosvirtoja voidaan laskea kuinka suuri osa käytetystä kuorellisesta puuraaka-aineesta sitoutuu jalosteisiin eri teollisuusryhmissä. Arvioidut puunkäyttötehokkuudet olivat metsäteollisuudessa seuraavat vuonna 1972: kuitulevyteollisuus 89 %, mekaaninen massateollisuus 86 %, lastulevyteollisuus 83 %, puolikemiallinen massateollisuus 72 %, sahateollisuus 48 %, sulfaattimassateollisuus 43 %, sulfiittimassateollisuus 41 % ja vaneriteollisuus 32 %.

Arvioidun kokonaispuutaseen mukaan ensiasteen metsäteollisuudessa vuonna 1972 noin 56 % käytetystä kuorellisesta puuraaka-aineesta sitoutui jalosteisiin, 28 % poltettiin muodossa tai toisessa energiaksi ja 16 % menetettiin hävikkinä jalostusprosessissa.

Tutkittaessa massa- ja paperiteollisuuden kokonaisainetaseita arvioitiin, että vuosittaiset keskimääräiset aineen jalostushävikit ajanjaksona 1968—1973 olivat seuraavat: 24 % puolikemiallisessa massateollisuudessa, 28 % sulfiittimassateollisuudessa, 23 % sulfaattimassateollisuudessa, 8 % paperiteollisuudessa ja 13 % kartonkiteollisuudessa. Massa- ja paperiteollisuuden arvioidun kokonaisainetaseen mukaan vuonna 1972 noin 49 % käytetyistä raaka-aineista sitoutui jalosteisiin, 19 % käytettiin tavalla tai toisella uudestaan ja 32 % menetettiin hävikkinä jalostusprosessissa. Metsäteollisuus kulutti suoraan ja välillisesti noin 30 % Suomessa 1973 tuotetusta energiasta. Metsäteollisuuden tärkeimmät polttoainelähteet olivat öljy ja sen jalosteet (47 %) ja puu sekä erilaiset puun johdannaiset mukaan lukien sulfiitti- ja sulfaattijäteliemet (44 %).

Metsäteollisuuden aineen ja energian käytön tehokkuutta voidaan parantaa teollisuuden sisäisin toimenpitein, jotka liittyvät raaka-aineiden, polttoaineiden ja muun energian tehokkaampaan hyväksikäyttöön, jalostusprosessijätteiden uudelleenkäyttöön ja metsäteollisuuden sisäisiin rakenteellisiin muutoksiin. Tehokkuutta voidaan parantaa huomattavasti myös metsäteollisuuden ulkoisin toimenpitein kierrättämällä kulutuksesta hylättyjä materiaaleja takaisin teollisuuden raaka- tai polttoaineeksi.

Tutkimus osoitti selvästi, että vaikka suhteellisen runsaasti käyttökelpoista fyysisin mittayksiköin mitattua aineistoa on kerätty rahassa mitatun tilastoaineiston keräämisen yhteydessä, se ei kuitenkaan tarjoa riittävää aineistoperustaa yksityiskohtaisten ja luotettavien materiaali- ja energiavirta ja -taseanalyysien tekoon. Materiaali- ja energiatilinpidon kannalta nykyisten tilastojen suurin puute on seuraava: aineen ja energian häviämättömyyden periaatteita ei noudateta tilastoja kerättäessä ja laadittaessa. Tämän seurauksena käytetyt mittayksiköt ovat kirjavia ja sellaisia aine- ja energiavirtoja, joilla ei ole markkinahintaa, ei ole yleensä otettu lainkaan mukaan.

CUTTING AREAS AS REINDEER PASTURAGE

OLLI SAASTAMOINEN

Seloste

HAKKUUTYÖMAAT POROJEN LAITUMENA

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Wood production and reindeer husbandry are multiple uses of forestry land in Northern Finland. The study concerns the significance of cutting areas as reindeer pasturage. Tree lichens are the principal natural food resource for reindeer when hard snow prevents them digging for ground lichens and other vegetation. Reindeer obtain abundant tree lichens from the felled trees in the cutting areas.
About one tenth of reindeer were pasturing in the cutting areas between January and March during the study period. However, the seasonal and regional differences were large. In the southern part of the reindeer management area the significance of cutting areas as pasturage was largest. An estimate of the number of reindeer killed by falling trees is also given.
The cutting rhythm from the stand point of reindeer husbandry is important. By cutting the tree lichen bearing forests in winter time it is possible to help reindeer's food supply.

Puuntuotanto ja porotalous ovat metsätalouden maan päällekkäisiä moninaiskäyttömuotoja Pohjois-Suomessa. Tutkimus käsittelee erästä puuntuotannon ja porotalouden liittymäkohtaa: hakkuutyömaiden merkitystä porojen laitumena.
Luppo on kovan hangen aikana tärkein poron luontainen ravintovara. Hakkuutyömailla kaadetuista puista porot saavat sitä runsaasti.
Keskimäärin kymmenesosa koko poronhoitoalueen poroista laidunsi tammi—maaliskuussa hakkuutyömailla 1970-luvun puolivälissä. Ajalliset ja alueelliset vaihtelut olivat kuitenkin suuret. Poronhoitoalueen eteläosassa hakkuutyömaiden merkitys laitumena oli suurin. Hakkuutyömailla puiden alle jääneiden porojen määrästä tehtiin karkea arvio.
Hakkuiden ajoitus on porotalouden kannalta tärkeä seikka. Ajoittamalla luppoisten metsien hakkuut talvikauteen voidaan porojen lupon saantia helpottaa.

Helsinki 1978. Valtion painatuskeskus

PREFACE

This report is part of a larger study concerning the significance of old spruce forests from the stand point of reindeer husbandry. The study is being undertaken at the Rovaniemi Research Station of the Finnish Forest Research Institute.

Professors Lauri Heikinheimo, Kullervo Kuusela, Päiviö Riihinen and Dr Eljas Pohtila have commented the manuscript. Dr Paavo Rajala, the Finnish Game and Fisheries Research Institute, has provided me with some unpublished data. Ashley Selby, B.Sc., checked the translation.

The data collection was made possible with the help of foremen of different cutting organizations and by reindeer management associations.

Field work was done by Mr Unto Matinlompolo and Mr Kimmo Leinonen. Miss Johanna Niemelä, Miss Hannele Nivala and Mr Seppo Lohiniva assisted in data compiling.

The Finnish Natural Resource Research Foundation has financially supported the project.

My best thanks.

Rovaniemi, September 1978

Olli Saastamoinen

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1. INTRODUCTION

The reindeer management area of Finland extends deep into the coniferous forest zone. It is estimated that three fourths of all 200 000 reindeer in Finland are pasturing in the coniferous forest zone, which is also intensively used for timber production.

The important role of forest pastures is a typical feature of Finnish reindeer husbandry. In other countries reindeer pasture mostly in the tundra and forest tundra zones and less often in the forest zone (e.g. Vostrjakov 1971, Sulkava & Helle 1972). However, the situation in Sweden is rather similar to Finland (Eriksson 1972). The Finnish reindeer management area, with the forest limits, is shown in Figure 1.

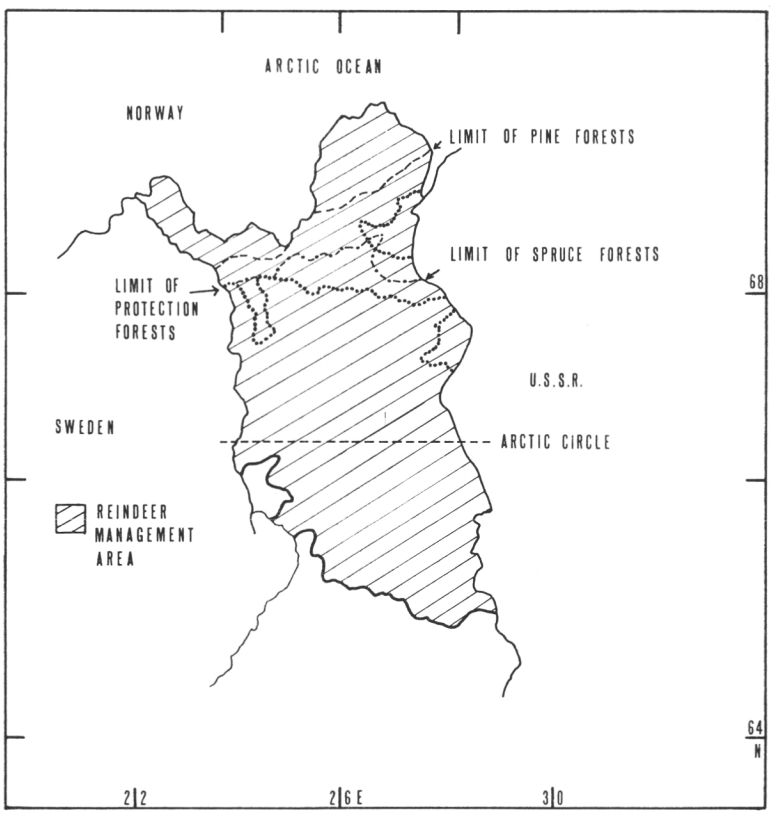


Figure 1. The reindeer management area of Finland.
Kuva 1. Suomen poronhoitoalue.

Forestry and reindeer husbandry are multiple uses of forestry land. According to the concepts of production economics, both timber and reindeer forage (ground and tree lichens, hay, foliage of deciduous trees etc.) are united products of forest production. They are both parts in the forest biogeocenose and as such they have certain biological links with each other. At the same time they are products of forest production and production factors of reindeer husbandry and timber harvesting.

It is easy to see that modern forestry practices have profound influences to reindeer pastures (Helle, R. 1966, Pohtila 1970, Vaara 1972, Eriksson 1972, Mikola 1973, Saastamoinen 1977). Some of these influences can be regarded as positive, some as negative, as exemplified by the case of tree lichens.

Tree lichens are the only natural feed for reindeer during the time in winter when hard and thick snow prevent the reindeer from digging down to the ground lichens. During that time reindeer find their way to old forests, especially to spruce forests where tree lichens are available (Helle 1972). A similar relationship to tree lichens was found in the case of the caribou in British Columbia and Northern Canada (Edwards *et al* 1960, Scotter 1965).

The availability of tree lichens within the limited reach of reindeer is very restricted (Ahti 1961, cf. Segal' 1962). Therefore, in winter time, it was a general practise for reindeer keepers to fell spruces dense with tree lichens.

According to Heikinheimo (1922) lichen fellings of spruce forests has a long history. The peak of lichen fellings was reached at the end of nineteenth century. The fellings were heaviest during hard winters (Porolaidunkomisiooni 1914) and mostly in the areas where spruce forests were very abundant. The fellings have also been practised in Northern Lapland (Sirén 1961).

The right to cut trees with dense lichen for reindeer in winter time is maintained in the legislation concerning reindeer husbandry (Asetus . . .).

However, Alaruikka (1964) reports that the fellings for reindeer have become more and more uncommon during recent decades because the reindeer are getting the tree lichen they need from numerous timber cutting areas.

Rajala (1965) studied the mortality of reindeer in the cutting areas. He found that reindeer are attracted by the noise of the chainsaw, and so gather in the cutting areas.

The easy availability of tree lichens in the cutting areas is no doubt an advantage for reindeer husbandry. But modern timber harvesting also creates some problems. The most severe problem is the insufficiency of tree lichen resources. This is largely related to a question of different treatment alternatives of old spruce forests from the stand point of reindeer husbandry. This study is a part of a larger research project concerning that problem.

The objective of the study is

1) to examine the prevalance of cutting areas as a reindeer pasture in the mid-1970s;
2) to determine its regional, seasonal and annual fluctuations;
3) to determine the mortality of reindeer in the cutting areas; and
4) to elaborate on the changes in cutting rhythms from the stand point of reindeer husbandry.

2. CUTTINGS IN THE REINDEER MANAGEMENT AREA

The reindeer management area of Finland is fixed by the 1948 Reindeer Management Law. Its southern boundary extends to the latitude 64°30'N (Figure 1).

The total land area of the reindeer management area is about 11,6 mill. ha of which forestry land comprises 97 per cent. A fifth of the total forestry land area is treeless or almost treeless land which is regarded as waste land by the forestry land classification (Table 1). Most waste land is situated beyond the forest limit (Figure 1). The northernmost part of the reindeer management area lies in the protection forest zone, where the intensity of cuttings is restricted. However, there — as well as throughout the whole reindeer management area — commercial cuttings are carried out.

The quantity of the annual commercial cuttings in the reindeer management area in recent years has been just under 5 mill. m^3 (Table 2). Due to the fact that the southern boundary of the reindeer management area does not coincide with the administrative boundaries of forestry the estimates are not quite exact.

Most of the commercial wood is felled in the private forests in spite of the fact that State owns more than a half of the forest land. This is because of the more favorable natural conditions in private forests.

Table 1. Land classes and ownership categories in reindeer management area
Taulukko 1. Poronhoitoalueen maaluokat ja omistussuhteet

	Total *Yhteensä*		By ownership categories *Omistajaryhmittäin*		
	1 000 ha	Per cent %	State *Valtio*	Private *Yksityiset*	Total *Yhteensä*
			per cent — %		
Forest land — *Metsämaa*	6 448	56	58	42	100
Poorly productive land — *Kitumaa*	2 249	19	42	58	100
Waste land — *Joutomaa*	2 579	22	74	26	100
Roads, depots, etc. — *Tiet, varastot, jne.* ..	21	0			
Forestry land, total — *Metsätalouden maa*	11 297	97	63	37	100
Other land — *Muu maa*	322	3			
Total land area — *Maa-ala yhteensä*	11 619	100			

Sources: National Forest Inventory. Data was also obtained from Forestry Board Districts and Regional Planning Authorities. — *Lähteet: Valtakunnan metsien inventointitiedot. Tietoja saatu myös piirimetsälautakunnilta ja seutukaavaliitoilta.*

Table 2. Number and volume of commercial cuttings in state and private forests in the reindeer management area, 1973—1976

Taulukko 2. Poronhoitoalueen kaupalliset hakkuut valtion ja yksityismetsissä vuosina 1973—1976

	1973	1974	1975	1976
	Number of cuttings — *Hakkuiden lukumäärä, kpl*			
State forests — *Valtion metsät*	177	198	215	236
Private forests — *Yksityismetsät*	6 178	6 240	3 100	5 546
Total — *Yhteensä*	6 355	6 438	3 315	5 782
	Volume of cuttings, 1 000 m³ — *Hakkuumäärä, 1 000 m³*			
State forests — *Valtion metsät*	1 473	1 637	1 782	1 947
Private forests — *Yksityismetsät*	3 101	3 356	2 713	2 921
Total — *Yhteensä*	4 574	4 993	4 495	4 686

The cuttings in state forests and private forests are on quite a different scale. In state forests the number of cutting areas is small but the average cuttings are large, usually many thousand cubic meters. In small-sized private forests the yearly number of cuttings is large but the average cuttings are only some four — five hundred cubic meters (Table 2).

Besides the commercial cuttings some timber is also cut for the forest owner's own use; probably about 10—20 per cent of the commercial cuttings (cf. Hutt u n e n 1977).

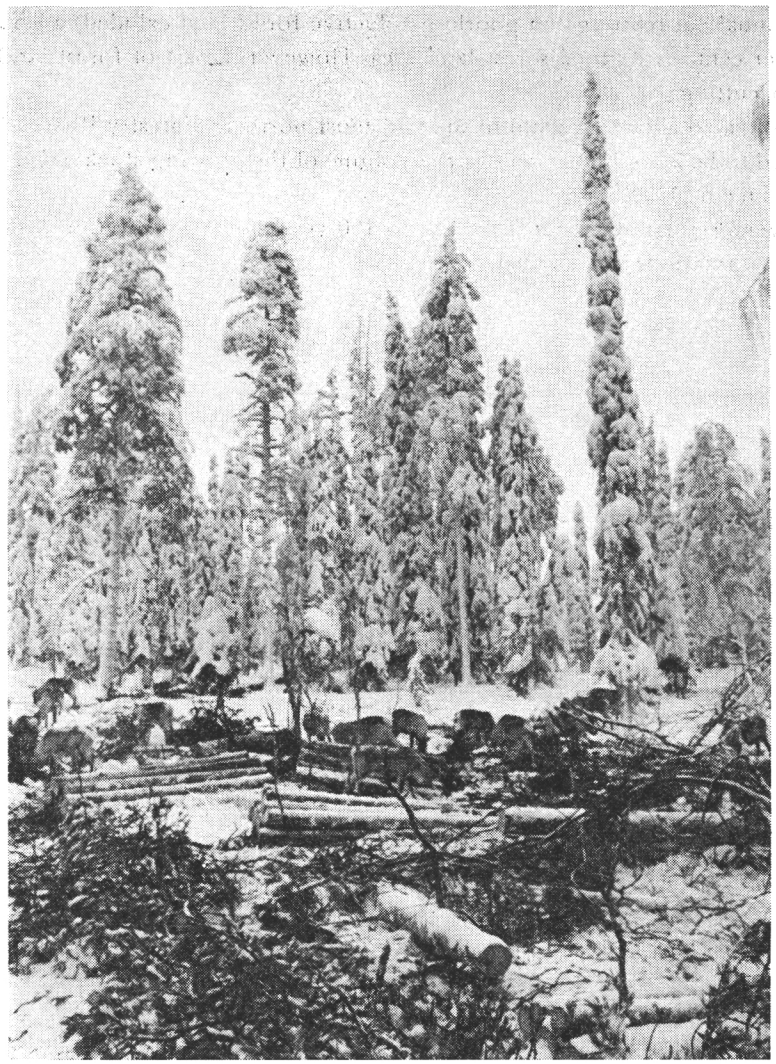
Table 3. Forest area cut in the reindeer management area,[1]) 1972—1976, by cutting treatments.

Taulukko 3. Eri hakkuutavoin käsitellyt pinta-alat metsätaloudellisissa hakkuissa poronhoitoalueella [1]) vuosina 1972—1976

Year — *Vuosi*	Thinnings on forest land *Harvennus-hakkuut metsämaalla*	Clear cutting *Paljaaksi hakk..u*	Seed tree and shelter-wood cutting *Siemen- ja suojuspuu-hakkuu*	Removal of seed tree and shelter-wood *Siemen- ja suojuspuiden poisto*	Other cuttings on forest land *Muut hakkuut metsämaalla*	Cuttings on poorly productive forest land *Hakkuut kitumaalla*	Forest area cut, total *Hakkuin käsitelty ala kaikkiaan*
	Hectares — *Hehtaaria*						
1972	7 542	10 229	16 967	19 405	231	12 042	66 416
1973	6 694	14 608	13 152	25 503	573	13 771	74 301
1974	8 784	15 107	16 251	26 675	1 596	15 372	87 785
1975	6 584	12 027	9 858	21 930	3 072	9 490	62 961
1976	3 627	13 848	6 119	10 674	577	9 004	43 849
	per cent — %						
1972	11	16	26	29	0	18	100
1973	9	20	18	34	1	18	100
1974	11	18	19	32	2	18	100
1975	10	19	16	35	5	15	100
1976	8	32	14	24	1	21	100

[1]) The data comprises the Forestry Board Districts of Lappi and Koillis-Suomi, which together cover 84 per cent of the reindeer management area. — *Tiedot koskevat Lapin ja Koillis-Suomen piirimetsälautakuntien alueita, jotka käsittävät 84 % poronhoitoalueesta.*

Source: Yearbook of Forest Statistics. — *Lähde: Metsätilastollinen vuosikirja.*



(Photo — *Kuva:* Kalle A. Kuittinen)

Figure 2. Reindeer in a cutting area.
Kuva 2. Poroja hakkuutyömaalla.

The main cutting treatments in regeneration cuttings on forest land are clear cutting, seed tree cutting and shelterwood cutting. Clear cutting accounts for about 20 % of all forest areas cut (cuttings on poorly productive forest land included). The share of seed tree and shelterwood cutting is about the same size. Thinnings and the removal of seed trees and shelterwood together account for nearly a half of all the forest areas cut. The data concerns the two northernmost Forestry Board Districts, which cover 84 per cent of the reindeer management area (Table 3).

The annual cut (cuttings on poorly productive forest land exluded) accounts for about 1 per cent of the total forest land area. However, a part of forest land is not subject to cutting.

The estimated allowable drain in the two most northern Forestry Board Districts is estimated to be 2,0—2,5 per cent of the volume of the growing stock (K u u s e l a & S a l m i n e n 1978).

The average rotation varies from 120 to 150 years. In the protection forest zone even longer rotations are applied.

3. MATERIAL AND METHODS

The research material was collected in two ways. In the cutting areas, observations concerning the numbers of reindeer were made weekly by foremen using a special form. The second method involved a questionnaire which was sent to all reindeer management co-operatives.

The weekly observations were made during the winters of 1974 and 1975. The cutting areas studied were chosen subjectively. A goal was to obtain as good coverage as possible of cutting areas inside certain reindeer management co-operative areas. Data was obtained from 60 cutting areas in 1974. In 1975 material consisted 7 cutting areas. The cutting areas consisted only those of the National Board of Forestry and the biggest forest companies. In most cases the forms were personally supplied to the cutting areas. The reliability of the weekly observations can be regarded as satisfactory because the foremen have a good overall knowledge of their cutting area. The January 1974 estimates of the number of reindeer were made afterwards and represent a monthly average. A third of the February and March estimates were also made this way. The reliability of these monthly estimations is weaker. The reliability of the data concerning the number of reindeer killed by falling trees can be regarded as good, because the workers are bound to declare such accidents.

The questionnaire concerning the reindeer's winter pastures was sent to all reindeer management co-operatives in 1975 and in 1977. The inquiry was made together with H e l l e (cf. H e l l e & S a a s t a m o i n e n 1975). Here only the data concerning cutting areas as a reindeer pasture in January—March is dealed with.

In 1975 the questionnaire was filled by 52 reindeer management co-operatives and the reply percentage was 94 %. In 1977 number of replies was 53 and the reply percentage was 95 %. In many cases the questionnaire was discussed in the meetings of the boards of the reindeer management co-operatives. The average number of reindeer pasturing in cutting areas in January—March is difficult to estimate because it is changing all the time during the three month period. This partly depends on the changes of the number and size of the cutting areas inside the reindeer co-operative management area. Snow conditions and other factors also change the situation. However, the number of reindeer pasturing in the cutting areas is probably rather well-known for two reasons: one is the problems relating to pasturing in the cutting areas (e.g. accidents); the other is that the reindeer keepers in many cases organize supplementary feeding for the reindeer in the cutting areas.

4. REINDEER IN THE CUTTING AREAS

41. Total number of reindeer in the cutting areas

The total numbers of reindeer obtaining food from the cutting areas during January—March in 1974, 1975 and 1977 are shown in Table 4.

The estimates for 1975 and 1977 are from the questionnaire. The estimate for 1974 was obtained by using the ratio of the number of workers in the sample cutting areas to the total number of workers in commercial fellings in the Province of Lapland. The number of reindeer in the Lappish cutting areas was then assumed to be in the same proportion to the total number of reindeer in the cutting areas in the whole reindeer management area as was the case in 1975 and 1977.

In the whole reindeer management area 13 000—20 000 reindeer have obtained food from the felled trees in the cutting areas yearly during the most severe winter time from January to March. That is about a tenth of all reindeer.

R a j a l a (1965 and unpublished data) has estimated that during the winters of 1964 and 1965 18 000—25 000 reindeer gathered in the cutting areas. At that time the volume of cuttings was larger, as can be seen from the felling statistics, which cover about 70 per cent of the commercial fellings in the reindeer management area (Figure 3).

Table 4. Total number of reindeer in the cutting areas in the whole reindeer management area in January—March, 1974, 1975 and 1977

Taulukko 4. Porojen lukumäärä koko poronhoitoalueen hakkuutyömailla tammi—maaliskuussa vuosina 1974, 1975 ja 1977

	Year — *Vuosi*		
	1974	1975	1977
Number of reindeer in the cutting areas — *Porojen lukumäärä hakkuutyömailla*	15 700	19 500	13 200
All reindeer in the reindeer management area [1]) — *Porojen kokonaismäärä* [1])	128 100	141 100	171 200
Percentage of reindeer in the cutting areas *Hakkuutyömailla olevien osuus*, %	12,1	13,8	7,7

[1]) Reindeer older than one year and calves according to the statistics of the Association of Reindeer Management Organizations. — *Vuotta vanhemmat ja vasat Paliskuntain Yhdistyksen tilaston mukaan.*

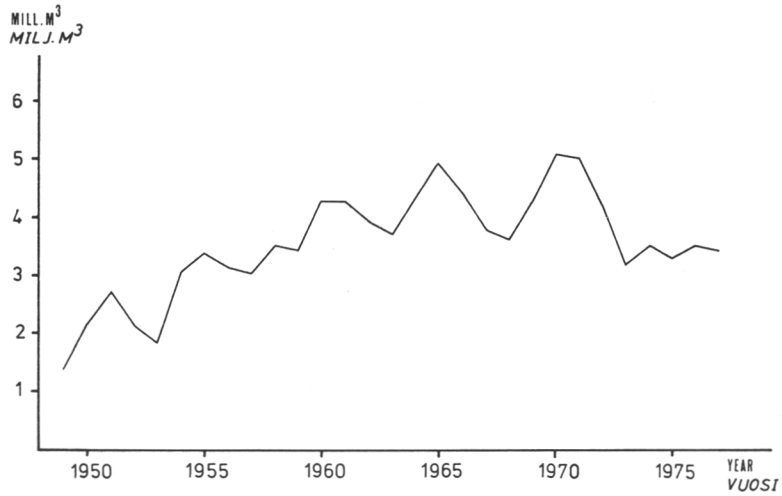


Figure 3. Commercial fellings in the Province of Lapland
Kuva 3. Markkinahakkuut Lapin läänissä.

The cutting areas play an appreciable role among the wintertime food resources of reindeer. However, the regional and temporal variations are large. These variations will be examined next.

42. Temporal variations in the numbers of reindeer in the cutting areas

The number of reindeer in the cutting areas fluctuates not only seasonally but even monthly and weekly.

In 1974 the average number of reindeer per cutting area was high and rather constant from January to March. From April it began to decrease and was lowest in May (Figure 4). The high average in January indicates that the gathering of reindeer in the cutting areas had begun before January. Observations are not available for the period before January.

In the following year the average number of reindeer was very low in December 1974 and in January 1975, but began to grow in February and reached its highest point at the end of March. After that it began to decrease (Figure 5).

The monthly averages of 1974 and 1975 are presented together with those of 1964 and 1965 from R a j a l a (1965 and unpublished data), see Table 5. In each winter, the averages have been highest in March. Data from the sixties also show that the gathering of the reindeer in the cutting areas can begin early in the winter.

The total number of reindeer in the cutting areas also fluctuate monthly. It is determined by the average number of reindeer per cutting area and the number of cutting areas. The monthly development of the latter is not known. However, the

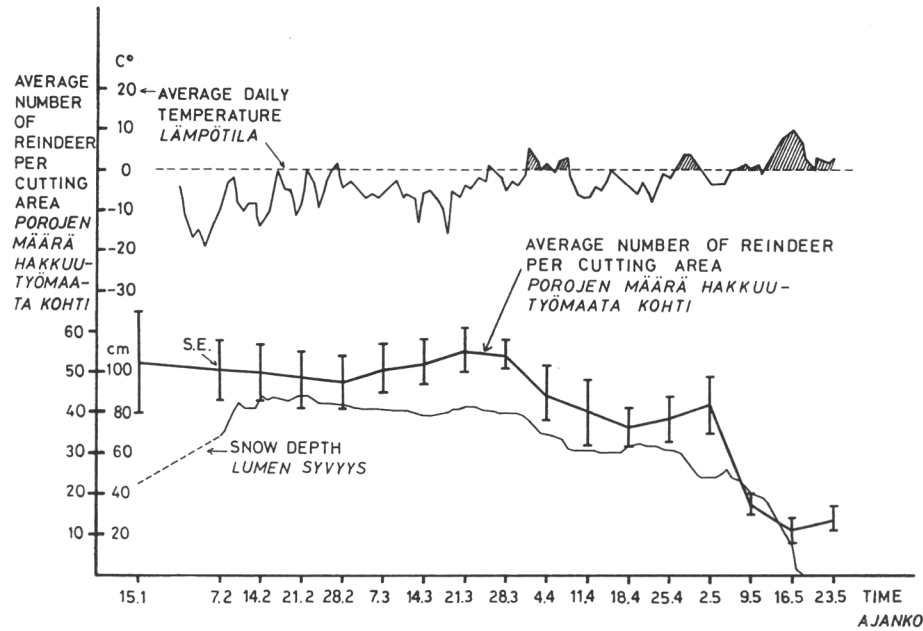


Figure 4. Average number of reindeer pasturing in cutting areas in January—May, 1974 (60 cutting areas).

Kuva 4. Poroja keskimäärin hakkuutyömaata kohti tammi—toukokuussa vuonna 1974 (60 työmaata).

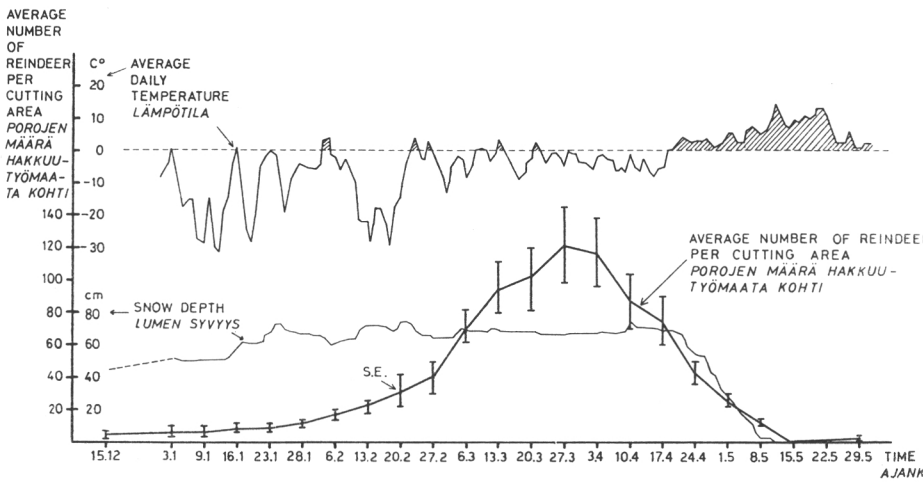


Figure 5. Average number of reindeer pasturing in cutting areas in December 1974—May 1975 (7 cutting areas).

Kuva 5. Poroja keskimäärin hakkuutyömaata kohti joulukuussa 1974—toukokuussa 1975 (7 työmaata).

Table 5. The average number of reindeer per cutting area monthly in some winters according to this study and R a j a l a

Taulukko 5. Porojen lukumäärä kuukausittain hakkuutyömaata kohti eräinä talvina tämän tutkimuksen ja R a j a l a n mukaan

Winter — *Talvi*	Number of cutting areas *Hakkuutyömaita, kpl*	Month — *Kuukausi*						
		November *Marraskuu*	December *Joulukuu*	January *Tammikuu*	February *Helmikuu*	March *Maaliskuu*	April *Huhtikuu*	May *Toukokuu*
		Number of reindeer — *Poroja kpl*						
1963—64 [1])	124	48	67	89	87	98	47	..
1964—65 [2])	138	58	61	60	70	78	53	..
1973—74	60	..	..	52	49	53	40	21
1974—75	7	..	6	9	33	98	81	9

[1]) R a j a l a 1965.
[2]) R a j a l a, unpublished data.

monthly number of workers engaged in commercial fellings is known, and this information together with information about the number of workers in the cutting areas of the sample makes it possible to estimate the total number of reindeer in all cutting areas monthly winter 1974 (Figure 6). The total number of reindeer in the cutting areas was, in January, a little bit higher than in February, and reached its highest point in March, decreasing thereafter rather steeply to May.

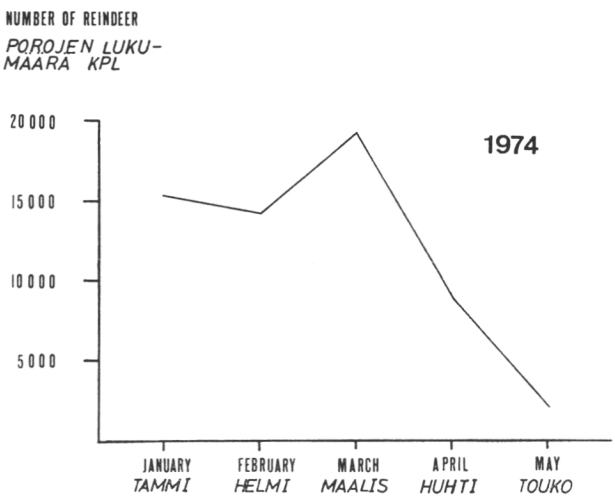


Figure 6. Total number of reindeer in the cutting areas during January—May, 1974, in the whole reindeer management area.

Kuva 6. Hakkuutyömailla olevien porojen kokonaismäärä tammi—toukokuussa vuonna 1974 koko poronhoitoalueella.

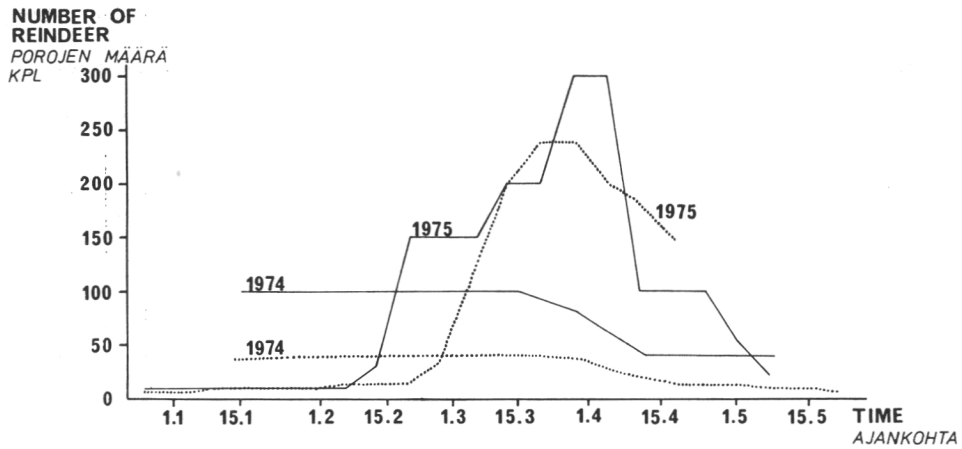


Figure 7. The number of reindeer in two cutting areas during January—May in 1974 and 1975.
Kuva 7. Porojen määrä kahdella työmaalla tammi—toukokuussa vuosina 1974 ja 1975.

The gathering of reindeer in the cutting areas fluctuates from year to year. E.g. in the two cutting areas, which were included in both samples, the gathering of reindeer in 1975 began later but developed more rapidly than in 1974 (Figure 7).

It is assumed that the principal factor causing reindeer to shift their pasture to cutting areas is the variations in the snow conditions. Hard and thick snow prevents reindeer digging up ground lichens (H e l l e 1975, L o p a t i n 1962). Snow can become very hard when, after a warm and wet period, the temperature falls very low. Such weather sequences occurred e.g. 25. 2.—5. 3. 1974 and 21. 2.—2. 3. 1975 (Figures 4 and 5).

43. Regional differences of the numbers of reindeer pasturing in cutting areas

The reindeer management area of Finland is divided into 56 reindeer management co-operatives. The percentages of reindeer pasturing in the cutting areas in the co-operatives during January—March is shown in Figures 8 and 9. The data was obtained by questionnaire and it presents the estimates made by the reindeer keepers themselves.

There are great differences in the prevalance of cutting areas for reindeer pasture between the reindeer management co-operatives. In the northern parts of the reindeer management area the cutting areas play little or no role at all. In the southern parts there are some reindeer management co-operatives where more than forty per cent of all reindeer had been in the cutting areas at some time between January—March, 1975.

A reason for such variations is the regionality of the cuttings. The northernmost part of the reindeer management area belongs to the protection forest zone, where the volume of cuttings is modest (Figure 1).

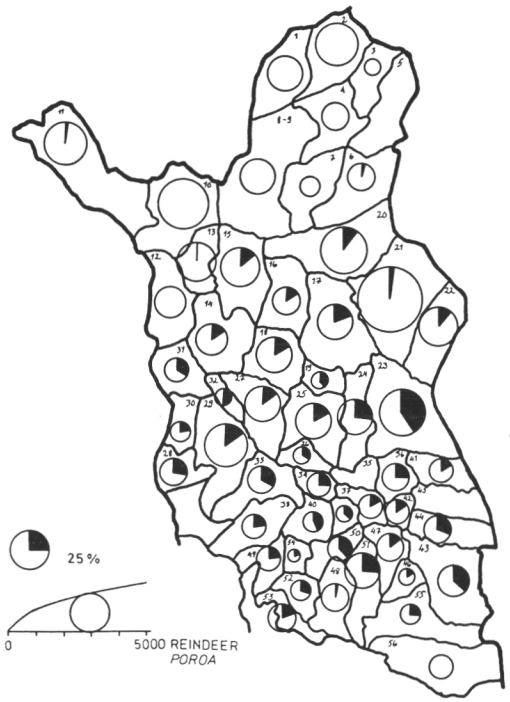


Figure 8. Percentage of reindeer pasturing in cutting areas in January—March in 1975 by reindeer management units.

Kuva 8. Hakkuutyömailla olevien porojen suhteellinen osuus tammi—maaliskuussa vuonna 1975 paliskunnittain.

There are also differences in the species composition of the forests. In the northernmost areas pine is a dominant tree species whereas the proportion of spruce increases southwards.

The percentages of reindeer in the cutting areas in 1977 was smaller than in 1975. The decrease is relatively large in many southern reindeer management areas whereas near the protection forest zone it is rather small. Only in a few reindeer management areas did the percentage increase.

The regionality of the prevalance of reindeer in the cutting areas is presented more concisely in Table 6. The changes between 1975 and 1977 are also presented in this table.

The northern zone roughly consists of the reindeer management areas in the protection forest zone, whilst the southern zone consists about one half of the whole reindeer management area. About three quarters of all reindeer pasturing in the cutting areas were in the southern zone in the two years studied.

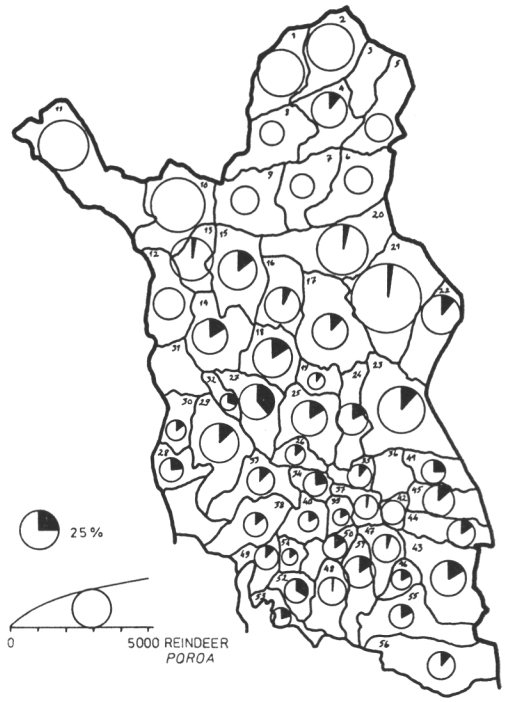


Figure 9. Percentage of reindeer pasturing in cutting areas in January—March in 1977 by reindeer management units.

Kuva 9. Hakkuutyömailla olevien porojen suhteellinen osuus tammi—maaliskuussa vuonna 1977 paliskunnittain.

Table 6. The cutting areas as reindeer pasture in January—March in three zones of reindeer husbandry area

Taulukko 6. Porojen määrä hakkuutyömailla tammi—maaliskuussa poronhoitoalueen eri osissa

Zone — *Osa-alue*	Number of reindeer in the cutting areas *Porojen määrä hakkuutyömailla* A		Total number of reindeer [4] *Poroja kaikkiaan* [4] B		A/B Per cent %	
	1975	1977	1975	1977	1975	1977
Northern [1] — *Pohjoinen* [1]	300	300	30 427	44 806	1,0	0,7
Central [2] — *Keskinen* [2]	3 950	3 500	40 251	52 468	9,8	6,7
Southern [3] — *Eteläinen* [3]	15 150	9 400	64 004	67 069	23,4	14,1

[1]) Reindeer management units 1—11 in Figures 8 and 9. — *Paliskunnat 1—11 kuvissa 8 ja 9.*
[2]) Reindeer management units 12—22. — *Paliskunnat 12—22.*
[3]) Reindeer management units 23—56. — *Paliskunnat 23—56.*
[4]) Reindeer older than one year and calves according to the questionnaire. — *Vuotta vanhemmat ja vasat kyselyn mukaan.*

Table 7. Number of reindeer killed monthly by falling trees in cutting areas of the 1974 sample
Taulukko 7. Puiden alle kuolleet porot näytteen työmailla vuonna 1974

Month — *Kuukausi*	Number of the cutting areas in the sample *Työmaita näytteessä kpl*	Number of reindeer killed in the cutting areas of the sample *Näytteen työmailla kuolleet porot* A	Number of reindeer in the cutting areas of the sample *Poroja kaikkiaan näytteen työmailla* B	A/B Per cent %
January — *Tammikuu*	19	4	994	0,4
February — *Helmikuu*	40	28	1 799	1,6
March — *Maaliskuu*	54	21	2 636	0,8
April — *Huhtikuu*	26	4	989	0,4
May — *Toukokuu*	11	0	262	0,0
Total — *Kaikkiaan*	60	57		

44. Number of reindeer killed by falling trees

In their search for food from the felled trees reindeer are in danger of being killed by falling trees.

In 1974 57 reindeer were killed by falling trees in 60 cutting areas. In Table 7 the numbers of reindeer killed monthly are presented.

Most reindeer were killed in February, both absolutely and relatively. March was also a bad month. In 1964 the situation was rather similar. Most reindeer were killed by trees in February, followed by March and January (R a j a l a 1965).

It is possible tentatively to estimate the total number of reindeer killed by trees from January to May, 1974. This can be done by using the ratio of the number of workers in the cutting areas of the sample to the total number of workers in commercial fellings in the county of Lapland.

The calculation shows that 350 reindeer in the county of Lapland and more than 400 reindeer in the whole reindeer management area were killed between January and May, 1974.

This figure roughly corresponds with the estimate made by the Association of Reindeer Management Organizations. It is greater than the 150—200 reindeer killed estimated by R a j a l a (1967).

In Sweden it is estimated that about 200 reindeer were killed yearly by falling trees in the cutting areas of the Royal Board of Forestry alone (E n g s å s 1975, Lantbruksstyrelsen 1976).

45. Supplementary feeding in the cutting areas

The cutting areas provide good possibilities for organizing supplementary feeding for reindeer. The benefits of supplementary feeding in the cutting areas are, according to R a j a l a (1967), the decrease of the »cutting area mortality» of reindeer and the possibility to utilize natural food from felled trees.

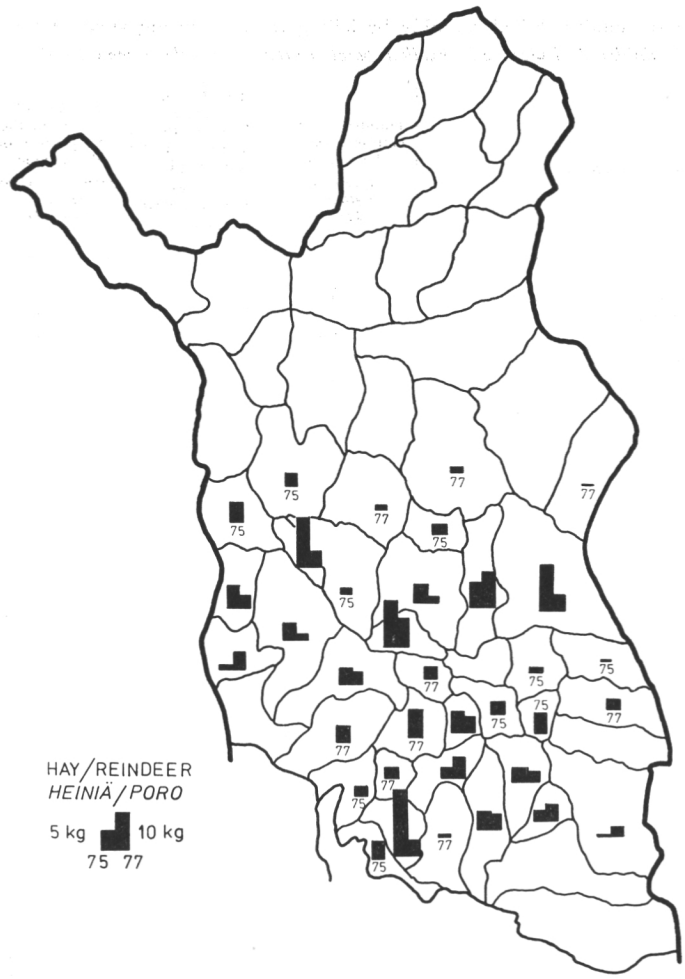


Figure 10. Supplementary feeding of reindeer in cutting areas in 1975 and 1977 by reindeer management units (kg hay per reindeer).
Kuva 10. Hakkuutyömaiden yhteyteen järjestetty lisäruokinta (kg heiniä/poro) paliskunnittain vuosina 1975 ja 1977.

In 1975 supplementary feeding was organized in 26 reindeer management areas and 203 380 kg of feed was distributed into the cutting areas. In 1977 the figure was 144 650 kg in 25 reindeer management areas.

The amount of supplementary feeding per reindeer by reindeer management areas is shown in Figure 10. It is largely confined to the central and southern reindeer management areas.

5. SEASONAL FLUCTUATIONS OF CUTTINGS

Reindeer's need for tree lichens is most essential when hard snow prevents them from obtaining ground lichens. It is therefore favorable for reindeer husbandry if the fellings occur at that time.

Figure 11 shows the percentage of fellings between January and March of the total annual commercial fellings. The data concern the Province of Lapland and covers about 70 per cent of the fellings of the whole reindeer management area.

In the early fifties half of all fellings occurred during the period January to March. By the middle of seventies the seasonality of fellings had clearly decreased.

Reindeer eat tree lichen from all tree species but spruce is the most important tree lichen supplier. However, the monthly felling statistics only show the number of spruce pulpwood fellings — statistics for spruce saw-logs appear together with pine saw-logs under the title of large-sized timber. On the other hand, most spruce in the

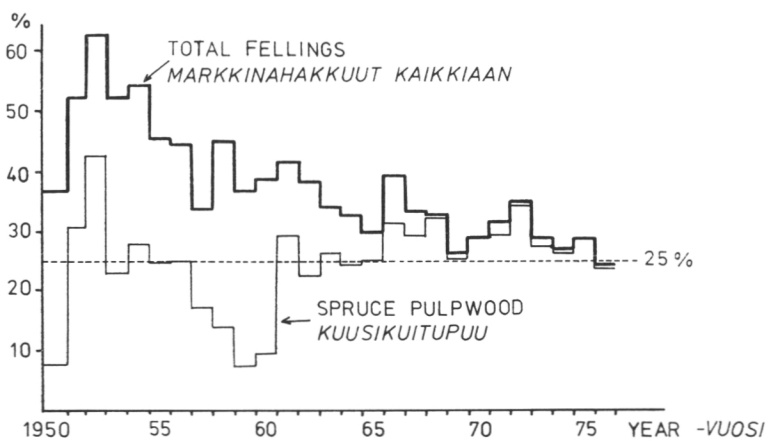


Figure 11. Percentage of total and spruce pulpwood fellings in January—March of all commercial and spruce pulpwood fellings in the Province of Lapland. (25 per cent represents the level of seasonally equal fellings.)

Kuva 11. Tammi—maaliskuun hakkuiden osuus kaikista markkinahakkuista ja kuusikuitupuun hakkuista Lapin läänissä. (25 % edustaa hakkuiden tasoa ilman kausivaihteluita.)

reindeer management area is prepared pulpwood and therefore some light can be shed on the question by examining the fellings of spruce pulpwood.

The seasonality of the fellings of spruce pulpwood has differred from that of total commercial fellings in the fifties and early sixties (Figure 11). A reason was the barking of pulpwood which was best done in summer and autumn. In addition, the winter was the most advantageous season for hauling the saw-logs by horse.

In the seventies the rhythm of spruce pulpwood fellings closely followed that of total fellings. To some degree this may have reduced the negative effects of decreasing seasonality for reindeer husbandry.

6. DISCUSSION

The old spruce forests were earlier felled by reindeer keepers to provide winter feed for reindeer. In recent decades such fellings have ceased because reindeer obtain the tree lichen they need from numerous commercial timber cutting areas. The cutting areas make tree lichens abundantly available for reindeer and as such are beneficial to reindeer husbandry. However, the benefits are not without their problems.

First, there is the question of the cutting rhythm from the stand point of tree lichen needs of the reindeer. The second problem, which closely relates to the first, is the sufficiency of tree lichen resources.

The reindeer's need for tree lichen not only varies seasonally but also yearly. In different years the weather and snow conditions provide varying possibilities for reindeer to dig for ground lichens and other vegetation. The need for tree lichens is proportional to the availability of other winter forage. In some years the digging conditions remain favourable through most of the winter, whilst in some years digging conditions may become difficult from the early winter onwards because of the freezing of the ground lichen. The situation is still complicated by the actual poor condition of ground lichen stock (M a t t i l a & H e l l e 1978).

It is clear that modern felling techniques, which are organized to provide an all-year round even supply of wood for industry, do not fluctuate according to the highly varying needs of reindeer for tree lichens. Naturally, the modern fellings do not follow the needs of reindeer husbandry as it did, to a large extent, earlier. Today, a conscious effort is required if the needs of the reindeer are to be met. It is, of course, difficult but solutions can be found. For instance, it may be possible to restrict the fellings of tree lichen rich forests to winter time. This kind of solution has been discussed in consequence of the growing cooperation between forestry and reindeer management interests.

The sufficiency of tree lichen resources is perhaps the more difficult problem. The problem very largely concerns the destiny of the remaining over-aged spruce forests, which from the stand point of wood production are unproductive. However, an analysis of different treatment alternatives of old spruce forests goes beyond the scope of this study.

7. SUMMARY

The significance of cutting areas as reindeer pasturage in different years in the mid seventies were studied.

From the felled trees in the cutting areas reindeer obtain abundant tree lichens, which are the principal natural food resource for reindeer when hard and thick snow prevents them digging ground lichens and other ground vegetation.

During the three years studied about one tenth of reindeer in January—March were pasturing in the cutting areas. However, the seasonal differences were large. The largest number of reindeer in the cutting areas was in March.

The regional differences were significant. The number of reindeer in the cutting areas was smallest in the protection forest zone, where about only 1 per cent of the total number of reindeer were in the cutting areas. In the southern part of the reindeer management area 23 per cent of all reindeer in 1975 and 14 per cent in 1977 were in the cutting areas.

Pasturing by reindeer in the cutting areas is not without risk. The number of reindeer killed by falling trees was roughly estimated.

The study also considers the cutting rhythm from the stand point of reindeer husbandry. Nowadays the cuttings are all-year round and the seasonal variations have decreased. However, by cutting the tree lichen bearing forests in winter time it is possible to help the reindeer's food supply.

REFERENCES

AHTI, T. 1961. Poron ravinnosta ja laitumista. Summary: On food and pastures of the reindeer. Lapin Tutkimusseuran vuosikirja 2: 18—24.

ALARUIKKA, Y. 1964. Suomen porotalous. Rovaniemi. Asetus poronhoitolain täytäntöönpanosta 20. 8. 1948/629.

EDWARDS, R. Y., SOOS, J. & RITCEY, R. W. 1960. Quantitative observations on epidendric lichens used as food by caribou. Ecology 41: 425—431.

ENGSÅS, J. 1975. Skogsbruk och/eller renskötsel. En konflikt mellan två former av skogsutnyttjande. Troedssonska Forskningskuratoriet Information 5 (1975): 1—19.

ERIKSSON, O. 1972. Silvicultural practises and reindeer grazing in Northern Sweden. Proceedings of the first international reindeer and caribou symposium 9—11. 8. 1972. Biological papers of the University of Alaska. Spec. Rep. 1. 1975.

HEIKINHEIMO, O. 1922. Pohjois-Suomen kuusimetsien hoito. Referat: Über die Bewirtschaftung der Fichtenwälder Nordfinnlands. Commun. ex Inst. Queest. For. Finl. Ed. 5: 1—132.

HELLE, R. 1966. An investigation of reindeer husbandry in Finland. Acta Lapponica Fenniae 5: 1—65.

HELLE, T. 1972. Porojen talvilaitumista ja niiden käytöstä Alakitkan paliskunnassa talvella 1971/72. Poromies 4: 6—8.

—»— 1975. Porojen talvilaitumista havumetsävyöhykkeessä. Metsäntutkimuslaitos. Rovaniemen tutkimusaseman tiedonantoja 11: 1—15.

HELLE, T. & SAASTAMOINEN, O. 1976. Porojen laitumet ja lisäruokinta talvella 1974—75. Metsäntutkimuslaitos. Rovaniemen tutkimusaseman tiedonantoja 12: 1—14.

HUTTUNEN, T. 1977. Suomen puunkäyttö, poistuma ja metsätase 1974—76. Summary: Wood consumption, total drain and forest balance in Finland 1974—76. Folia For. 308: 1—49.

Lantbruksstyrelsen. 1976. Rennäring-skogsbruk. En analys av intressekonflikter mellan näringarna. Meddelanden 3: 1—31.

KUUSELA, K. & SALMINEN, S. 1978. Koillis-Suomen metsävarat vuonna 1976 ja Lapin metsävarat vuosina 1970 ja 1974—76. Forest resources in the Forestry Board Districts of Koillis-Suomi in 1976 and Lappi in 1970 and 1974—76. Folia For. 337: 1—35.

LOPATIN, V. D. 1962. Fiziko-geograficheskie usloviya severnoi Karelii kak baza sushchestvovaniya severnogo olenya. Severnyi olen' v Karel'skoi ASSR. 180. Moskva. Izd. Akad. Nauk SSSR.

MATTILA, E. & HELLE, T. 1978. Keskisen poronhoitoalueen talvilaidunten inventointi. Summary: Inventory of winter ranges of semi-domestic reindeer in Finnish Central Lapland. Folia For. 358: 1—31.

MIKOLA, P. 1973. Metsätalouden ympäristövaikutukset ja niiden merkitys metsien käytön suunnittelussa. Helsingin yliopiston metsänhoitotieteen laitos. Tiedonantoja 9: 1—51.

POHTILA, E. 1970. Lapin metsät ja porotalous. Niin metsä vastaa . . . Toim. Haukioja, M. & Lovén, L. Pori. Metsäylioppilaat r.y.

Porolaidunkomisioonin mietintö. Komiteanmietintö 1914: 2.

RAJALA, P. 1965. Porojen savottakuolleisuudesta talvella 1963/64. Poromies 3: 4—7.
—»— 1967. Porojen ruokinta metsätyömailla. Poromies 1: 4—7.
SAASTAMOINEN, O. 1975. Hakkuutyömaista porojen ravintolähteenä vuoden 1974 kevättalvella. Metsäntutkimuslaitos. Rovaniemen tutkimusaseman tiedonantoja 11: 16—30.
—»— 1977. Poronhoito ja puuntuotanto. Summary: Reindeer and Forestry. Suomen Luonto 2: 124—127.
SCOTTER, G. W. 1965. Kanadalaisen tutkijan vaikutelmia pohjoismaiden poronhoidosta. Poromies 3: 10—14.
SEGAL', A. N. 1962. Opyt perevoda i akklimatizatsii v Karelii tundrovykh olenei iz Murmanskoi oblasti. Severnyi olen' v Karel'skoi ASSR. 180. Moskva. Izd. Akad. Nauk. SSSR.
SIRÉN, G. 1961. Taka-Lapin metsien historiasta ja ilmastosta historiallisena aikana. Lapin Tutkimusseuran vuosikirja 2: 29—45.
Statistics on fellings for commercial purposes. The Ministry of Labour. Mimeographed.
SULKAVA, S. & HELLE, T. 1972. Range ecology of the domesticated reindeer in the Finnish coniferous forest area. Proceedings of the first international reindeer and caribou symposium 9.—11. 8. 1972. Biological papers of the University of Alaska. Spec. Rep. 1. 1975.
VAARA, L. 1972. Metsänparannustöiden vaikutus porolaitumiin. Poromies 3: 12—18.
VOSTRYAKOV, P. N. 1971. Olenevodstvo v SSSR i plemennaya rabota. Porosymposiumi Rovaniemellä 26.—27. 6. 1971. Helsinki.

SELOSTE

Työ on osa vanhojen kuusikoiden poronhoidollista merkitystä selvittävää tutkimusta. Vanhoissa kuusikoissa on runsaasti luppoa, joka paksun ja kovan hangen aikana on tärkein poron luontainen ravintovara.

Hakkuutyömailla kaadetuista puista porot saavat helposti ja runsaasti luppoa, ja tästä syystä poroja esiintyy hakkuutyömailla joka talvi.

Tutkimuksen tarkoituksena oli selvittää porojen määrää hakkuutyömailla 1970-luvun puolivälissä, määrittää siinä esiintyviä alueellisia ja ajallisia vaihteluita, selvittää porojen puiden alle jäämistä sekä tarkastella hakkuiden kausivaihteluita.

Tutkimusmenetelminä oli hakkuutyömaille toimitettu viikottainen seurantalomake sekä paliskunnille osoitettu kysely. Hakkuutyömaiden näytteeseen kuului vuonna 1974 60 työmaata ja vuonna 1975 7 työmaata. Näyte valittiin harkinnanvaraisesti. Paliskuntien kyselyyn vastasi vuonna 1975 52 paliskuntaa (palautusprosentti 94) ja vuonna 1977 53 paliskuntaa (palautusprosentti 95). Kysely koski talvilaitumia kokonaisuudessaan. Tässä esitetään vain hakkuutyömaita koskevat tiedot.

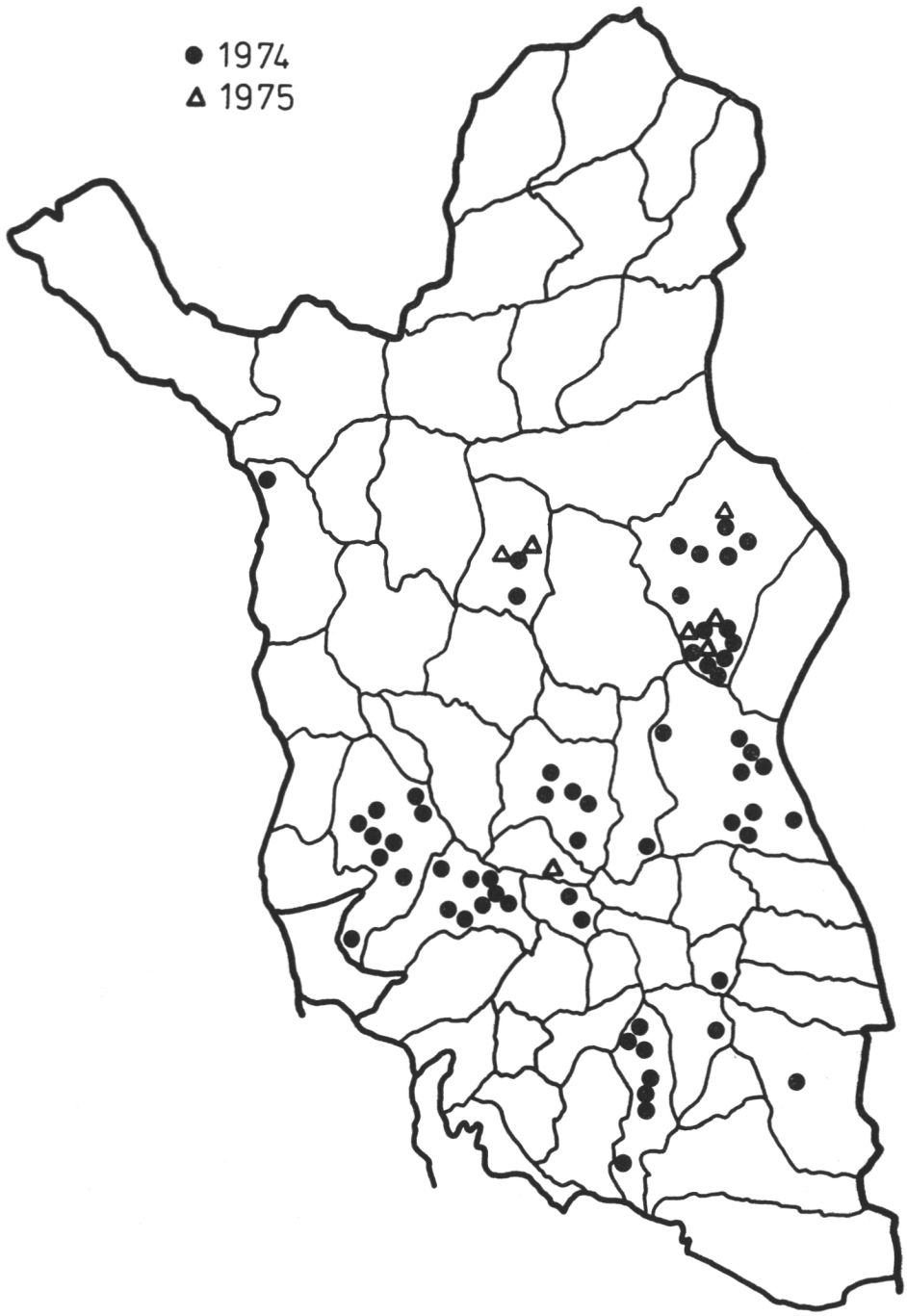
Poronhoitoalueen hakkuutyömailla oli vuosina 1974, 1975 ja 1977 tammi—maaliskuun keskiarvona 13 000—20 000 poroa eli suunnilleen kymmenesosa poroista. Korkeimmillaan porojen määrä oli maaliskuussa, jonka jälkeen se melko nopeasti väheni. Vuoden 1974 tammikuun korkeat poroluvut ja aikaisemmat tutkimukset osoittavat, että poroja alkaa keräytyä hakkuutyömaille jo alkutalvesta.

Alueelliset erot porojen hakkuutyömailla oleskelussa olivat suuret. Poronhoitoalueen pohjoisimmassa osassa vain 1 % poroista oli hakkuutyömailla. Eteläisimmässä osassa sen sijaan vuonna 1975 23 % ja vuonna 1977 14 % poroista oli tammi—maaliskuussa hakkuutyömailla.

Hakkuutyömailla sai vuonna 1974 surmansa puiden alle jäämisen vuoksi karkean arvion mukaan yli 400 poroa. Eniten poroja kuoli helmikuussa.

Hakkuutyömailla on epäilemättä tärkeä merkitys porojen talviaikaisen lupporavinnon turvaamisessa etenkin keskisellä ja eteläisellä poronhoitoalueella. Merkitystä lisää myös se, että työmaiden yhteyteen on helppo järjestää lisäruokintaa. Poronhoidon kannalta hakkuutyömaat eivät kuitenkaan ole vailla ongelmia.

Eräs ongelma, jota tutkimuksessa on tarkasteltu, liittyy hakkuiden ajoittumiseen. Porotalouden kannalta olisi edullisinta, että luppoisten metsien hakkuut tehtäisiin talvella siihen aikaan, jolloin porojen lupon tarve on suurin. Hakkuiden ympärivuotistuminen on kuitenkin johtanut kausivaihteluiden vähentymiseen. Tämän kehityksen haitallisia vaikutuksia porotaloudelle voidaan kuitenkin ainakin jossakin määrin vähentää ajoittamalla luppometsien hakkuut talvikaudeksi. Metsätalouden ja porotalouden yhteistoimintaelimissä tähän onkin kiinnitetty huomiota.



Appendix. The cutting areas of the sample
Liite. Näytteen hakkuutyömaat

OPTIMAL DISTRIBUTION OF REGIONAL SEEDLING PRODUCTION BY NURSERIES:

AN ECONOMIC STUDY

OLAVI LAAKKONEN

Seloste

TUOTANTOMÄÄRIEN OPTIMAALINEN JAKAMINEN
ALUEEN TAIMITARHOILLE:

TALOUDELLISUUSTARKASTELU

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In this study it is examined how to divide the market demand for seedlings being produced at different nurseries in a certain region. The goal of the study is to minimize the combined costs of seedling production and transportation. At the beginning emphasis is mainly on the determination of the prices of the forest tree seedlings and to the present state of the seedling production organizations in general.

To attain the goal of the study both a linear programming model and a chance-constrained programming model were formulated. In a chance-constrained model the parameters (capacity factors of cultivation, production costs and market demand) of a linear model are allowed to be random by nature. They are assumed to be normally distributed and independent of each other. These restrictions can be moderated if needed. In a chance-constrained model the decision maker can choose the probabilities for the existence of the constraints and at the same time he can decide how great a risk he is willing to take for the constraints to be violated.

Finally a hypothetical case situation is constructed to which these models are applied. Then, the interpretation of the solutions and the differences between them, generated by the different models, are studied.

Tutkimuksessa on tarkasteltu tietyn alueen taimien markkinakysynnän jakamista tuon alueen taimitarhojen tuotettavaksi. Tavoitteeksi on asetettu taimien tuottamisesta ja käyttöpaikalle kuljetuksesta aiheutuvien kustannusten summan minimointi. Tätä varten on aluksi kiinnitetty huomiota metsäpuiden taimien hinnan määräytymiseen sekä taimien tuotanto-organisaatioiden asemaan yleensä.

Edellä mainitun tavoitteen saavuttamiseksi on muodostettu sekä lineaarinen että riskirajoitteinen malli. Riskirajoitteisessa mallissa sallitaan vastaavan lineaarisen mallin parametrien (viljelyn kapasiteettitarpeiden, viljelykustannusten ja markkinakysynnän) olevan luonteeltaan satunnaisia. Tällöin on edellytetty niiden olevan normaalisti jakautuneita ja keskenään riippumattomia. Näitä rajoituksia on tarvittaessa mahdollista lieventää. Riskirajoitteista mallia sovellettaessa voi päätöksentekijä valita todennäköisyydet rajoitusten voimassaololle ja samalla siis päättää kuinka suuren riskin hän ottaa sille, että rajoitukset eivät toteudu.

Lopuksi on konstruoitu hypoteettinen esimerkkitapaus, johon esitettyjä malleja on sovellettu. Tällöin on tarkasteltu pääasiassa ratkaisujen tulkintaa ja eri mallien generoimien ratkaisujen välisiä eroja.

Helsinki 1979. Valtion painatuskeskus

FOREWORD

This study has been made in the section of Business Economics of Forestry in the Finnish Forest Research Institute. It is part of a more extensive work, concerning nursery economics. Prof. Jouko Hämäläinen, Prof. Matti Leikola and Prof. Risto Seppälä offered valuable criticism and guidance in both the execution of the research and during the preparations of the manuscript. The manuscript has also been read by Pentti K. Räsänen and Raimo Laakkonen.

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In this context I wish to thank all these persons and all those not mentioned who have contributed to the progress of the study.

Helsinki April 1979

Olavi Laakkonen

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1. INTRODUCTION

11. Seedling production in Finland

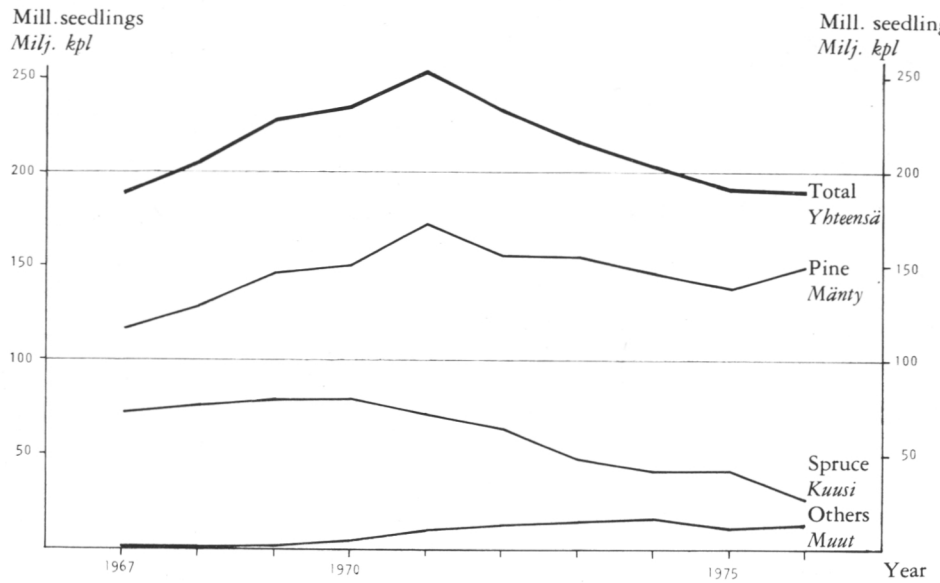
The 1967 Private Forest Act (Law 412/1967) dictates the institutional frames for private forestry. The leading principle of the law is to prevent the destruction of forests. The law also directs that a new forest must be established in the cut area. If natural regeneration of the logging area is not possible or if artificial regeneration is more economical, seeding or planting must be used. The Finnish tree nurseries therefore have an important duty to produce the nursery stock, to meet the quality required and to supply the volume of seedlings needed in the regeneration areas.

The development of the number of seedlings used yearly for planting in regeneration areas and comlementary planting (planting spaces in a young stand) during period of the 1967—1976 is presented in Fig. 1.

Most of the seedlings have been Scots pine (*Pinus sylvestris*). The demand for pine seedlings increased rapidly at the end of the 1960's and reached its peak of approx. 172 mill. plants in 1971. This was also the year when the total number of planted forest-tree seedlings was at its maximum. The planting of Norway spruce (*Picea abies*) has been decreasing and the number of planted spruce seedlings has dropped from its maximum of about 79 million in 1970 to 27,5 million in 1976. The development of deciduous trees, mainly silver birch planting has been the opposite of spruce. Thus the number of planted deciduous seedlings increased up to 1974, after which time it has slowly decreased.

The total amount of seedlings planted in 1976 had dropped back to the 1967 level. A considerable change has occurred on the proportional shares of planted tree species. Pine accounted for 61,6 % and spruce 38,0 % of all the planted seedlings in 1967. By 1976 the percentage of pine seedlings had increased to 78,7 % and that of spruce had decreased to 14,4 %, while the percentage of deciduous tree seedlings had increased from 0,4 to 6,9 % during the same period.

The Finnish Forestry Seed and Seedling Council (Metsätaloùden siemen- ja taimilautakunnan siemen- ja taimijaosto) has made a preliminary estimate of the planting and seedling requirements for the period 1981—83 by tree species. According to the estimate the annual seedling requirement in Finland during this period will be 149,4 mill. pine, 41,5 mill. spruce and 10,9 mill. birch seedlings. The estimate



Source: Yearbooks of Forest Statistics, 1967–1975
Lähde: Metsätilastolliset Vuosikirjat, 1967–1975

Fig. 1. Number of seedlings used for planting and complementary planting in Finland by tree species, 1967—1976.

Kuva 1. Metsänistutuksiin ja täydennysistutuksiin yhteensä Suomessa käytetyt taimimäärät puulajeittain vuosina 1967—1976.

Table 1. Seedling material delivered for planting by nursery owner groups in Finland, 1976.
Taulukko 1. Taimitarhoilta metsänviljelyyn Suomessa vuonna 1976 luovutetut taimimäärät taimitarhojen omistajaryhmittäin.

Nursery owner group *Taimitarhan omistajaryhmä*	Seedling material (1 000 seedlings) *Taimimäärä (1 000 kpl)*	Persentage *Prosenttiosuus*
National Board of Forestry — *Metsähallitus*	26 614	14,5
Central Forestry Board Tapio — *Keskusmetsälautakunta Tapio*	27 462	15,0
District Forestry Boards and Forest Management Associations — *Piirimetsälautakunnat ja metsänhoitoyhdistykset*	92 195	50,3
Private — *Yksityiset*	8 598	4,7
Forest Breeding Foundation — *Metsänjalostussäätiö*	13 757	7,5
Companies — *Yhtiöt*	10 960	6,0
Forest Research Institute — *Metsäntutkimuslaitos*	3 564	2,0
Total — *Yhteensä*	183 150	100,0

assumes planting densities of 2 000 pine and spruce plants and 1 600 birch plants per hectare. This will result as an increase in the share of spruce and correspondingly a decrease in the share of pine and birch from the present level of planting.

The plant producers, plant stock quantities and corresponding percentage figures concerning the total production volume of the nurseries in 1976 is presented in Table 1 (Yearbook of Forest Statistics 1976).

The nurseries owned by forest industry companies have been producing either too many or too few seedlings during recent years, but for the most part company nurseries have provided the seedlings which have been used in their own forests. The share of seedling production of the Forest Research Institute's nursery has been small and part of the production has been used in the Institute's own experimental forests. The importance of private nurseries as a plant stock supplier for private forests was greater than the situation today. Private nurseries have gradually been forced to lower their production mainly due to strong price competition. The remaining private nurseries are small, generally 4H-Club nurseries, which carry out transplanting.

The users of forest tree seedlings are organizationally tied to certain nurseries: The National Board of Forestry to its own nurseries and the private forest owners to the nurseries run by Forestry Board Districts, which are situated in the same districts as their forest holdings. The forest tree seedling market has few sellers and a large number of buyers (private forest owners) thus making the Finnish plant market oligopolistic (see Fog and Rasmussen 1960).

Every year the Finnish Forestry Seed and Seedling Council makes a proposal to the National Board of Forestry for seedling prices. The proposal is based on a fully-allocated mean price estimate, calculated from several nurseries with an additional cost of about 5 % for risk. The maximum prices for forest tree seedlings based on this proposal are then confirmed by the National Board of Forestry. These prices not only bind the sales of the seedlings produced to state loans and financial aid through the forest improvement programmes, but also to nurseries which have been founded with direct financial aid from the State.

Due to the ownership structure of the nurseries the prices of the forest tree seedlings do not follow the interaction of supply and demand in the market (see e.g. Lipsey 1966 pp. 99—107) despite the fact that this kind of interaction can be seen in the trade of many other commodities in Finland as well as in the other so-called market economies. The mean price is not applicable when the production volume strongly fluctuates. As the production volume increases the fixed costs of seedlings production are distributed among a greater number of seedlings thus decreasing the average unit costs. The situation is reversed when the production volume decreases. The results based on the mean price vary due to the fluctuation in rate of output even though no changes occur in the other factors influencing the profitability or economy of production.

The present study examines the distribution of production volume among the nurseries in a certain district. It is assumed that a forecast can be made of the demand of the plants in the district in question. The nurseries in the district subject to planning may all be owned either by one group of owners (cf. Table 1) or there may be nurseries of several owner groups. If the nurseries of different owners in a district are not willing to co-operate in planning the production volume, the study will exclusively be directed towards nurseries of a certain group of owners. This means that besides

forecasting the demand for the seedlings in the whole district, one has to be able to determine the market shares of the nurseries in the district. From the national economic point of view the co-operation between nurseries of different owner groups is desirable. This would lead to considerable savings in production and especially transportation costs.

The benefits gained through planning must be verifiable in one way or another before planning can be rational. It must be understood that although planning does not always bring about immediate changes in the activity towards which it is directed, it is of great assistance in understanding the system examined. However, for the present the benefits of planning are examined without exception, from the point of view of economic gain. Money is eventually used in evaluating benefits. The benefits gained through planning the production volumes of the nurseries in a district can be measured in terms of savings in costs. The accomplished costs in a certain district are then compared to the expected costs according to the plan. Under certain assumptions the other part in the comparison may also be another similar district where planning the distribution of production volumes of the nurseries is not centralized.

12. Problem definition and the goals of the study

As mentioned before there are only a few plant producers. Essentially this means better possibilities for planning regional production volumes of nurseries than if there were several entrepreneurs competing with each other in this field.

In more exact terms the goal of the present study is to develop a method for distributing the demand for seedlings in a certain district among the nurseries in this district thus minimizing the combined sum of costs of seedling production and transportation to the planting site. Both the endeavour of the nurseries to produce the seedling material as cheaply as possible and the efforts of the users to obtain seedlings from the closest possible nursery are included in the goal setting. The latter goal is justified under the assumption that the buyer finds no essential difference between seedlings produced in different nurseries. Considering that the sale prices are the same in various nurseries and only the transportation costs remain to be paid by the buyers of the seedlings, it is natural that the users aim at cutting the transportation costs. When the degree of attainment of the goal in question is examined only from the seedling producer's point of view, the cost of transportation has to be deducted. The feasibility of the solution and consequently the degree of attainment of the goal is limited not only by the requirement of satisfying the demand but also by the potential production possibilities of the nurseries.

2. FORMULATION OF THE MODEL

21. Premises for the use of linear programming

Traditional methods can be applied to distributing the production volumes. A few feasible production plans are formulated and the best one is chosen. In addition to the actual calculations extra variables can be used as decision making tools in choosing the best plan. Other advantages of this method are its simplicity and low cost. However, the number of possible alternatives in a practical planning situation is so great that it is impossible to include more than a fraction of the alternatives in the sample of the method described above. The significance of experience should not be underestimated. Actually, solutions of this method have proven to be very useful. Nevertheless, this method obviously does not lead to the best solution. The best solution (decision) is reached by combining the use of mathematical model- with a lot of practical experience.

Nowadays, linear programming is often being used to facilitate larger production planning problems. A linear programming problem is characterized by three requires ments (T h e i l *et al.* 1965):

1) it should be possible to describe the objective of the problem as a linear function which is either maximized or minimized
2) the decision variables assume exclusively non-negative values
3) the decision variables must satisfy a number of linear side conditions, usually in the form of inequalities.

Evidently linear programming cannot be applied to an oligopolistic market. This would lead to a non-linear programming problem (H a d l e y 1963 p. 483). Linear programming has been applied to this kind of situation presuming that the prices remain fixed and the demand is not affected by them. Prices in the seedling market are fixed and the price of seedling is not a critical factor in determining the demand for them. As far as these factors are concerned, it is not necessary to simplify the description of reality, i.e. the model, to linearize it. The relationship between production volumes and the corresponding variable costs of seedling cultivation can be considered proportional. The unit for the volume transported can be chosen so that transporting one additional unit requires one additional unit of transportation

capacity (e.g. a truckload). This stepwise increase in the transportation costs as a function of the volume transported is described in Figure 2. In this case, however, the transportation costs can be linearized so that the average error of linearization equals 0 (see Figure 2). In reality the transportation costs depend not only on the volume transported but also on the distance and the method of transportation. This reality is simplified here in the manner described above, because it is assumed that transport distances and methods are fixed.

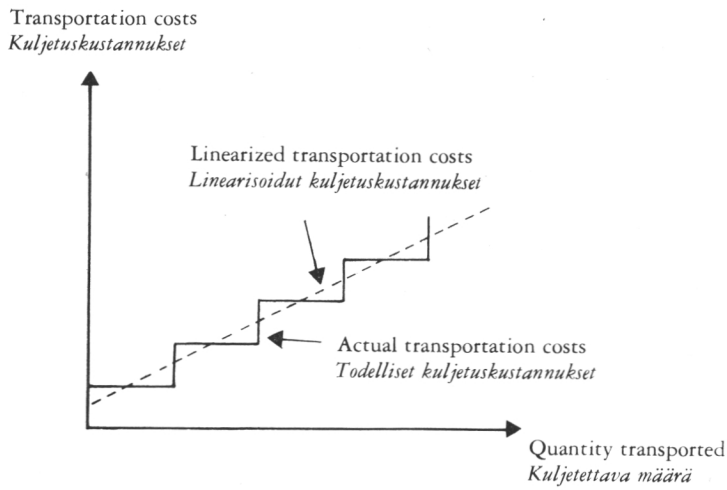


Fig. 2. Transportation cost as a function of quantity.
Kuva 2. Kuljetuskustannukset kuljetettavan määrän funktiona.

There is a corresponding dual problem closely associated with every linear programming problem. The solution to the original linear programming problem (primal) with the simplex technique produces simultaneously the solution to the corresponding dual problem (e.g. B e a l e 1968). The values of the decision variables of the dual are called shadow prices of the decision variables of the original problem. The shadow prices included in the optimum solution represent the marginal revenue and costs of the side constraints of the primal problem. In practice it is often more important to know what is likely to happen if the environmental conditions change or if they can be changed than to know exactly how good a result can be obtained under the existing conditions. Shadow prices are of great help in anticipating changes. The convexity of the feasible region guarantees that the global optimum solution is reached with this technique (e.g. Z a n g w i l l 1969, p. 25—36).

The increasing use of ball rooted seedlings in forest regeneration makes production planning more flexible in single nurseries due to the short raising period (M e t s ä m u u r o n e n et al. 1978). This is why a single period planning model was considered to be sufficient in this study.

22. Demand

The following investigation is based on the idea that the district subject to planning is divided into smaller market districts. A market district may consist of a single commune. In practice it is difficult to get information of units smaller than a commune. The purpose of this study is not to determine methods for estimating the demand for seedlings but it is assumed that the excepted values of the demand for various seedlings types in each market district are given.

The ecological conditions of the habit determine the types of seedlings which are needed for regeneration. These conditions do not, however, determine unambiguously the only acceptable seedling type but rather the number of suitable seedling types for the planting site. Thus it is sufficient to know the expected values of the demand for groups of seedling types equal in regard to regeneration, rather than to know expected values of the demand for various seedling types in each market area. Division of seedlings into groups of seedling types can, for example, be based on the tree species or on the seedling type. Accordingly, the most commonly grown seedlings in Finland can be divided into 12 groups. On a higher aggregate level the division into groups can be made according to the tree species.

23. Capacity

The potential factors (open ground area, plastic greenhouse area etc.) and above all labour force of the employment factors determine the capacity of a nursery. Due to the temporary nature of the work it is increasingly more difficult to obtain labour for the nurseries during the summer, when the seasonal demand for labour force is at its greatest. This disadvantage should diminish as a change toward permanent labour force and higher degree of mechanization takes place in nurseries. This kind of development presupposes an increase in the professional training of nursery employees. For simplicity it is assumed that the capacity of a nursery can be described with a single figure. It is also assumed that the excepted value of the required capacity calculated per unit for each group of seedling type grown in a nursery is known. The production capacity of a nursery is determined by the most scarce factor of production. Accordingly, capacity should always be expressed in relation to the most scarce factor of production. The estimate for the required capacity can be based on the mean value of the earlier yield figures of the same group of seedling types. It is assumed that additional capacity, i.e. rented land, is available up to a certain limit during the planning period. Firstly, the yearly rent for this additional area is taken into account in calculating the costs per hectare during the planning period (in this study one year). The cost of preparing the additional area is then added using the equal annual depreciation. The preparation activities include clearing, soil improvement and preparation of seedbeds. The equal annual depreciation is

based on the assumption that the benefits of the preparation of additional area for seedling cultivation are evenly distributed for each year of renting. Thus an equal share of the preparation costs is allocated to each year of renting. The soil improvement activities following the primary preparation of the rented area are included in the variable costs of seedling cultivation.

24. Linear programming model

In the business economic debate there has been controversy about the objective of profit maximization in enterprises. The supporters consider the maximization of profits measured in one way or another to be the only rational goal for an enterprise. They find the criticism useless, claiming that the critics do not suggest any other objectives in place of maximization to be impossible in practice due to fact that during the time of decision it is not possible for the decision maker to know all the possible alternatives of action and their consequences. In their opinion, instead of maximizing the enterprises should set forth an objective for reaching a certain aspiration level (Johnsen 1968 p. 337).

Without underestimating the value of the latter point of view the minimization of production costs was set forth as an objective in this study. Due to the fixed seedling prices it leads to the same result as a profit maximization section. In the model, the sum of seedlings transported from a nursery to the market areas equals the sum of seedlings produced in the nursery. Thus it can also be assumed that the volume transported determines the volume produced within the given limits. The same unit is used in measuring production and transportation volumes. The following symbols are used:

x_{ijk} = the volume of seedlings in the group of seedling type i transported from the nursery j to the marketing district k
c_{ij} = the average variable cost per unit of seedling cultivation in the group of seedling type i in the nursery j
c'_{jk} = the average cost per unit of transportation from the nursery j to the marketing district k
d_{ik} = the expected value of the demand for the group of seedling type i in the marketing district k
e_{ij} = the average required capacity of seedling cultivation for the group of seedling type i in the nursery j
f_j = the annual fixed costs for the nursery j
b_j = the capacity of the nursery j
l_j = the additional capacity required by the nursery j
l'_j = the additional capacity available to the nursery j
h_j = the price of the additional capacity per year in the nursery j
I_{ij} = the group of market areas to which it is possible to transport seedlings of the group of seedling type i from the nursery j
J_{ik} = the group of nurseries from which it is possible to transport seedlings of the group of seedling type i to the marketing district k
I = the number of groups of seedling types
J = the number of nurseries
K = the number of marketing districts.

The calculations concerning the average transportation costs can for example be based on the average transportation distance by road from a nursery to one or several centers in the marketing district. The expected average variable costs per unit of seedling cultivation are obtained from the bookeeping and cost calculation system of the nurseries which are involved in the procedure of seedling price determination. Also the problems concerning the capacity of a single nursery are easily resolved. The feasible marketing district for each nursery are determined mainly by the origin of the seeds used in the nursery, location between the area where the seedlings are used (marketing district) and the nursery (concerning the employments the nursery should be slightly southwards from the area where the seedlings are used) and by factors concerning transportation technology.

The cultivation areas of various seedling type groups in each nursery can be determined by making each x_{ijk} in the model correspond to the cultivated area but not to the volume produced and transported. In this case the coefficients of the objective function must be changed to correspond to the original objective. The coefficients of the side constraints describing capacity and demand must be changed correspondingly.

Using the symbols presented above the model can be formulated as follows:

$$\min \sum_{I=1}^{I} \sum_{j=1}^{J} \sum_{k \in I_{ij}} x_{ijk} (c_{ij} + c'_{jk}) + \sum_{j=1}^{J} (l_j h_j + f_j)$$

subject to:

$$\sum_{I=1}^{I} \sum_{k \in I_{ij}} e_{ij} x_{ijk} \leq b_j + l_j, \; j = 1, 2, \ldots, J$$

$$\sum_{j \in J_{ik}} x_{ijk} \geq d_{ik}, \; i = 1, 2, \ldots, I$$
$$, \; k = 1, 2, \ldots, K$$

$$l_j \leq l'_j, \; j = 1, \ldots, J$$

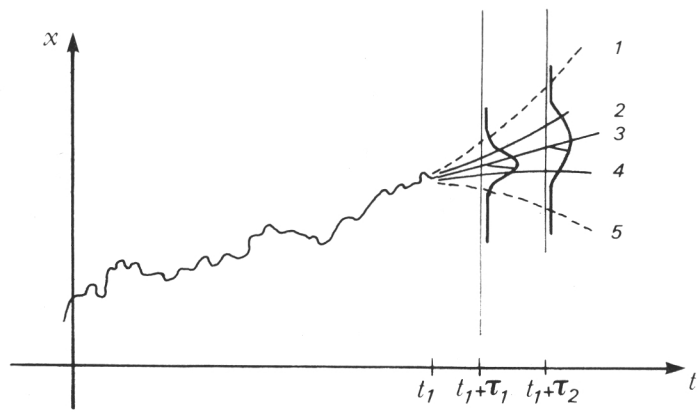
$$x_{ijk} \geq 0, \; i = 1, \ldots, I$$
$$, \; j = 1, \ldots, J$$
$$l_j \geq 0, \; k = 1, \ldots, K$$

3. RISK FACTORS

31. Chance-constrained programming models

In the above formula the variables, which in reality have distribution, have been replaced with their expectation values. As the future is always uncertain, the parameters must be forecast and for that reason there are always prophesy errors. It is necessary that the forecast method can be verified and the computed expectation value should also include some information about the prophesy errors (T h e i l *et al.* 1965). In practice this is done by giving the most likely value of the forecast together with the minimum and maximum values between which the values of the phenomena are believed to remain within certain probability (T ö r n q v i s t 1974).

If a more exact forecast is desired one must try to estimate the distribution of all possible values. A possible solution for a prediction problem is given in Figure 3 (T ö r n q v i s t 1974).



1 = 97,5 %:n fractile – fraktiili
2 = 75,0 %:n –"– – –"–
3 = 50,0 %:n –"– (mean) – –"– (odotusarvo)
4 = 25,0 %:n –"– – –"–
5 = 2,5 %:n –"– – –"–

Fig. 3. A possible solution for a prediction problem.
Kuva 3. Ennustusongelman kuviteltu ratkaisu.

The prophesy errors of economical phenomena are normally greater than those, for example, of astronomical ones. This is due to the fact that the forecasts of the economy concern phenomena which are results of (more or less) free action of millions of individuals (T h e i l *et al.* 1965). The greatest difficulties are faced when trying to obtain reasonably reliable input data for a linear programming model when applying it to economic problems.

As the models often deal with the planning of future operations, they include more or less random parameters. In these cases the input data of the model may be guesses of the decision maker and thus reflect his expectations and hopes.

The model can be made more realistic if the random nature of the input data is considered. A linear programming model becomes a stochastic one if at least one of the parameters is stochastic. Stochastic linear programming models can be classified into three groups (N ä s l u n d 1967)

— proper stochastic linear programming
— linear programming under uncertainty
— chance-constrained programming.

In the following, a chance-constrained programming model will be developed. This corresponds to the linear programming model represented in section 24. The chance-constrained is an exception in that it does not require of the linear model absolute existance of constraints. It is only supposed that a constraint holds with a certain probability level α. A chance-constrained model becomes linear when $\alpha = 1$. Probability $1-\alpha$ reflects the highest risk which the decision maker allows for a constraint not to be valid.

A linear programming model in universal form can be described as follows

$$\begin{aligned} &\min\ c^T x \\ &\text{st.}\quad Ax \leq b \\ &\qquad x \geq 0 \end{aligned}$$

and the corresponding chance-constrained programming model is (N ä s l u n d 1967)

$$\begin{aligned} &\min.\ f(c^T x) \\ &\text{st.}\quad P\,(Ax \leq b) \geq \alpha \\ &\qquad x \geq 0 \end{aligned}$$

in which P (Q) is the probability that Q is true and f is a function of x.

The theory of chance-constrained programming models has been developed in several papers (i.e. C h a r n e s *et al.* 1958, C h a r n e s and C o o p e r 1959, N ä s l u n d 1967). As described in section 28 the linear programming model will be developed into a chance-contrained model. This can be solved by CHAPS-algorithm (S e p p ä l ä 1972). In CHAPS-algorithm a chance-constrained problem is replaced by a deterministic one. In order to do this one must know the distribution

of the stochastic parameters and their mutual correlation in the model. Parameters are assumed to be independent of each other and normally distributed.

If the parameters are not normally distributed the required confidence coefficients can be estimated with Tsebysev's theorem (Cox and Miller 1965 p. 219). If the parameters are dependent on each other, and an ortogal alternation must be made (Seppälä 1971) and the inequalities of the change of the basis become the constraints of the model. CHAPS-algorithm replaces the nonlinear chance-constraints of the deterministic model with a group of uniformly tighter linear constraints. The resulting linear programming problem is solved by a standard simplex method. The linear programming model is then revised using the solution data and solved again. This is repeated until the required exactness has been reached.

Besides the stochastic constraints, the model can also include normal linear constraints. The convergence of the algorithm presupposes that $0{,}5 \leq \alpha \leq 1$. In practice the decision maker chooses α to be near 1. The algorithm has been developed for the cases where the elements of matrix A and vector b can be random variables.

32. Risk caused by demand

In the above it was assumed that the expectation value (d_{ik}) of seedling demand in each marketing district is known. As a prediction this demand includes prophesy errors. Demand is assumed to be normally distributed. The deviation of the demand can be calculated from either the expectation values or the already completed results. As the demand is expected to follow normal distribution, one can claim that demand, in theory, is allowed to have extremely high values on one hand and small, even negative values, on the other. This is a problem of no practical significance. For example, it the expected demand for seedlings is 20 units and the deviation is 2,5 units, the theoretical probability for negative demand is less than 10^{-15} (cf. Theil *et al.* 1965).

33. Risk caused by variation in seedling yield

The yield of seedlings meeting the quality requirements per unit area varies annually according to factors of seed origin, weather conditions, etc. Some research data exists concerning the expected yield figures for certain seedling types (Kuokkanen 1971), but distributions of the yield are not given. The expectation values and distributions of the capacity needs can be calculated by groups of seedling types and by nurseries from the inventories made earlier. Also the capacity needs are assumed to have a normal distribution.

As the yield figures vary, so do the variables costs of seedling cultivation. The the greater the yield figure (i.e. the smaller the demand of capacity per production unit), the smaller are the variable unit costs and vice-versa. These variations are expected to be proportional in accordance with the contribution profit method.

Then

$$c_{ij} = \frac{e_{ij}}{\mu(e_{ij})} \cdot \mu(c_{ij})$$

where

$\mu(e_{ij})$ is the expectation of e_{ij}
$\mu(c_{ij})$ is the expectation of c_{ij}.

34. Chance-constrained programming model

As mentioned in section 31 CHAPS-algorithm can be used in solving chance-constrained problems in which the parameters of the coefficient matrix A, vector b or of the both are normally distributed and independent of each other. In section 33 it was assumed that the yield figures have a normal distribution. Further, it was concluded that the variable costs and the capacity needs were proportional which means that they have linear correlation with each other. This results in the production costs being normally distributed.

In the following, the expectation operator is marked as μ and deviation operator as δ. In accordance with the above mentioned and Chapter 32 and 33 the following formulas can be written:

$$c_{ij} \sim N\left(\mu(c_{ij}), \frac{\mu^2(c_{ij})}{\mu^2(e_{ij})} \cdot \delta^2(e_{ij})\right)$$

$$e_{ij} \sim N\left(\mu(e_{ij}),\ \delta^2(e_{ij})\right)$$
$$d_{ik} \sim N\left(\mu(d_{ik}),\ \delta^2(d_{ik})\right)$$

$$c_{ij} + c'_{ik} \sim N\left(\mu(c_{ij}) + c'_{jk}, \frac{\mu^2(c_{ij})}{\mu^2(e_{ij})} \cdot \delta^2(e_{ij})\right)$$

Now the linear model presented in section 24 equals the chance-constrained model

$$\min \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k \in I_j} x_{ijk}\,(c_{ij} + c'_{jk}) + \sum_{j=1}^{J} (l_j\, h + f_j)$$

subject to

$$P\left(\sum_{i=1}^{I} \sum_{k \in I_{ij}} e_{ij} x_{ijk} \leq b_j + I_j\right) \geq \alpha_j,\ j = 1, 2, \ldots, J$$

$$P\left(\sum_{j \in J_{ik}} x_{ijk} \geq d_{ik}\right) \geq \alpha_{ik},\ i = 1, 2, \ldots, I$$
$$, \ k = 1, 2, \ldots, K$$

$$l_j \leq l'_j \qquad , \ j = 1, 2, \ldots, J$$

$$x_{ijk} \geq 0 \quad , i = 1, 2, \ldots, I$$
$$\quad , j = 1, 2, \ldots, J$$
$$l_j \geq 0 \quad , k = 1, 2, \ldots, K$$

As the cost coefficients are random variables, a fractile approach transformation (see Geoffrin 1967, Sengubta and Portillo-Gambell 1970) will be made to the model in order to make it suitable for CHAPS-algorith

min q

subject to

$$P\left(-q + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k \epsilon I_{ij}} x_{ijk}(c_{ij} + c'_{jk}) + \sum_{j=1}^{J} (I_j h_j + f_j) \leq 0\right) \geq \alpha$$

(other constraints as above) and $q \geq 0$.

When the formulas of the expectation values and deviations are placed into the model and when marking $F^{-1}(\alpha) = K_a$, $F^{-1}(\alpha_{jk}) = K_{ajk}$ and $F^{-1}(\alpha_j) = K_{aj}$ where F is the cumulative distribution function of an N (0,1) variable, the model assumes the final form (see Seppälä 1972).

min q

subject to

$$-q + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k \epsilon I_{ij}} (\mu(c_{ij}) + c'_{jk}) x_{ijk} + \sum_{j=1}^{J} (I_j h_j + f_j) +$$

$$K_a \left(\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k \epsilon I_{ij}} \frac{\mu^2(c_{ij})}{\mu^2(e_{ij})} \cdot \delta^2(e_{ij}) \cdot x^2_{ijk}\right)^{1/2} \leq 0$$

$$\sum_{i=1}^{I} \sum_{k \epsilon I_{ij}} \mu(e_{ij}) \cdot x_{ijk} + K_{aj} \left(\sum_{i=1}^{I} \sum_{k \epsilon I_{ij}} \delta^2(e_{ij}) \cdot x^2_{ijk}\right)^{1/2} \leq b_j + I_j, \; j = 1, 2, \ldots, J$$

$$\sum_{j \epsilon J_{ik}} x_{ijk} - K_{aik}(\delta^2(d_{ik}))^{1/2} \geq \mu(d_{ik}), \; i = 1, 2, \ldots, I$$
$$\quad , k = 1, 2, \ldots, K$$

$$l_j \leq l'_j, \; j = 1, 2, \ldots, J$$

$$x_{ijk} \geq 0 \quad , i = 1, 2, \ldots, I$$
$$\quad , j = 1, 2, \ldots, J$$
$$l_j \geq 0 \quad , k = 1, 2, \ldots, K$$

$$q \geq 0$$

4. A HYPOTHETICAL EXAMPLE

41. Introduction

In order to test the programming models described in Chapters 2 and 3 they will be used only in a hypothetical example rather than in practice. The planning area has been divided into ten market districts, as shown in Figure 4. It is assumed that the area includes three nurseries. The market demand for seedlings in this area will be divided between three nurseries using the above mentioned programming models. In this case the seedlings to be produced are divided into two groups (pine and spruce). Attention is mainly paid to the difference between the solutions generated by these programming models and to the consequences in choosing the parameters. Thus the solutions themselves have no significance.

42. Input data (of the models)

The case situation has been constructed to fulfill the circumstances of the year 1972. Thus the variable costs of seedling cultivation have been assumed to be about the same as Kuokkanen has estimated in 1969 (K u o k k a n e n 1969). The unit costs and the corresponding deviations (in parenthesis) of different nurseries for pine are: 869 (81), 725 (67) and 834 (78) Fmk/10 000 seedlings and for spruce: 893 (90), 1 024 (105) and 913 (95) Fmk/10 000 seedlings. The deviation figures have no statistical background as they have not been studied. They have been estimated here from the expectation values (to be presented later) and the deviations of the capacity needs as described in section 34. It is assumed here that the land area is the most scarce production factor of a nursery. The definition of the capacity needs can be based on the yield figures, which are obtained from K u o k k a n e n (1969). The average expectation values for capacity needs and their deviations (in parenthesis) of different nurseries for pine are 99 (9,2), 94 (8,7) and 96 (9,0) m^2/10 000 seedlings and similarly for spruce 85 (8,6), 87 (8,9) and 82 (8,5) m^2/10 000 seedlings. The deviation figures are not based on the studies but are assumed to be about 10 % of the average capacity need for cultivation of the seedling in question.

The average transportation costs of seedlings have been assumed to be about



Fig. 4. The case nurseries, marketing districts and transportation routes.
Kuva 4. Esimerkkitilanteen taimitarhat, markkina-alueet ja taimien kuljetusreitit.

0,4 Fmk/km/10 000 seedlings (see Ruottinen 1975). Transportation distance from a nursery to the markets (here to the weighted central point of the market district; cf. Fig. 4) has been assumed to be twice the straight-line distance. The transportation costs of seedlings from different nurseries to different market districts were calculated and are presented in Table 2. A dash in the costs-column indicates that seedlings were unable to be transported from the nursery to the market district in question.

The demand (expectation values) for pine and spruce seedlings in each market district has been estimated as follows: the amount of pine and spruce seedlings used for planting and blanking in 1972 was divided among the market districts according

Table 2. Transportation cost of plants from nurseries to marketing districts.
Taulukko 2. Taimien kuljetuskustannukset taimitarhoilta markkina-alueille.

Fmk/10 000 seedlings — *mk/10 000 kpl*

Marketing district [1]) *Markkina-alue* [1])	Nursery [1]) — *Taimitarha* [1])		
	1	2	3
1	33	140	—
2	86	71	—
3	41	90	77
4	149	48	—
5	111	15	133
6	72	68	69
7	—	62	192
8	—	53	119
9	138	93	68
10	125	—	36

[1]) The marketing districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*

Table 3. Mean values and standard deviations (in parentheses) of demand for plants in the marketing districts.
Taulukko 3. Männyn ja kuusen taimien kysynnän odotusarvot ja hajonnat (suluissa) markkina-alueittain.

10 000 seedlings — *10 000 kpl*

Marketing district [1]) *Markkina-alue* [1])	Pine *Mänty*	Spruce *Kuusi*
1	325 (37)	33 (4,0)
2	157 (15)	16 (1,7)
3	92 (7)	9 (1,0)
4	70 (7)	7 (1,1)
5	71 (6)	7 (0,9)
6	58 (4)	6 (0,8)
7	41 (4)	4 (0,6)
8	87 (8)	9 (1,3)
9	206 (21)	21 (2,5)
10	318 (30)	33 (3,8)

[1]) The marketing districts are shown in fig. 4. — *Markkina-alueet on esitetty kuvassa 4.*

to the proportional share of forest land of the district. The deviation of the demand has been assumed to be about 10 %. The expectation values and deviations of the demand for pine and spruce in each district are shown in Table 3.

The effective cultivation areas of the nurseries were chosen in our case study so that the combined sum of production capacity exceeded the demand for seedlings with about 20 % in the whole area when combined production capacity was randomly divided between nurseries. The effective cultivation areas of nurseries were 7,44, 4,30 and 6,48 hectares. These cultivation areas were equal to a production capacity of 7,5, 4,6 and 6,7 million seedlings yearly. It was assumed that each nursery was able to obtain about 40 % of additional production capacity i. e. 3,0, 1,7 and 2,6 hectares. The additional costs per hectare (including the rent and the preparation of the land for nursery cultivation) were assumed to be 9 800, 12 000 and 10 700 Fmk per year for each nursery, respectively.

The fixed costs of the nurseries (including the salary of the nursery's foreman, depreciations of the buildings etc.) were assumed to be about 15 % of the total costs of the nursery running at a normal degree of activity (80 % of the capacity). In practice, the proportional share of the fixed costs decreases as the size of the nursery increases. In our case, the fixed annual costs of the nurseries are 90 000, 44 000 and 76 000 mk. The fixed costs have no importance in the order of profitability between the production plans generated by the programming models. This is because they are used only as constants in the target function. They naturally affect the absolute value of the target function.

Figure 4 shows the possible alternatives for the transportation of seedlings from the nurseries to the markets. It is assumed that both the pine and the spruce seedlings can be transported from every nursery to the same market districts. The arrow from the nursery (i) to the market district (k) indicates this possibility.

43. Problem solution

The linear model and the chance-constrained models were solved using UNIVAC 1008 computer library programmes. The solution of the constructed linear model, the basic model, gives a natural basis for making comparisons when studying the effect of risk on the optimal production plan. The detailed solution of the basic model will be presented. The value of the target function of the basic model is 1,34 mill. Fmk. This minimum value will be reached if used in accordance with the production and transportation plans given in Table 4. Only one market district is provided with pine seedlings from more than one nursery. Spruce seedlings are transported to only one market district from each nursery for the following reasons; firstly, because each nursery is optimally located therefore the sum of the transportation and cultivation costs is at its minimum. Secondly, because the nurseries have sufficient cultivation area (production capacity). Only in nursery (2) will the cultivation area be totally used and for this reason the pine seedlings for the market district (6) must be obtained from nursery (3) which is the next most profitable nursery. This procedure is more economical than obtaining additional land for nursery (2). The combined sum of the unit costs of seedling cultivation and transportation is less than the unit cost for obtaining additional land for the nursery. Shadow prices can be used when analyzing the behavior of the model in the surroundings of the optimal solution when the basic data is slightly altered.

If the land area of nursery (2) had been 10 sq.m larger to start with then the minimum value of the target function would decrease by 11,7 Fmk. Thus, if the additional land for the nursery cost less than 11 700 Fmk per hectare it would be worth purchasing. From the basic data it was assumed that the additional land for nursery (2) would cause annual costs of 12 000 Fmk. The decrease in costs per hectare should exceed 300 Fmk before the additional land would be profitable. The above case is only

Table 4. Production and transportation plan obtained by linear programming [3]).
Taulukko 4. Lineaarisen mallin tuottama tuotanto- ja kuljetussuunnitelma [3]).

10 000 seedlings — *10 000 kpl*

Marketing district [1]) *Markkina-alue* [1])	Pine — *Mänty*			Spruce — *Kuusi*		
	Nursery [1]) — *Taimitarha* [1])					
	1	2	3	1	2	3
1	325	(8,4 %)	[2])	33	(29,2 %)	[2])
2	(5,1 %)	157	[2])	16	(19,8 %)	[2])
3	91	(1,8 %)	(0,1 %)	9	(25,3 %)	(5,7 %)
4	(13,3 %)	70	[2])	7	(12,3 %)	[2])
5	(13,3 %)	71	(12,1 %)	7	(13,2 %)	(4,0 %)
6	(4,0 %)	31	27	6	(21,0 %)	(1,7 %)
7	[2])	41	(12,6 %)	[2])	(7,6 %)	4
8	[2])	87	(6,8 %)	[2])	(13,6 %)	9
9	(10,4 %)	(3,2 %)	206	(4,8 %)	(21,3 %)	21
10	(12,5 %)	[2])	318	(6,8 %)	[2])	33
Total — *Yhteensä*	416	457	551	78	—	67

[1]) Marketing districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*
[2]) Seedlings can not be transported from the nursery to the corresponding marketing district. — *Taimia ei esimerkkitapauksessa voida kuljettaa ko. taimitarhalta vastaavalle markkina-alueelle.*
[3]) The percentage in brackets indicates how much the sum of the raising and transportation costs should be decreased in order to get the transportation route into the optimal plan. — *Suluissa oleva prosenttiluku ilmaisee kuinka paljon yhteenlaskettujen viljely- ja kuljetuskustannusten olisi laskettava, jotta ko. kuljetusreitti tulisi mukaan optimaaliseen tuotantosuunnitelmaan.*

valid in surroundings of the optimal solution. In other words, it is not clear whether the minimum value of the target function actually decreased 1 170 Fmk, if the purchase of 0,1 hectare of land for 1 170 Fmk was possible. The other nurseries have land in excess (nursery 1 2,66 hectares and nursery 3 0,65 hectares) in the optimal solution and the question of obtaining additional land does not even arise.

Table 4 describes how much the combined sum of cultivation and transportation costs should decrease before this cultivation and transportation alternative can be placed into the optimal production plan. From these percentage figures it is easy to calculate how much the production unit costs should decrease in a nursery so that the transportation route in question would be profitable. In order to transport pine seedlings economically from nursery (1) to market district (2) the sum of cultivation and transportation costs should decrease by 5,1 %. Once the unit costs of cultivation and transportation are known it can be concluded that the unit costs for pine seedling cultivation in nursery (1) should decrease by 5,7 % before it can profitable to supply them to market district (2). The situation differs when we take the deviation of the seedling yield figures into consideration. For pine seedlings, the optimal cultivation areas in the nurseries are 4,12, 4,30 and 5,30 hectares (Table 6) and for spruce 0,67 hectares in nursery (1) 0,54 hectares in nursery (3). As mentioned earlier according to the optimal solution it is not profitable to produce spruce seedlings in nursery (2).

Thus, according to the model it is worth cultivating pine seedlings in every nursery but not spruce. The unit costs of the spruce in nursery (2) are considerably higher than the unit costs in other nurseries.

The basic data for the linear programming model was assumed to be exact. In

Table 5. Production and transportation plan obtained by chance-constrained programming when the risk level is 0,5 % and the yield figures are random variables [3]).

Taulukko 5. Riskirajoitteisen mallin tuottama tuotanto- ja kuljetussuunnitelma riskitasolla 0,5 %, kun saantoluvut ovat satunnaismuuttujia [3]).

10 000 seedlings — *10 000 kpl*

Marketing district [1]) *Markkina-alue* [1])	Pine — *Mänty*			Total *Yhteensä*
	Nursery [1]) — *Taimitarha* [1])			
	1	2	3	
1	285	40	[2])	325
2	78	78	[2])	156
3	64	(2,7 %)	27	91
4	(4,1 %)	70	[2])	70
5	(3,8 %)	71	(4,2 %)	71
6	7	(0,2 %)	51	58
7	[2])	41	(6,2 %)	41
8	[2])	77	10	87
9	(0,8 %)	39	167	206
10	43	[2])	275	318
Total — *Yhteensä*	477	416	530	1 423

[1]) Marketing-districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*
[2]) Seedlings can not be transported from the nursery to the corresponding marketing district. — *Taimia ei esimerkkitapauksessa voida kuljettaa ko. taimitarhalta vastaavalle markkina-alueelle.*
[3]) For the figures in parenthesis, see table 4. — *Suluissa olevien prosenttilukujen tulkinta sama kuin taulukon 4 yhteydessä.*

reality this assumption is not valid as there is always deviation in the seedling yield figures as well as in the demand for them. The yield of seedlings is based on many factors; weather conditions, the origin of seeds etc. The yield per cultivation area of a certain seedling group can never be constant from year to year. It would also be unnatural to assume that the demand for certain seedlings from a certain nursery could be forecast without prophesy error.

Firstly, the effect of the random nature of the seedling yield figures on the seedling production plan and the minimum costs is examined. Secondly, the case in which random variation occurs only in demand is studied and finally the most realistic case in which the yield figures and demand volumes have the random nature which is characteristic to them.

In the optimal solution of the linear model, where there was no random variation in the yield figures, seedlings were mainly transported to each market district from only one nursery. The situation is quite different when the annual random variation in the seedling yield figures is taken into consideration. The expected yield figure, and consequently the expected production costs in a nursery, do not alone determine the nursery for each market district. This is largely influenced by the deviation of the yield figures and how great a risk the decision maker is willing to take. Here the risk means how large a cultivation area is reserved for the seedlings in order to avoid the shortage of them due to the deviation. The higher the risk the more likely it is that too few seedlings are produced to meet the demand because the cultivation area is too small (the probability corresponds to the level of risk).

Table 5 shows the production and transportation plan in which the cultivation

Table 6. The pine cultivation area in different nurseries according to the models obtained by linear programming and chance-constrained programming at different levels of risk when the yield figures are random variables.

Taulukko 6. Lineaarisen ja riskirajoitteisen mallin mukaiset männyn viljelypinta-alat taimitarhoittain eri riskitasoilla, kun saantoluvut ovat satunnaismuuttujia.

Hectares — *Hehtaaria*

Risk level *Riskitaso*	Pine — *Mänty*			Total *Yhteensä*
	Nursery [1]) — *Taimitarha* [1])			
	1	2	3	
LP	4,12	4,30	5,30	13,72
20 %	4,43	4,30	5,88	14,61
15 %	4,54	4,30	5,88	14,72
10 %	4,68	4,30	5,87	14,85
5 %	4,93	4,30	5,86	15,09
2 %	5,13	4,30	5,85	15,28
1 %	5,26	4,30	5,84	15,40
0,5 %	5,40	4,30	5,84	15,54

[1]) Marketing-districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*

area of the nursery was anticipated to be sufficient to meet the assumed demand for seedlings from each nursery with a probability of 99,5 %. As an exception to the solution of the linear model, pine seedlings are transported to market districts from more than one nursery in almost every case. This is due to the deviation in the yield figures. Spruce seedlings are transported to market districts from the same nurseries as in the solution of the linear model regardless of the level of risk. For this reason they are not presented in Table 5. Only the transportation volume varies according to the risk.

There is reason to introduce the detailed plans for seedling production and transportation. However, a good picture concerning the effects of the deviation in yield figures for the seedling production can be obtained from Table 6 which shows how the cultivation area of pine seedlings changes in each nursery as the risk changes. In comparison, the corresponding cultivation areas according to the linear model are also presented in Table 6. In conclusion, it can be said that the increase in the cultivation area is nonlinear with the decrease in the risk. Nonlinearity occurs in such a way that when the level of risk is high, any drop in risk requires a smaller increase in the cultivation area than at lower levels of risk. None of the nurseries had to obtain additional capacity (land) at any level of risk.

When only demand figures are assumed to have deviation, the chance-constrained model becomes linear. Then the product of demand deviation and confidence coefficient of the level of risk must be added to the right hand side of the expectation value of the demand constraints. Instead of giving the detailed plans for production and transportation, only the cultivation areas of pine seedlings are given to each nursery at different levels of risk (Table 7). When we compare the cases in which on the one hand only the yield figures have deviation and on the other only the demand figures have deviation, it can be observed that when the

Table 7. The pine cultivation area in different nurseries according to the chance-constrained programming model at different levels of risk when the demand figures are random variables.

Taulukko 7. Riskirajoitteisen mallin mukaiset männyn viljelypinta-alat taimitarhoittain eri riskitasoilla, kun kysyntäluvut ovat satunnaismuuttujia.

Hectares — *Hehtaaria*

Risk level *Riskitaso*	Pine — *Mänty*			Total *Yhteensä*
	Nursery [1]) — *Taimitarha* [1])			
	1	2	3	
20 %	5,32	4,30	5,84	15,46
15 %	5,54	4,30	5,84	15,68
10 %	5,82	4,30	5,84	15,96
5 %	6,10	4,30	5,99	16,39
2 %	6,42	4,30	6,17	16,89
1 %	6,56	4,36	6,29	17,21
0 5 %	6,55	4,57	6,40	17,52

[1]) Marketing-districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*

risk decreases, the latter case demands about 0,4—0,8 hectares more additional land than the case with deviation in yield figures. When operating at a risk level of 2 % 0,23 hectares of additional land are needed in nursery (3). At a risk level of 1 % the required additional land area is 0,06 hectares for nursery (2) and 0,53 hectares for nursery (3). Corresponding areas at a risk level of 0,5 % are 0,27 and 0,66 hectares. Nursery (1) has an excess capacity at every level of risk.

When the deviation of both demand and yield is taken into consideration the required additional area grows considerably faster than in the above (where deviation was included only with either the demand or the yield) as the admissible risk increases. Now obtaining additional land becomes necessary even when operating at a much higher level of risk than previously. Thus, even at the risk level of 15 %, 0,017 hectares of additional land must be obtained by nursery (1) and at the level of 10 % correspondingly 0,48 hectares. When the risk decreases further land must also be obtained for nursery (2). At the 0,5 % level the required additional land is 2,55 hectares for nursery (1) and 0,61 hectares for nursery (2). Nursery (3) never

Table 8. The pine cultivation area in different nurseries according to the chance-constrained programming model at different levels of risk when both the yield figures and the demand figures are random variables.

Taulukko 8. Riskirajoitteisen mallin mukaiset männyn viljelypinta-alat taimitarhoittain eri riskitasoilla, kun sekä saanto- että kysyntäluvut ovat satunnaismuuttujia.

Hectares — *Hehtaaria*

Risk level *Riskitaso*	Pine — *Mänty*			Total *Yhteensä*
	Nursery [1]) — *Taimitarha* [1])			
	1	2	3	
20 %	6,55	4,28	5,77	16,58
15 %	6,65	4,30	5,75	16,70
10 %	7,04	4,30	5,73	17,07
5 %	7,60	4,38	5,67	17,65
2 %	8,18	4,60	5,64	18,42
1 %	8,58	4,76	5,61	18,95
0,5 %	8,93	4,91	5,59	19,43

[1]) Marketing-districts and nurseries are shown in fig. 4. — *Markkina-alueet ja taimitarhat on esitetty kuvassa 4.*

needs additional land. Thus the situation with nursery (3) is just the opposite of the case where only the demand figures were random variables.

The cultivation areas of pine seedlings at different levels of risk for each nursery are presented in Table 8.

Finally, the minimum value of the target function is studied as a function of the risk in all three cases presented above. For comparison purposes, it is worth keeping in mind the minimum value of the target function of the linear model which was 1,34 mill. Fmk. Figure 5 shows the correlation between the minimum costs and the level of risk when only the yield figures are assumed to have deviation. Figure 6 shows the situation where deviation occurs only in the demand. Finally, Figure 7 shows the situation where both the demand and the yield are random variables. When the risk approaches zero indefinitely, the required cultivation area per seedling

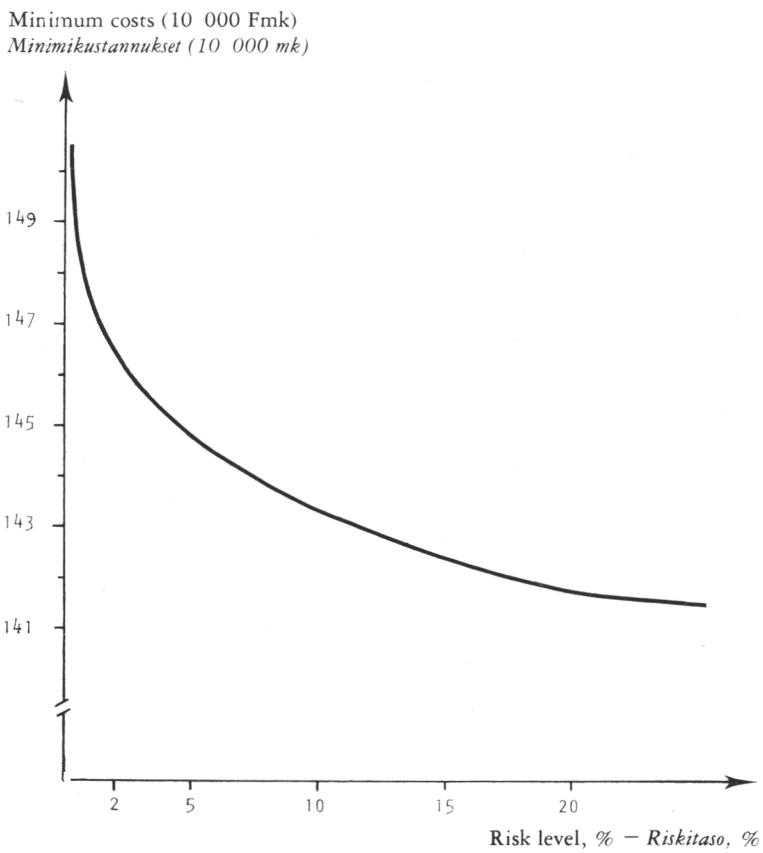


Fig. 5. Minimum value of the objective function in the chance-constrained programming model. Minimum value as a function of the risk when the yield figures are random variables.

Kuva 5. Riskirajoitteisen mallin tavoitefunktion minimiarvo riskin funktiona saantolukujen ollessa satunnaismuuttujia.

increases to infinity. Due to limited capacity resources of the nurseries there exists a certain risk level, under which seedling production is no longer possible. Then the chance-constrained programming model has no feasible solution. This is presented in Figures 5—7 where the curve of the minimum costs approaches infinity as the risk approaches zero, although the curve should be cut at the above mentioned marginal level of risk. This marginal risk level can be found only through iteration, i.e. solving the problem several times at different levels of risk using, for example, the method of bisecting search. This would, at any rate, become too expensive, and as the marginal risk level has no practical importance, the above mentioned procedure has been used.

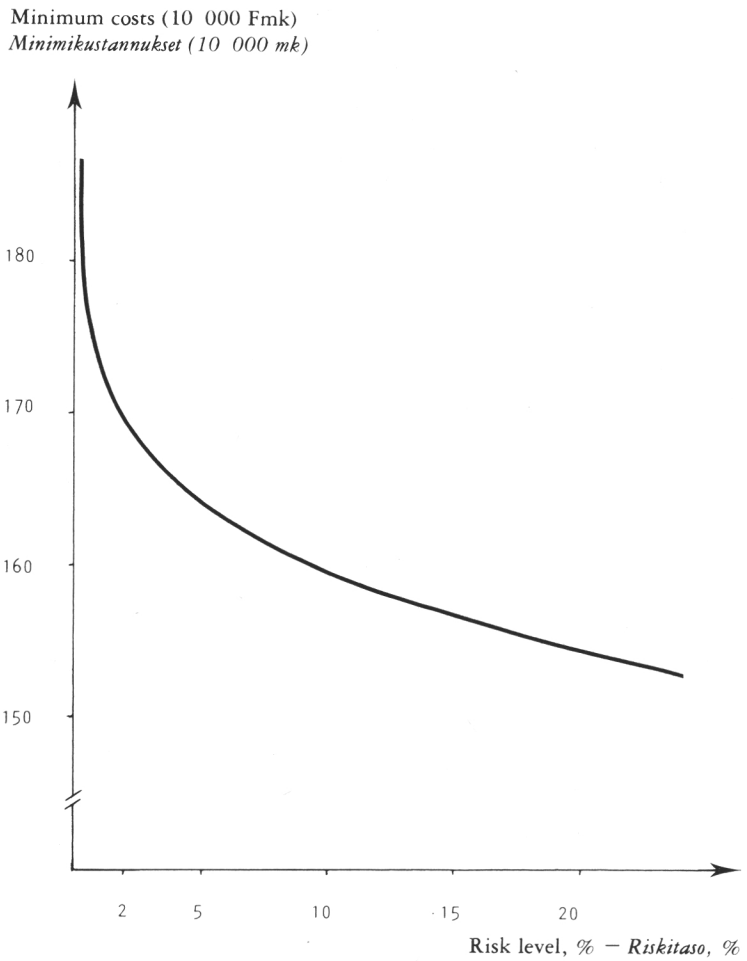


Fig. 6. Minimum value of the objective function in the chance-constrained programming model. Minimum value as a function of the risk when the demand figures are random variables.

Kuva 6. Riskirajoitteisen mallin tavoitefunktion minimiarvo riskin funktiona kysyntälukujen ollessa satunnaismuuttujia.

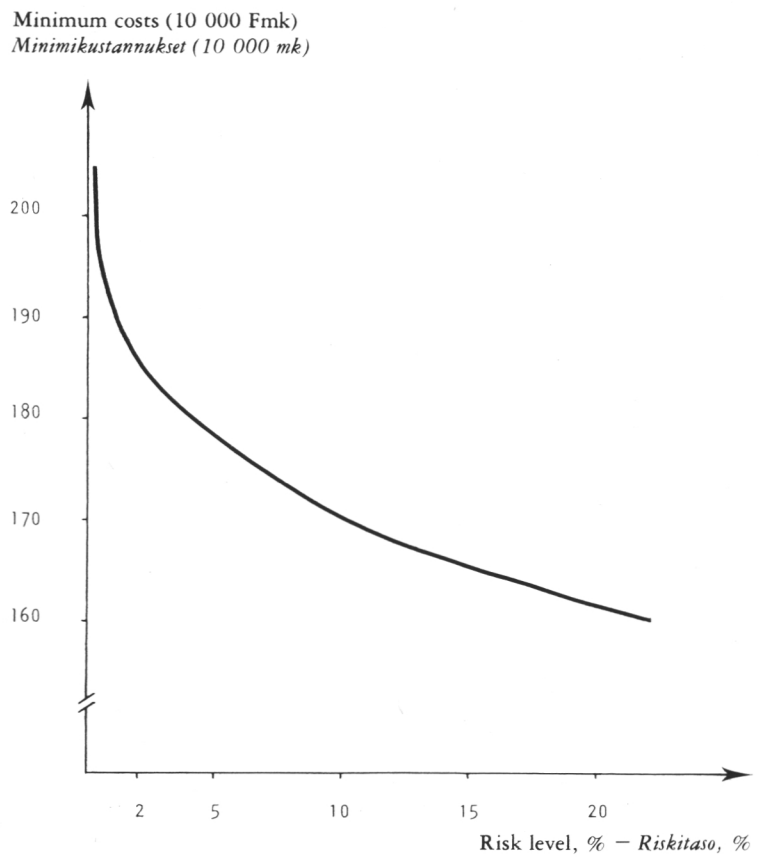


Fig. 7. Minimum value of the objective function in the chance-constrained programming model. Minimum value as a function of the risk when both the yield figures and the demand figures are random variables.

Kuva 7. Riskirajoitteisen mallin tavoitefunktion minimiarvo riskin funktiona sekä sekä saanto- että kysyntälukujen ollessa satunnaismuuttujia.

A general characteristic for the curves of minimum costs is that when the risk decreases from the level of 2—3 %, the increase of costs is very high. On the other hand, when the risk increases over the level of 10 per cent, the decrease of costs is low. In this hypothetical example these figures can be considered to be limits for the level of risk which may be profitable to select for the production and transportation plans. In the application of the model, the optimal level of risk cannot be given beforehand. Thus the level of risk is a variable which is based on the intuition of the decision maker. Decision making can be made easier when computing the model at several levels of risk as has been done in the case situation.

5. CONCLUSIONS

The constructed models can be used for dividing the market demand for seedlings between the nurseries in a certain district. The target of the problem is to minimize the combined costs of seedling production and transportation. Models can be utilized for planning new nurseries or replacing old ones. The one or more hypothetical nurseries must be introduced into the model. In a chance-constrained programming model one or more of the basic data are stochastic. Thus the absolute existence of the constraints is not required but they should come into effect at a certain level of risk (α), chosen by the decision maker for each of the constraints. This means, that with the risk of $1-\alpha$ the constraint is not valid.

The effect of the chosen risk level (α) on the production plans of the nursery can be studied with the chance-constrained model when the capacity needs and costs of the seedling cultivation and/or the market demand are random variables which are normally distributed and independent of each other. These restrictions can be eased if needed. The solution method, CHAPS-algorithm, assumes that $0{,}5 \leq \alpha \leq 1$.

The production planning can be further adjusted when applying the (economic) model for selecting production alternatives in each nursery (L a a k k o n e n 1978). This model, as well as the models formulated here, are a part of an improvement in the information system of the nurseries.

REFERENCES

BEALE, E. M.L. 1968. Mathematical programming in practice. 191 p. London. Pitman Publishing.

CHARNES, A. & COOPER, W. 1959. Chance-constrained programming. Management Science 10: 73—79.

— & SYMONDS, G. 1958. Cost horizons and certaining equivalents: An approach to stochastic programming of heating oil. Management Science 10: 73—79.

COX, D. & MILLER, H. 1965. The theory of stochastic processes. 398 p. London. Methuen & Co Ltd.

FOG, B. & RASMUSSEN, A. 1960. Driftsøkonomi I. 311 p. Kööpenhamina. Einar Harcks Forlag.

GEOFFRION, A. 1967. Stochastic programming with aspiration or fractile criteria. Management Science. 9: 672—679.

HADLEY, G. 1963. Linear programming. 520 p. Reading. Addison-Wesley.

JOHNSEN, E. 1968. Studies in multiobjective decision models. 628 p. Lund. Berlingska Boktryckeriet.

KUOKKANEN, P. 1971. Metsäviljelytaimien kasvatuskustannukset vuosina 1969 ja 1972. Summary: Costs of growing forest-tree seedlings in nurseries in 1969 and 1972. Folia For. 122: 1—24.

LAAKKONEN, O. 1978. Taimitarhan toimintavaihtoehtojen liiketaloudellinen malli. Summary: An economic model for selecting production alternatives in a forest nursery. Commun. Inst. For. Fenn. 95(3): 1—95.

LIPSEY, R. 1966. An introduction to positive economics. 871 p. London. Weidenfeld & Nicolson.

McGUIRE, J. 1964. Theories of business behavior. 268 p. Englewood Cliffs, N. J. Prentice-Hall.

METSÄMUURONEN, M., KAILA, S. & RÄSÄNEN, P. K. 1978. Männyn paakkutaimien alkukehitys vuoden 1973 istutuksissa. Summary: First-year planting results with containerized Scots pine seedlings in 1973. Folia For. 349: 1—36.

Yearbook of Forest Statistics. 1967—1975. Folia For. 47, 70, 96, 130, 165, 195, 225, 295.

NÄSLUND, B. 1967. Decisions under risk. 188 p. Stockholm. Repro Print Ab.

RUOTTINEN, M. 1975. Suonenjoen ja Pieksämäen taimitarhojen taimitoimitukset vuosina 1971 ja 1972. Metsäntutkimusl. metsänvilj. koeas. tiedonant. 13: 1—27.

SENGUPTA, J. & PORTILLO-CAMPBELL, J. 1970. A fractile approach to linear programming under risk. Management Science 5: 298—308.

SEPPÄLÄ, Y. 1971. Constructing sets of uniformly tighter linear approximations for a chance constraint. Management Science 17: 736—749.

— 1972. A chance-constrained programming algorithm. Stockholm. BIT 12: 376—399.

THEIL, H., BOOT, U. & KLOEK, T. 1965. Operations research and quantitative economics. 258 p. New York. McGraw-Hill.

TÖRNQVIST, L. 1974. Aikasarjojen analyysi ja ennustaminen. 125 s. Jyväskylä. Oy Gaudeamus Ab.

VILJO, T. 1974. Vuoden 1967 yksityismetsälaki selityksineen. 139 s. Helsinki. Kirjayhtymä.

ZANGWILL, W. I. 1969. Nonlinear Programming: A unified Approach. 356 p. Englewood Cliffs, N. J. Prentice Hall.

SELOSTE

Tutkimuksessa on tarkasteltu tietyn alueen taimien markkinakysynnän jakamista tuon alueen taimitarhojen tuotettavaksi. Tavoitteeksi on asetettu taimien tuottamisesta ja käyttöpaikalle kuljetuksesta aiheutuvien kustannusten summan minimointi. Tätä varten on aluksi kiinnitetty huomiota metsäpuiden taimien hinnan määräytymiseen sekä taimien tuotanto-organisaatioiden asemaan yleensä.

Edellä mainitun tavoitteen saavuttamiseksi on muodostettu sekä lineaarinen että riskirajoitteinen malli. Riskirajoitteisessa mallissa sallitaan vastaavan lineaarisen mallin parametrinen (viljelyn kapasiteettitarpeiden, viljelykustannusten ja markkinakysynnän) olevan luonteeltaan satunnaisia. Tällöin on edellytetty niiden olevan normaalisti jakautuneita ja keskenään riippumattomia. Näitä rajoituksia on tarvittaessa mahdollista lieventää. Riskirajoitteista mallia sovellettaessa voi päätöksentekijä valita todennäköisyydet rajoitusten voimassaololle ja samalla siis päättää kuinka suuren riskin hän ottaa sille, että rajoitukset eivät toteudu.

Lopuksi on konstruoitu hypoteettinen esimerkkitapaus, johon esitettyjä malleja on sovellettu. Kuvaan 4 on piirretty esimerkkitilanne taimitarhoineen, markkina-alueineen ja kuljetusreitteineen. Mallien muut lähtötiedot on esitetty taulukoissa 2 ja 3. Lineaarisella mallilla ja riskirajoitteisilla malleilla eri riskitasoilla saadut tuotanto- ja kuljetussuunnitelmat sekä näiden edellyttämät taimitarhakohtaiset viljelypinta-alat on esitetty taulukoissa 5—8. Kuvista 5—7 näkyy em. taulukoissa esitettyjä tuotanto- ja kuljetussuunnitelmia vastaavat minimikustannukset.

THE WINTER USE OF FOOD RESOURCES OF SEMI-DOMESTIC REINDEER IN NORTHERN FINLAND

TIMO HELLE AND OLLI SAASTAMOINEN

Seloste

POROJEN TALVINEN RAVINTOVAROJEN KÄYTTÖ

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HELLE, T. & SAASTAMOINEN, O. 1979. The winter use of food resources of semi-domestic reindeer in Northern Finland. Seloste: Porojen talvinen ravintovarojen käyttö. Commun. Inst. For. Fenn. 95(6) :1—27.

The purpose of the study was to gain a comprehensive survey of the present use of semi-domestic reindeer's (*Rangifer tarandus tarandus* L.) winter pastures and feeding resources. The data was collected by a questionnaire which was sent in 1975 and in 1977 to all reindeer management co-operatives. The study ranges from January to March, the most severe winter months.

Three fourths of the reindeer got their food on natural ranges in both study winters. The remainder sought arboreal lichens in the cutting areas or were fed in the corrals.

Among the natural ranges, lichen stands were most often used in the northern part of the reindeer management area. On the contrary, in many parts of central and southern areas the forests rich in arboreal lichens were more important than the lichen ranges. Supplementary feeding in the wild was mostly organized in forests with arboreal lichens. The *Deshampsia flexuosa* (clear cutting-) ranges were used only locally in the mid-winter.

The forests rich in arboreal lichens, mostly old spruce forests, constitute the most common minimal ecological grazing factor according to the considerations of reindeer management co-operatives. In the northern areas, however, the lichen ranges are reported as minimum factors.

Tutkimuksen tarkoituksena oli saada yleiskuva porojen talvilaidunten ja ruokintatapojen nykyisestä käytöstä. Aineisto on kerätty kyselymenetelmällä paliskunnilta vuosina 1975 ja 1977. Tiedustelu kohdistui tammi—maaliskuun väliseen ankarimpaan talvikauteen.

Molempina vuosina kolme neljäsosaa poroista hankki ravintonsa luonnonlaitumilta. Loput hakivat luppoa hakkuutyömailta tai olivat piharuokinnassa.

Luonnonlaitumista jäkäliköt olivat käytetyin laiduntyyppi poronhoitoalueen pohjoisosissa. Sen sijaan keskisellä ja eteläisellä poronhoitoalueella monen paliskunnan alueella luppometsät olivat jäkälikköjä tärkeämpiä laitumia. Lisäruokinta maastossa oli useimmiten järjestetty luppometsien yhteyteen. Metsälauhalaitumia (avohakkuualueita) käytettiin sydäntalven aikana vain paikallisesti.

Luppometsät, pääasiassa vanhat kuusikot, ovat paliskuntien arvioinnin mukaan tavallisin minimitekijä laiduntilanteen kannalta. Pohjoisella alueella minimitekijänä ovat kuitenkin jäkäliköt.

Helsinki 1979. Valtion painatuskeskus

PREFACE

The study is a part of the project concerning the significance of old spruce forests from the standpoint of reindeer husbandry. The study is being undertaken at the Rovaniemi Research Station of the Finnish Forest Research Institute. Besides the authors Yrjö N o r o k o r p i, DF., is a member of the research group.

The division of the work between the authors was as follows: Planning was done together. The data collecting and analysis was supervised by S a a s t a m o i n e n, who also wrote the chapters 1, 2, 3 and 521. H e l l e, University of Oulu, Research Institute of Northern Finland, wrote the chapters 4, 51, 522 and 6. Chapter 7 was written together.

Professors Lauri H e i k i n h e i m o, Kullervo K u u s e l a and Päiviö R i i h i n e n criticized the manuscript. Seppo L o h i n i v a and Hannele N i v a l a assisted in data compiling and drawing. The translation was checked by Malcolm H i c k s and Nancy M e r i d e t h - N u o t t a m o.

In addition we would like to thank the reindeer management co-operatives, the Association of Reindeer Management Co-operatives and the Finnish Natural Resource Research Foundation for the help and the support we have received.

Rovaniemi, June 1979.

Timo Helle *Olli Saastamoinen*

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1. INTRODUCTION

One of the most essential requirements of modern forestry is the multiple-use of forestry land. From the standpoint of forestry practice it means the management of forests in such a way that the required number and quantities of forestry land products will be supplied.

Forest production is unique compared to any other production processes not only for its product diversity but also for the complex relationships between the different products and production factors.

The complexity of influences is highly relevant to the relationships between wood production and reindeer husbandry in Northern Finland.

Half a century ago the prevailing idea concerning the relationships between reindeer husbandry and wood production was the harmfullness of reindeer for forest regeneration.

From the fifties as the volume of cuttings in Northern Finland began to grow and the silvicultural methods became more intensive forestry's effects on the reindeer pastures increasingly aroused concern. The same kind of conflicts between reindeer husbandry and wood production had also risen in Sweden (see E r i k s s o n 1975, E n g s å s 1975). The study of the relationships between wood production and reindeer husbandry has therefore changed emphasis.

The developments in forestry have not only changed the traditional distribution of reindeer pastures, it has also created new types of pasture and thereby has changed the traditional pattern of reindeer husbandry (cf. A i k i o 1977). There is, therefore, an increasing real need for knowledge about these developments.

The purpose of this study was to gain an overall picture of the present use of semi-domestic reindeer's (*Rangifer tarandus tarandus* L.) winter pastures, reindeer owners' views on pastures and to consider the possible long term changes which have occurred in pasture conditions.

The study is part of a larger project concerning the importance of old spruce forests for reindeer. The management of overmature spruce stands is problematic also from the standpoint of timber production (cf. N o r o k o r p i 1979).

2. REINDEER HUSBANDRY AND FORESTRY IN NORTHERN FINLAND

The area available for reindeer husbandry in Finland is determined by the Reindeer Management Law. Its area is shown in Figure 1. The reindeer husbandry area is divided into 56 reindeer management co-operatives. In each co-operative the reindeer are managed collectively. However, the reindeer are privately owned. The reindeer owners themselves provide the labour required for the different tasks demanded by reindeer husbandry.

There are some differences in reindeer husbandry between the northern and southern parts of the reindeer husbandry area. These are partly due to the differences in land ownership. State owned land is most prevalent in the north, whilst in the south there is also much private land. According to the legislation, reindeer have free access to both state-owned and private forestry land but herding is not allowed in private forests. Therefore in the northern parts of the reindeer husbandry area there are better possibilities for the planned use of pastures. This is also helped by the fact that the northern forests belong to the protection forest zone where the intensity of timber production is restricted.

The total number of reindeer in Finland varies around the level of 200 000 animals. About 30 000—50 000 animals are slaughtered annually producing about 1,0—1,5 mill. kg of reindeer meat. The total gross income of reindeer husbandry was about 20 mill. Fmk in 1976. It is estimated that the annual number of working days in reindeer husbandry is about 200 000. About 800 families get their main income and 1 300 families an essential secondary income from reindeer husbandry. The total number of reindeer owners is 6 700 but there can be many owners in one family.

The total land area of the reindeer husbandry area is about 11,6 mill. ha. It is almost exclusively (97 per cent) forestry land, of which 57 per cent is forest land, 20 per cent is poorly productive forest land and 23 per cent is waste land of forestry. The volume of commercial cuttings in the reindeer husbandry area is about 5 mill. m^3 annually (S a a s t a m o i n e n 1978).

Forestry, timber transporting and forest industries together are very important branches of the economy of Northern Finland. For instance, in 1970, in the Province of Lapland (which consists a major part of reindeer husbandry area) the share of the gross national product in forestry and forest industries was 30 per cent of the province's GNP (S e p p ä l ä 1976).

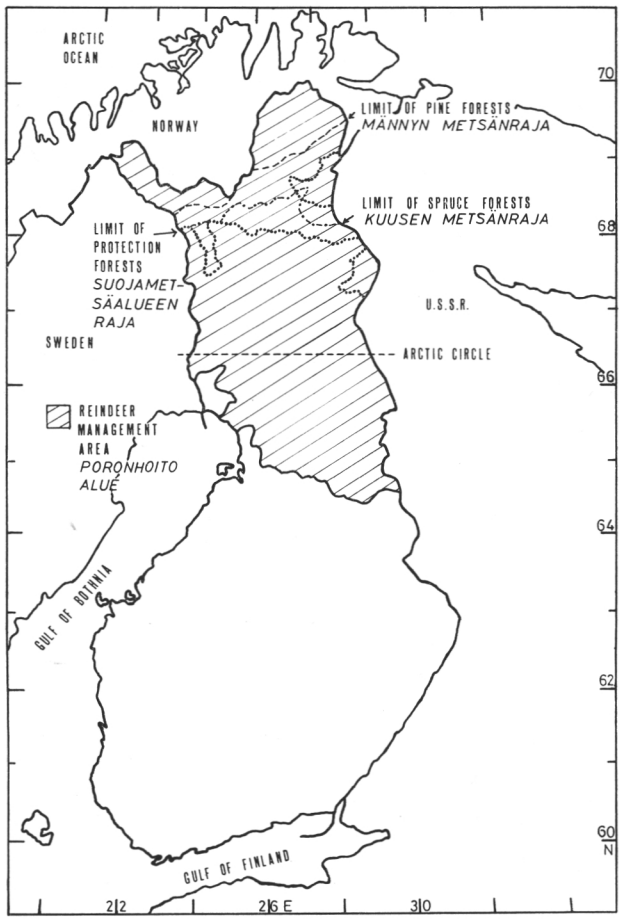


Figure 1. The reindeer management area of Finland.

Kuva 1. Suomen poronhoitoalue.

The regional importance of reindeer husbandry also is considerable. In the northern part of reindeer management area it is one of the basic sources of income. In central and southern parts it gives supplementary incomes to farming. Notwithstanding the rather modest value of production compared e.g. to forestry (cf. S a a s t a m o i n e n 1977) it is regarded as a vital industry in supporting the settlement of rural areas of Northern Finland.



Figure 2. Reindeer digging *Cladonia* lichens in early winter (Photo: Veikko V a s a m a).
Kuva 2. Porot jäkälän kaivussa syystalvella (Kuva: Veikko V a s a m a).



Figure 3. Reindeer seeking for arboreal lichens in spruce forests in mid-winter (Photo: Martti R i k k o n e n).
Kuva 3. Poro luppokuusikossa keskitalvella (Kuva: Martti R i k k o n e n).

3. MATERIAL AND METHOD

The purpose of the study was to obtain an overall view of the present use and conditions of winter pastures by reindeer management co-operatives in the whole reindeer husbandry area. Undoubtedly the best knowledge concerning the pastures, their use and reindeer feeding in each reindeer management co-operative is held by the reindeer owners themselves. Thus the questionnaire method was chosen. All reindeer management co-operatives were recipients of the eventual questionnaire form.

The inquiry focussed only on winter ranges because they are known to be the minimum factors of reindeer husbandry. The study period was restricted to the most severe winter months from January to March.

The questionnaire concerned

- the distribution of reindeer in different range types and means of feeding during the period January to March;
- the date of the end of ground lichen digging;
- the amounts of supplementary feeding;
- the sufficiency of different winter ranges; and
- the type of winter pasture which is the scarcest.

The inquiry was made twice, in 1975 and in 1977. In 1975 the questionnaire was filled by 52 reindeer management co-operatives and the reply percentage was 94. In 1977 53 reindeer management co-operatives replied and the reply percentage was 95.

Replies were made by the head of each reindeer management co-operative and in many cases the questionnaire was handled in the meetings of the boards of reindeer management co-operatives. The questionnaire covered 125 000 reindeer older than one year and calves in 1975 and 160 000 reindeer in 1977. These figures are respectively 89 and 93 per cent of the corresponding reindeer numbers in the statistics of the Association of Reindeer Management Co-operatives.



Figure 4. Reindeer use arboreal lichens also from pines (Photo: Veikko V a s a m a).
Kuva 4. Porot käyttävät myös männyn luppoa (Kuva: Veikko V a s a m a).



Figure 5. Feeding in corrals decreases winter mortality of reindeer (Photo: Olli S a a s t a m o i n e n).
Kuva 5. Pihahoito vähentää talvisia eläintappioita (Kuva: Olli S a a s t a m o i n e n).

4. THE HERDING PATTERNS AND THE COMPOSITION OF WINTER FOOD OF REINDEER

The traditional manner of herding the reindeer in the fell regions of the north involved keeping them in a herd throughout the year, whereas in the forest region they were herded only during the winter (Itkonen 1948, Alaruikka 1964, Kortesalmi 1960). The primary reasons for herding were to ward off predators and prevent the reindeer from straying into other territories, and consequently, with the disappearance or scarcity of the larger predators and the establishment of an agreement between the reindeer herding associations to return animals to their rightful owners, this custom has been relaxed. A further critical factor in this change in practice was the clause in the reindeer herding legislation which prohibited herding on private lands or forest regeneration areas. Herding as such is practised nowadays only in associations located totally or partially within the protected forest zone.

The free ranging form of husbandry possesses certain important advantages in the southern and central parts of the area. Firstly it reduces labour costs, and secondly it enables the animals to be distributed spatially in a manner corresponding to the nutrition available. In this way they are able to take advantage of sources of nutrition which are widely distributed or scattered, a fact of some significance in the late winter when they are living mainly of arboreal lichens. On the other hand, it seems that the present numbers of free ranging reindeer are inevitably leading to an over-grazing of the lichen forests, as has been pointed out by Ahti (1961), Kärenlampi (1973), Mattila & Helle (1978) and others. This may be put down to the fact that the reindeer lichens are the favoured sources of food in autumn and winter, but not the minimal factors which actually determine the numbers of reindeer.

Quantitative data concerning the composition of winter diet based on rumen or pellet analyses are available in two areas, Kuusamo and the reindeer co-operative Kyrö in Northern Kittilä (Mattila & Helle 1978). The reindeer husbandry practised in Kuusamo represents the typical Finnish reindeer husbandry, in which reindeer can select their ranges almost without herding.

Vegetationally, Northern Kittilä belongs to Forest Lapland, including even tundra-areas. Reindeer are herded in the winter, using motor-sledges and dogs and there exists a rotation between winter-spring and summer ranges.

In Kuusamo the winter period is divided nutritionally into two parts. The snow normally arrives at the beginning of November (Suomen kartasto 1960). The time during which reindeer have to dig for their food is, however, quite short, because they begin to use arboreal lichens, e.g. during the period 1970—75 generally from the beginning of January. From then, arboreal lichens remain the only natural food resource for 3—4 months. In Kittilä, on the other hand, winter nutrition is based on ground vegetation throughout the whole winter.

In both areas reindeer prefer *Cladonia* lichens even before the winter period. The role of lichens is greatest in Kuusamo during November—December and in Kyrö in January, when proportions of reindeer lichens in the diet are 20 and 32 per cent, respectively.

According to pellet analyses the role of grass and sedges is on the average more important than reindeer lichens. In Kuusamo the most used species is *Deschampsia flexuosa*, which appears in great amounts in clear cut areas having fresh mineral soil. In Kittilä, reindeer are more frequently digging on peatlands, which means that sedges are of larger importance than grasses. In Kittilä particularly the part of reindeer lichens and sedges decreases towards the spring. This is because with increasing depth and hardness of the snow, the reindeer eat the excavated vegetation more throughly. That is why the proportion of mosses, brushes and birch twigs in their diet increases at that time. The importance of brushes is largest in May, when reindeer are feeding in the tundra areas on places where the snow has already melted. Pellet analyses have shown that in Kittilä in normal snow conditions arboreal lichens do not exceed 10 per cent of pellet content in any winter month.

5. THE DEPENDENCE OF REINDEER ON DIFFERENT WINTER FOOD RESOURCES

51. Snow characteristics

The time at which reindeer are prevented from using ground vegetation because of the snow conditions varies locally and from year to year. In this aspect the winters involved in this study were quite normal. Digging ceased first in the southern part of reindeer husbandry area and continued longer in northernmost Lapland (Figure 6). The most relevant environmental factors in this topic of view, snow depth and weather conditions, are presented in Figure 7.

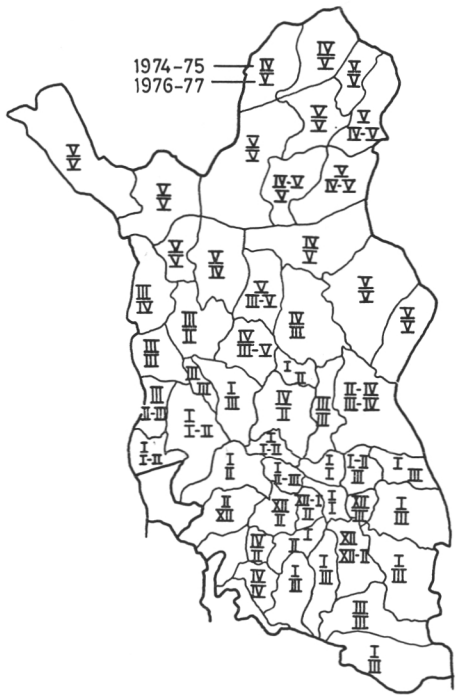


Figure 6. The finishing month of reindeer digging by reindeer management co-operatives, winters 1974—75 and 1976—77.

Kuva 6. Kaivun päättymiskuukausi paliskunnittain talvina 1974—75 ja 1976—77.

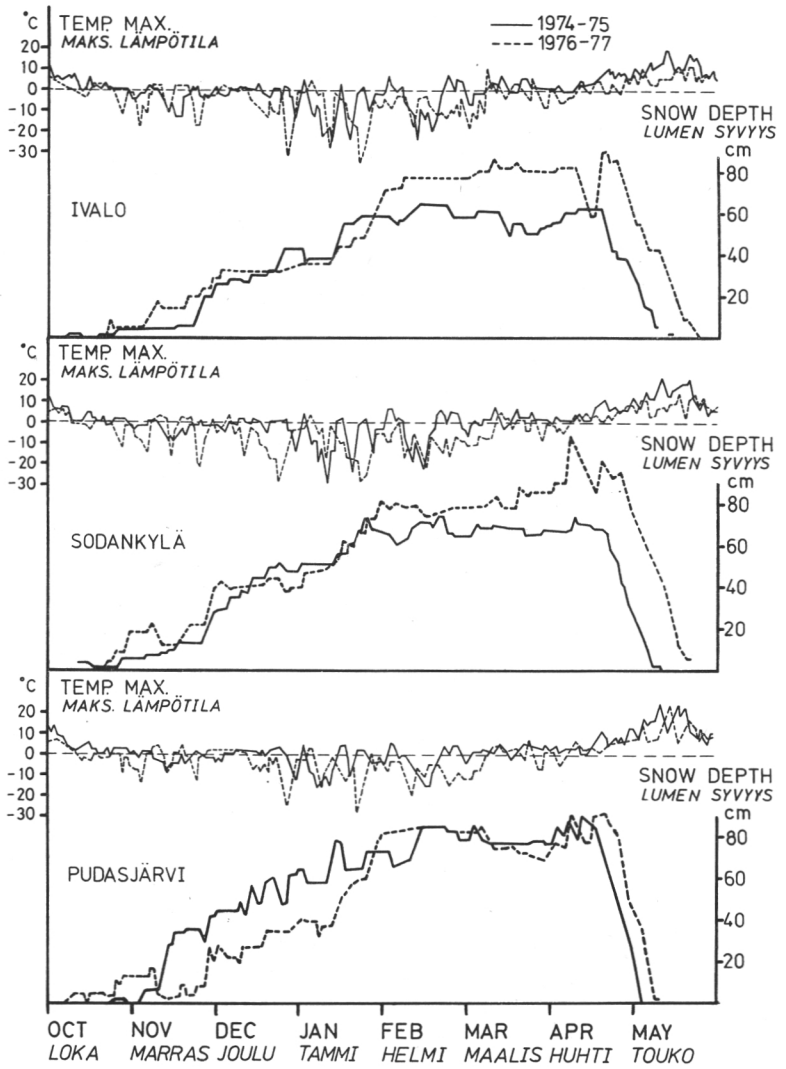


Figure 7. The daily snow depths and maximum temperatures in northern (Ivalo), central (Sodankylä) and southern (Pudasjärvi) part of reindeer management area in winters 1974—75 and 1976—77.

Kuva 7. Päivittäiset lumensyvyydet ja maksimilämpötilat poronhoitoalueen pohjois- (Ivalo), keski- (Sodankylä) ja eteläosassa (Pudasjärvi) talvina 1974—75 ja 1976—77.

In the winter of 1974—75 reindeer in the southern and partly in the central part of area began to feed on arboreal lichens in December—January, when the snow became glazed after very mild weather. The same phenomenon occurred in some areas in the winter of 1976—77, too. Generally, reindeer ceased digging in the central part of area gradually in mid-winter. Especially in the winter of 1976—77 this was affected

by snow depth exceeding over 80 cm. On many places on the central part of area deep and soft snow hindered even the movements of reindeer in seeking for arboreal lichens. Most favorable the snow conditions were in both winters in the northernmost Lapland, where reindeer could excavate for their food the whole winter. It is important, however, to note that in the tundra areas, where alternatives to ground vegetation are lacking reindeer dig for their food in more difficult snow conditions than forest reindeer (H e l l e 1977).

Concerning the survival of reindeer, both winters were quite normal. In the Northern Lapland the winter of 1974—75 was considered to be very easy for reindeer because of thin snow cover. Although the snow conditions in the 1976—77 were rather difficult, the loss remained, however, quite small in general.

52. The distribution of reindeer on different winter feeding types

521. Natural ranges

The distribution of reindeer on different types of winter feeding was in the main similar in the winters (a period January to March) of 1975 and 1977 (Table 1).

Three fourths of reindeer got their food on natural ranges in both study winters. The rest were seeking arboreal lichens in the cutting areas or were fed in corrals.

Table 1. The distribution of reindeer (calves included) on the different types of ranges during January—March, 1975 and 1977 according to the questionnaire.

Taulukko 1. Porojen (vasat ml.) jakaantuminen eri laiduntyypeille tammi—maaliskuussa vuosina 1975 ja 1977 kyselyn mukaan.

Range type *Laiduntyyppi*	Winter — *Talvi*			
	1975	1977	1975	1977
	Number of reindeer *Poroja kpl*		Per cent %	
Lichen ranges [1] — *Jäkäliköt* [1]	53 144	84 809	43,2	52,9
Spruce forests with arboreal lichens[2] — *Luppokuusikot* [2]	26 479	17 768	21,5	11,1
Pine forests with arboreal lichens[2] — *Luppomänniköt* [2]	10 155	11 208	8,2	7,0
Supplementary feeding in the forests [2] — *Lisäruokinta maastoon* [2]	114	5 067	0,1	3,2
Deshampsia flexuosa (clear cutting) ranges — *Metsälauha-(avohakkuu-) alueet*	1 888	2 573	1,5	1,6
Cutting areas — *Hakkuutyömaat*	18 781	12 768	15,2	7,9
Fields & others — *Niityt ym.*	83	642	0,1	0,4
Feeding in corrals — *Piharuokinta*	12 522	25 524	10,2	15,9
Total — *Yhteensä*	123 166	160 359	100,0	100,0

[1] Including fell areas — *Tunturialueet mukaanlukien.*

[2] Forests with arboreal lichens include most part of supplementary feeding. — *Lisäruokinta sisältyy suurimmaksi osaksi edellä oleviin luppometsäluokkiin.*

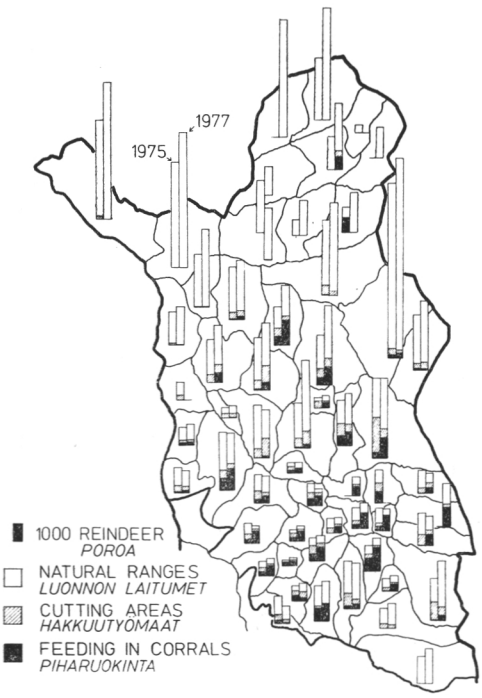


Figure 8. The distribution of reindeer on different types of winter feeding during January—March in 1975 and 1977.

Kuva 8. Porojen jakautuminen eri ruokintatavoille tammi—maaliskuussa 1975 ja1977.

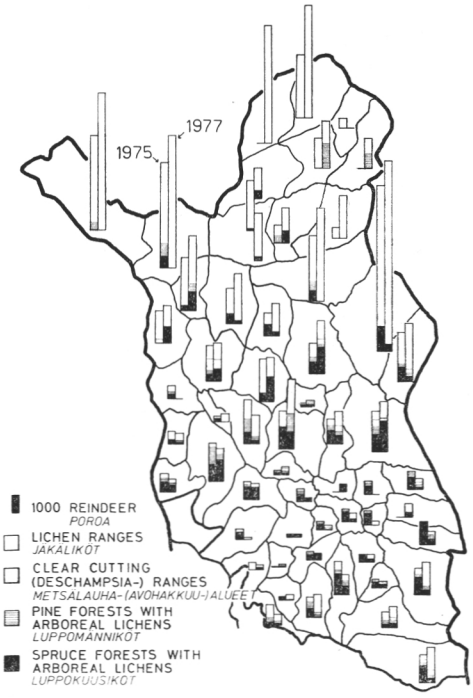


Figure 9. The distribution of reindeer on different types of natural winter ranges in January—March in 1975 and 1977.

Kuva 9. Porojen jakautuminen eri laiduntyypeille tammi—maaliskuussa 1975 ja 1977.

Most reindeer (43 per cent in 1975 and 53 per cent in 1977) fed themselves on lichen ranges including fell areas. Forests with arboreal lichens were next important winter range. In 1975 30 per cent and in 1977 21 per cent of reindeer were seeking arboreal lichens in forests. These figures include also most part of supplementary feeding. The number of reindeer in spruce forests with arboreal lichens was less in the winter of 1977 than in the winter of 1975. That may be due partly to the increased feeding in corrals. The *Deschampsia flexuosa* (clear cutting-) ranges have had only a minor significance as mid-winter ranges in these years.

There are great areal differences in the distribution of reindeer on different range types.

In the northern part of reindeer management area the natural ranges compose, with small exceptions, the only food resource for reindeer. In the central and southern parts the cutting areas and feeding in corrals also are significant (Figure 8).

Among the natural ranges the use of lichen stands was accentrated in the northern part of reindeer management area. In some areas only the lichen ranges (fell areas included) were used. On the contrary, in many areas of central and southern parts

of reindeer husbandry area, the importance of forests rich in arboreal lichens was greater than that of lichen ranges (Figure 9). As a rule the spruce forests with arboreal lichens were utilized more intensively than pine forests. However, in the north and also elsewhere where pine forests are prevailing, the arboreal lichens of pine forests get more important. The *Deschampsia flexuosa* (clear cutting-) ranges were used only locally in the central and southern parts of reindeer management area during the three mid-winter months.

522. Artificial feeding

The wide interest in artificial feeding which spread to reindeer herding circles in Finland around 1970 clearly has its origins in the grazing ecology of the animals. The drastic decline in the numbers of reindeer during the war had allowed their grazing lands to improve considerably in quality, and subsequent total herd figures showed a steady increase up until the early 1960's, the wide fluctuations in numbers which have been characteristic since that time, varying in the range 113 000—152 000 counted reindeer (without calves), serving as an indication that the grazing grounds have reached maximum capacity. The decisive impetus towards artificial feeding was given by the winter of 1968—69, when several thousands of reindeer died of hunger in the central part of the herding area. The widespread use of hay for feeding to the reindeer then received its own stimulus from the Field Reservation Scheme which was introduced at about the same time. This was a system by which the State paid a bounty to farmers for leaving their fields fallow in the interests of reducing over-production in the dairying sector. One was still allowed to feed the hay to reindeer under this agreement, however.

Artificial feeding has been organized in two ways: in the corrals and in the wild.

In the corrals it was started to feed reindeer which were in the need of specific food to survive a winter. Later on also other reindeer were taken into the corrals to get a special care, e.g. calves and primiparous females.

The extent of corralling was quite a considerable in the study years: 10 per cent in 1975 and 16 per cent in 1977 of all reindeer (Table 1). The intensity of corralling in 1977 was mainly caused by snow difficulties. Reindeer were transported also from cutting areas to corrals.

Most common the feeding in corrals was in the central and southern parts of the reindeer management area (Figure 8). Besides the range situation this was due to the fact that in these areas reindeer husbandry is a by-industry of farming. In the corrals the reindeer can be fed partly by the same feeds as cows.

The most used supplementary fodder was dried hay but also available were leaves of tree and water horsetail (*Equisetum fluviatile*). During the winter of 1974—75 on average of 5,7 kg of dried hay per reindeer was transported into the forests, plus 0,3 kg/reindeer of other supplementary fodder. During the winter of 1976—77 the respective figures were 11,9 kg/reindeer and 0,6 kg/reindeer.

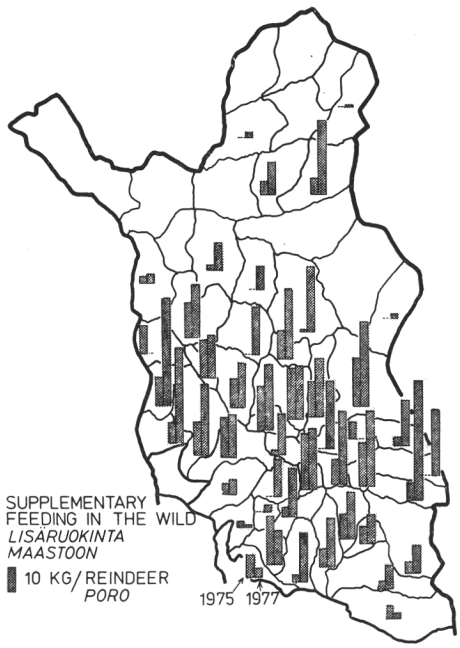


Figure 10. The amounts of dry hay kg/counted reindeer used as supplementary food in forests in winter of 1974—75 and 1976—77.
Kuva 10. Maastoon levitetyn kuivan heinän määrä kg/lukuporo talvina 1974—75 ja 1976—77.

Supplementary feeding was arranged most effectively in the southern and central part of area (Figure 10). The considerable increase in supplementary feeding in two years can be explained by the difficult snow conditions in winter 1976—77. In addition supplementary feeding is a relatively new phenomenon and is exhibiting a rising trend. It is also worth noting that reindeer breeders prefer supplementary feeding because the reindeer do not then lose contact with their natural ranges.

The current grazing situation renders it essential to resort to artificial feeding in the southern and central parts of the herding area, but this in turn entails increased costs. It is calculated, for instance, that the maintaining of a reindeer in an enclosure for three months in the winter costs 100 Fmk, and that hay taken into the forest for the reindeer costs 1 Fmk/kg (Paliskuntain Yhdistys 1976). The present research suggests that the total cost of artificial feeds was 1,7 mill. Fmk in 1974—75 and 3,8 mill. Fmk in 1976—77, corresponding to 12 and 15 per cent of the total gross income from reindeer husbandry for those herding years respectively.

The northern parts of the reindeer herding area are unable to benefit from such supplementary feeds. It is impossible to grow sufficient hay to meet such needs, and the transportation of hay purchased from elsewhere into such extensive tracts of

country with few roads would be far too expensive an operation. The key question in the attempt to ensure a steady income from reindeer husbandry from one year to the next then becomes one of adjusting the numbers of reindeer to correspond to the biological yield of the lichen pastures and developing systems of pasturing which will minimize lichen consumption other than as a winter source of nourishment.

6. THE WINTER RANGE SITUATION

The considerations on the winter range conditions mentioned by reindeer owners are summarized in Table 2.

Deschampsia ranges are considered to be in abundance or modestly in the whole reindeer management area, except some northernmost co-operatives. Co-operatives having lichen ranges sufficiently are dispersed throughout the area. Most part of co-operatives, which consider to have enough forest rich on arboreal lichens are situated on the protected forest zone in Forest Lapland.

In general the most co-operatives seem to have lichen ranges and forests with arboreal lichens only scarcely or very little.

The question on the minimum factor is of a particular interest already for reindeer management itself, and especially for the concepts of multiple use of forests. The results given in Table 3, were very similar with each other in both years showing that reindeer owners can recognize them with high plausibility.

About one half of co-operatives consider forests rich on arboreal lichens to be the minimum factor, most commonly old spruce forests. As expected, the lack of arboreal lichens is largest in the southern and central part of area, where the reindeer can excavate for their food generally only a part of the winter.

Most responses mentioning as minimum factor both lichen ranges and forests rich on arboreal lichens, are given from Central Lapland. It is clear that an unam-

Table 2. The relative abundance of different winter range types mentioned by reindeer owners in 1975 and 1977.

Taulukko 2. Eri talvilaiduntyyppien suhteellinen runsaus poronhoitajien arvion mukaan vuosina 1975 ja 1977.

Range type *Laiduntyyppi*	In abundance *Runsaasti*	Modestly *Sopivasti*	Scarcely *Vähänlaisesti*	Very little *Erittäin vähän*	Total *Yhteensä*
	Per cent — %				
Lichen ranges — *Jäkäliköt*	1	35	62	2	100
Deschampsia ranges — *Metsälauhalaitumet*	54	27	9	10	100
Spruce forests rich on arboreal lichens — *Luppokuusikot*	0	17	62	21	100
Pine forests rich on arboreal lichens — *Luppomänniköt*	0	12	41	47	100
Others — *Muut*	24	40	24	12	100

biguous answer is difficult to give in situation, where the digging period varies annually. In winters, when reindeer are able to excavate for their food, minimum factor seem to be lichen ranges, whereas forests with arboreal lichens appear as minimum factor in winters when digging period is short.

In the northern part of area, where the winter feeding bases on *Cladonia* lichens, lichen ranges are reported as minimum factors.

Table 3. The range ecological minimum factors mentioned by reindeer owners in 1975 and 1977.
Taulukko 3. Laidunekologiset minimitekijät poronhoitajien vuosina 1975 ja 1977 tekemän arvion mukaan.

Range type mentioned as minimum factor *Laiduntyyppi, josta paliskunnassa suurin puute*	Per cent %
Spruce forest rich on arboreal lichens — *Luppokuusikot*	35
Spruce and pine forests rich on arboreal lichens — *Luppokuusikot ja -männiköt*	16
Lichen ranges and forests rich on arboreal lichens — *Jäkäliköt ja luppometsät*	22
Lichen ranges — *Jäkäliköt*	20
Others — *Muut*	4
All range types sufficiently — *Kaikkia laiduntyyppejä riittävästi*	3
Total (106 replies) — *Yhteensä (106 vastausta)*	100

7. DISCUSSION

Although reindeer husbandry in Finland has undergone far-reaching changes in the last twenty years, it still remains impossible to analyse in detail the cause-and-effect relations lying behind these in the absence of adequate primary data. Certain general remarks can nevertheless be put forward concerning the utilization of winter pasturage and factors affecting the condition of these sources of nutrition.

The general socio-economic climate, into which even reindeer husbandry has become integrated, places great store upon the importance of a regular monetary income. This quite clearly gave rise to an attempt in the early stages of the integration process, from 1950 onwards, to maximize the net returns from the reindeer by increasing the herds and cutting down on the work involved. This effect was further exacerbated by the relatively low price commanded by reindeer meat in relation to other commodities well into the 1960's. The transformation of reindeer husbandry from a natural source of livelihood into a commercial undertaking is described in greater detail for the area of Northern Lapland in connection of motorization of herding methods (e.g. Linkola 1969, Lenstra 1975, Müller-Wille 1975).

Alongside its own attempts to intensify meat production, the practice of reindeer herding has also had to contend with new forms of land utilization emerging for the areas traditionally reserved for reindeer grazing, the greatest controversy having arisen over the effects of intensive forestry methods on the extent and quality of the grazing areas.

The report by Kärenlampi (1973) on the detrimental effects of regeneration fellings on dry and barren sites on the availability of lichen lends support to the observations of practical reindeer herders. The principal factor governing the growth of the reindeer lichen (*Cladonia* spp.) is the relative humidity of the atmosphere (Kärenlampi 1970), which decreases once the forest layer, which serves to restrict evaporation, is removed, leading to a lengthening of the inactive season of the lichens brought on by dryness and a consequent retardation of growth. In cases where fellings take place at times when there is little or no snow on the ground the lichens may also suffer severe mechanical damage from the heavy logging machinery used (cf. Lopatin 1962). The use of the forest ploughing technique in areas with a carpet of lichens has aroused particularly vehement criticism from the reindeer herders (see Aikio 1973).

The results obtained by Mattila & Helle (1978) in Central Lapland, however, suggest that the detrimental effects of regeneration fellings are generally felt only for a short time. It is nevertheless obvious that very wide fellings concentrated on dry, lichen-rich forests within a short period of time can reduce the local availability of lichens quite considerably even at the level of the reindeer herding co-operative.

On the other hand, forest regeneration on rich-to-subdry mineral soils frequently brings with it an abundance of the *Deschampsia* grass which also acts as a nutrient source for the reindeer. In Kuusamo, in the eastern part of the reindeer herding area in Finland, the maximum yield of *Deschampsia*, 800—1 000 kg/ha (dry weight), is achieved 5—10 years after clear felling (Helle 1975). This favourable effect of clear felling decreases in importance towards the north, however, so that by northern Sodankylä the maximum yield is only approx. 630 kg/ha (Ferm & Pohtila 1977). Mean values of 130 kg/ha in young forests and 61 kg/ha in older forests are reported for Central Lapland (Mattila & Helle 1978). The same authors go on to note that the total available *Deschampsia* is already greater than the total quantity of reindeer lichen by the latitude of the Arctic Circle.

A further factor to be taken into account in evaluating the effects of clear felling is that the surface of the snow hardens more easily as a result of wind action in wide clear-cutting areas than it does when protected by forest, and this makes it more difficult for the reindeer to dig down into the snow (Eriksson 1975). Although no research has been carried out into this point in Finland, it is apparent that the utilization of the *Deschampsia* grass is less regular than that of the reindeer lichen in Kuusamo, for instance, precisely because of the varying hardness of the snow, its exploitation being restricted normally to clear-felled areas, and even within these to places where its biomass exceeds 200 kg/ha (Sulkava & Helle 1975, Helle 1975). This means in practice that only a part of the total *Deschampsia* biomass is available as winter nutrient for the reindeer. Although its utilization has increased as a result of its greater abundance, this research suggests that *Deschampsia* is still first and foremost an early winter source of nutrition even in the southern and central parts of the reindeer herding area, where it is most plentiful.

Compared with the reindeer lichens and *Deschampsia* grass, the supply of arboreal lichens is extremely limited. The older spruce forests of Kuusamo, for example, contain only 7 kg/ha of arboreal lichens within the reach of a reindeer, i.e. below a height of 210 cm, and the older pine forests only 1—4 kg/ha. Winter storms are particularly important to the reindeer in this respect, since they may bring down as much as 10—15 kg/ha of arboreal lichens in older pine forests (Helle 1975). The optimum age for a forest in this respect is over 150 years (Mattila & Helle 1978), by which time it would be over-aged as far as timber production was concerned. Looked at in the short term, clear-cutting and reforestation in such cases would lead to an increase in food for the reindeer, in the form of *Deschampsia*, and in the form of arboreal lichens of felled trees. During the harshest part of the winter season about a

tenth of reindeer received their nutrients in cutting areas (cf. Saastamoinen 1978).

In the long term, however, such an exploitation of the arboreal lichens is not to the advantage of reindeer husbandry. In the estimation of the herders themselves such forests constitute the most common minimal ecological grazing factor even in the context of the whole reindeer herding area, but most of all in the southern and central parts, where arboreal lichens are the only natural source of nutrition for the reindeer for between two and four months in the winter. This emerges very clearly also from the calculations of Mattila & Helle (1978) on the mean relative abundances of the various winter foods of the reindeer by sub-areas of the reindeer management area. Even under optimal conditions there are only 74 kg of arboreal lichen per counted reindeer, which is only 1,3 per cent of the corresponding total biomass of reindeer lichen and *Deschampsia*.

The case of arboreal lichens is only one—but outstanding—example of the profound influences that modern forestry practices have on reindeer ranges.

In Northern Finland reindeer husbandry and wood production are multiple uses of forestry land and therefore they must compromise with each other. A major responsibility in this compromising must be laid on forestry because of the intensive character of forestry operations. Wood production has strong effects on reindeer ranges while the counteractions of reindeer on forestry are generally regarded as far less substantial.

The principal problems to emerge from within reindeer husbandry itself are the adjustment of herd sizes to conform with the biological production of the grazing grounds and the development of economic modes of husbandry partially based on artificial feeding. An important step towards a better understanding between the two forestry land uses was the local co-operation between the forestry authorities and herding associations instituted in the early 1970's. Consultations have concerned above all the various alternative silvicultural and felling regimes, the optimal solutions to which questions will also depend on the contributions of the research in the fields of reindeer husbandry and multiple use of forestry.

REFERENCES

AHTI, T. 1961. Poron ravinnosta ja laitumista. Summary: On food and pastures of the reindeer. Lapin Tutkimusseuran vuosikirja 2: 18—24.

AIKIO, O. 1973. Luontaiselinkeinojen turvalaki tarpeen. Poromies 40, 2: 30.

AIKIO, P. 1977. Saamelaisen ekosysteemin murtuminen Lapin paliskunnassa. Summary: Collapse of the Lapponian Ecosystem in Lapin Paliskunta. Suomen Luonto 36: 72—77.

ALARUIKKA, Y. 1964 Suomen porotalous. Rovaniemi 1964. 215 p.

ENGSÅS, J. 1975. Skogsbruk och/eller renskötsel. En konflikt mellan två former av skogsutnyttjande. Troedssonska Forskningskuratoriet Information 5 (1975): 1—19.

ERIKSSON, O. 1975. Silvicultural practices and reindeer grazing in Northern Sweden. Proc. at the First Int. Reindeer/Caribou Symp., Biol. Pap. of the Univ. of Alaska, special number 1: 108—121.

FERM, A. & POHTILA, E. 1977. Pintakasvillisuuden kehittyminen ja muokkausjäljen tasoittuminen auratuilla metsänuudistusaloilla Lapissa. Summary: Succession of ground vegetation and levelling of ploughed tracks on reforestation areas in Finnish Lapland. Folia For. 319: 1—34.

HELLE, T. 1975. Tutkimuksia poron (*Rangifer t. tarandus* L.) talvisesta laidunekologiasta Kuusamossa vv. 1970—75. Lisensiaattitutkimus, Oulun yliopisto. 113 p.

— 1977. Porot Metsä-Lapin talvessa. Summary: Reindeer, Winter and Woodland. Suomen Luonto 36: 105—110.

ITKONEN, T. 1948. Suomen lappalaiset vuoteen 1945. Osa II. Porvoo—Helsinki 1948. 629 p.

KORTESALMI, J. 1960. Entisaikaisesta kuusamolaisesta porotaloudesta. Pohjois-Pohjanmaan maakuntaliiton vuosikirja XVIII: 19—56.

KÄRENLAMPI, L. 1970. Studies on the relative growth rate of some fruticose lichens. Rep. Kevo Subarctic Res. Stat. 7: 33—39.

— 1973. Suomen poronhoitoalueen jäkälämaiden kunto, jäkälämäärät ja tuottoarvot vuonna 1972. Poromies 40, 3: 15—19.

LENSTRA, M. 1975. Poronhoito ja poronhoitaja muutosten kelkassa. Poromies 42, 6: 13—16.

LINKOLA, M. 1969. The snowmobile in Lapland—its economic and social effects. Wenner-Gren Center Int. Symp. Series, vol. 21: 127—134.

LOPATIN, V.D. 1962. Pastbishchnye vozmozhnosti olenevodstva v Karelii. Severnyj olen' v Karel'skoj ASSR. 180 p. Moskva, Izd. Akad. Nauk SSSR.

MATTILA, E. & HELLE, T. 1978. Keskisen poronhoitoalueen talvilaidunten inventointi. Summary: Inventory of winter ranges of semi-domestic reindeer in Finnish Central Lapland. Folia For. 358: 1—31.

MÜLLER-WILLE, L. 1975. Changes in Lappish reindeer herding in northern Finland caused by mechanization and motorization.—Proc. at the First Int. Reindeer/Caribou Symp., Biol. Pap. of the Univ. of Alaska, special number 1: 122—126.

NOROKORPI, Y. 1979. Old Norway spruce stands, amount of decay and decay-causing microbes in northern Finland. Seloste: Peräpohjolan vanhat kuusikot, niiden lahoisuus ja lahottajat. Commun. Inst. For. Fenn. 97(6): 1—77.

Paliskuntain yhdistys. 1976. 'Federation of Reindeer Herding Associations'. 1976.
SAASTAMOINEN, O. 1977. Economics of forest uses in Finnish Lapland. Seloste: Metsien käyttömuotojen taloudellinen merkitys Lapissa. Silva Fenn. 11(3): 162—168.
— 1978. Cutting areas as reindeer pasturage. Seloste: Hakkuutyömaat porojen laitumena. Commun. Inst. For. Fenn. 95(4): 1—28.
SEPPÄLÄ, H. 1976. Metsäsektorin alueellinen merkitys Suomessa. Summary: Regional importance of the forest sector in Finland. Folia For. 269: 1—26.
SULKAVA, S. & HELLE, T. 1975. Range ecology of the domesticated reindeer in the Finnish coniferous forest area. Proc. at the First Int. Reindeer/Caribou Symp., Biol. Pap. of the Univ. of Alaska, special number 1: 308—315.
Suomen kartasto 1960. [Atlas of Finland] Helsinki 1960.

SELOSTE

Tutkimuksen tarkoituksena oli saada paliskunnittain yleiskuva porojen talvilaidunten ja ruokintatapojen nykyisestä käytöstä. Aineisto kerättiin kyselymenetelmällä paliskunnilta kahdesti vuosina 1975 ja 1977. Tiedustelu kohdistui tammi—maaliskuun väliseen ravinnon saannin kannalta vaikeimpaan talven jaksoon.

Tiedustelulla selvitettiin porojen keskimääräistä jakautumista erilaisten talvilaitumien ja ruokintatapojen kesken, kaivun päättymisen ajankohtaa, lisäruokinnan järjestämistä sekä paliskuntien käsitystä eri talvilaiduntyyppien riittävyydestä sekä siitä, mistä talvilaiduntyypistä vallitsee suurin puute.

Kyselyyn vastasi 52 paliskuntaa (94 %) vuonna 1975 ja 53 paliskuntaa (95 %) vuonna 1977. Paliskuntain Yhdistyksen porotilastoon verrattuna kysely kattoi 89 ja 93 prosenttia vastaavien vuosien lukuporojen ja vasojen määristä.

Kumpanakin vuonna kolme neljännestä poroista haki ravintonsa luonnonlaitumilta tammi—maaliskuun aikana. Likipitäen puolet kaikista poroista laidunsi jäkäliköillä, joihin myös tunturialueet on luettu mukaan.

Luppometsistä ravintonsa haki kaikista poroista vajaa kolmannes v. 1975 ja viidennes v. 1977. Luvuissa on mukana myös maastoon järjestetyn lisäruokinnan vaikutus. Noin kaksi kolmasosaa luppometsissä laiduntavista poroista sai ravintonsa luppokuusikoista. Luppomänniköillä oli merkitystä paitsi suojametsäalueella myös paikoin keskisellä ja eteläisellä poronhoitoalueella.

Metsälauha- (avohakkuu-) alueiden merkitys sydäntalven laitumena on hyvin vähäinen. Paliskuntien arvion mukaan niillä laidunsi vain puolitoista prosenttia kaikista poroista.

Muilla kuin luonnonlaitumilla olevat porot saivat ravintonsa joko hakkuutyömailta tai olivat piharuokinnassa. Hakkuutyömailla kävi luppoa syömässä noin kymmenesosa kaikista poroista. Piharuokinnassa oli poroista 10 % v. 1975 ja 16 % v. 1977.

Lisäruokintaa maastoon tai hakkuutyömaille vietiin talven 1974—75 aikana 6,0 kg lukuporoa kohti ja talven 1976—77 aikana 12,5 kg lukuporoa kohti. Lisäruokana käytettiin pääasiassa heiniä. Eniten lisäruokaa käytettiin keskisellä ja eteläisellä poronhoitoalueella.

Lähinnä lumisuhteista johtuvassa jäkälän kaivun päättymisajankohdassa on sekä vuosittaisia että alueellisia eroja. Poronhoitoalueen pohjoisosissa porot kaivavat lähes koko talven. Muualla kaivu päättyi v. 1975 yleisimmin tammikuussa ja v. 1977 helmi—maaliskuussa.

Poronhoitajien arvioissa eri talvilaiduntyyppien runsaudesta on luonnollisesti suuria alueellisia ja paliskunnittaisia eroja. Poronhoitoaluetta kokonaisuutena tarkasteltaessa metsälauha- (avohakkuu-) alueita arvioitiin olevan pääasiassa runsaasti (54 %) tai sopivasti (27 %), jäkälikköjä vähänlaisesti (62 %) tai sopivasti (35 %), luppokuusikoita vähänlaisesti (62 %) tai erittäin vähän (21 %) ja luppomänniköitä erittäin vähän (47 %) tai vähänlaisesti (41 %).

Luppometsien niukkuus korostui vastauksissa kysymykseen, mistä talvilaiduntyypistä paliskunnassa on suurin puute. Laidunekologisten minimitekijöiden suhteellinen jakautuma oli seuraava: luppokuusikot (35 %), luppokuusikot ja -männiköt (16 %), jäkäliköt ja luppometsät (22 %), jäkäliköt (20 %) ja muut tai kaikkia laiduntyyppejä riittävästi (7 %).

Tutkimuksen tulokset korostavat luppometsien merkitystä nykyisessä talvilaiduntilanteessa.

SAMPLING OF TREE STOCK BY ANGLE GAUGE IN PROPORTION TO TREE CHARACTERISTICS

KULLERVO KUUSELA

Seloste

PUUSTON ARVIOINTI KULMAMITTARILLA
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Kulmamittaria eli relaskooppia on käytetty tähän asti pääasiassa siten, että kukin luettu puu antaa tietyn samansuuruisen määrän pohjapinta-alaa puuston arvioon. Julkaisussa kuvataan kulmamittarin yleisen käytön teoria, kun arvioinnin ensisijainen tavoite on joko puuston runkoluku, pohjapinta-ala, runkotilavuus tai arvo. Lisäksi esitetään laskentaesimerkki kulmamittarilla rajoitetun koealan käyttämisestä mitattaessa koealan puusto kahteen kertaan useampia vuosia käsittävän jakson alussa ja lopussa. Menetelmää voidaan käyttää ns. pysyviin koealoihin perustuvassa puuston runkotilavuuden, kasvun ja poistuman inventoinnissa.

The angle gauge (relascope) has been used in such a way that each tallied tree gives a unit of basal area to the estimate of the total basal area in a tree stand. The general theory of the use of the angle gauge is described for the cases where the primary object to be measured is the number of stems, basal area, volume of stems or the value of stem timber. An example of the use of the angle gauge sample plot for repeated measurements is also described. The method can be used for estimating volume, volume increment and drain as a part of forest inventory.

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1. INTRODUCTION

In estimating tree stock characteristics a problem is created by the different values of individual trees with respect to the aim of the survey. The number of small trees may be large but their volume and selling value are small compared with the big trees. However, the work and cost needed to enumerate and measure a tree is more or less equal regardless of its volume and value.

An optimum method for estimating tree stocks should be such that trees of different sizes are enumerated and measured in proportion to the characteristic which is considered to be of greatest importance. For example, if the stem volume is the principal object of the survey, each tree enumerated and measured should contribute an equal amount of volume to the estimate of total stem volume.

The most feasible technique for solving the problem seems to be angle gauge sampling. This was introduced by B i t t e r l i c h (1948) for estimating the basal area of tree stock and for enumerating the trees in proportion to their basal area. The angle gauge technique is well known and much in use, but many of its potential applications are still not fully realized.

Stimulated by an article by Z ö h r e r (1978) and discussions at the meeting of the IUFRO Subject Group: Forest Inventory, in Bucharest, June 1978, the present paper has been written with a purpose to clarify and illustrate the theory of angle gauge sampling as it can be applied in order to solve problems described above. Besides the applications of sampling trees in proportion to their characteristics, the angle gauge technique can also be used for sampling by re-measured plots.

The paper is based on the experience achieved in the Finnish National Forest Inventory where the angle gauge technique has been used extensively and with obvious success (K u u s e l a 1966; K u u s e l a and S a l m i n e n 1969).

2. BASIC CONCEPTS

A tree and a stock of trees have characteristics as follows:

d = diameter of tree stem at breast height, over bark
g = cross-sectional area of stem at breast height, over bark
v = volume of stem, over bark
va = value of stem
N = estimate of tree number per hectare (ha)
G = estimate of basal area of trees per ha
V = estimate of stem volume per ha
VA = estimate of stem value per ha.

In sampling by angle gauge from a point located in the forest, the sample plot is a circle or a set of circles having the same centre point. The following concepts and symbols are used:

r = plot radius
a = plot area
A = area unit of forest, 1 ha.

When sampling by angle gauge in proportion to the basal area, the angle and plot radius are determined in such a way that each tree to be enumerated and measured contributes an equal amount of basal area to the estimate of the tree stock basal area:

f = basal area factor; if $f = 1$, each tree enumerated on the plot contributes 1 m²/ha of basal area to the tree stock estimate; if $f = 2$, each tree contributes 2 m²/ha of basal area, etc.

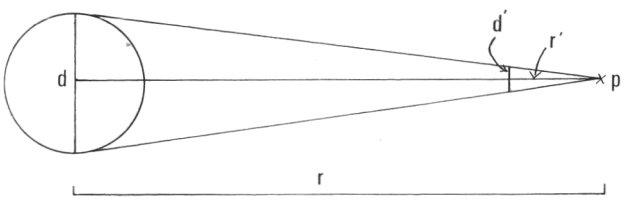
Plot radius, as a function of f and stem diameter d, is calculated as follows:

$$\frac{g}{a} = \frac{\frac{\pi d^2}{4}}{\pi r^2} = \frac{d^2}{4r^2} = \frac{f}{A};$$

$$r = 0{,}5d\sqrt{\frac{A}{f}}$$

If $f = 1$, $r = 50d$

Using angle gauge sampling in proportion to the basal area, the angle gauge characteristics can be illustrated and calculated as follows:



p = centre point of the plott
d' = width of the notch
r' = distance from the notch to the vertical line passing through the plot centre

$$\frac{d'}{r'} = \frac{d}{r}$$

Fig. 1. Angle gauge characteristics.
Kuva 1. Kulmamittarin tunnukset.

Example: If $d = 25$ cm, $f = 1$, d' $= 2$ cm, $A = 1$ ha,

$$r = 0{,}5 \times 0{,}25 \sqrt{\frac{10\,000}{1}} = 12{,}5 \text{ m}$$

$$r' = \frac{d' \times r}{d} = \frac{2 \times 1\,250}{25} = 100 \text{ cm.}$$

3. SAMPLING IN PROPORTION TO BASAL AREA

When sampling is carried out in proportion to basal area, each tree enumerated by angle gauge from the plot centre is called a basal area unit tree. It contributes a unit basal area G_u, a unit number of trees N_u, a unit volume V_u and a unit value VA_u to the estimates of tree stock basal area B, tree stock number N, tree stock volume V and tree stock value VA (all per hectare).

If f $= 1$, $G_u = 1$ m²/ha, d $=$ diameter in cm the other unit values are calculated as follows:

$$N_u = \frac{G_u}{g} = \frac{1}{\frac{\pi d^2}{4}} = \frac{12\,732{,}4}{d^2}$$

$$V_u = N_u \times v$$
$$VA_u = N_u \times va$$

Uses of the formulas are illustrated in table 1.

Estimates of the tree stock characteristics per hectare are the sums of unit values of those trees which are enumerated and measured on the plot with f $= 1$:

$$G \quad (\text{m}^2/\text{ha}) \quad = \Sigma\, G_u$$
$$N \quad (\text{trees per ha}) = \Sigma\, N_u$$
$$V \quad (\text{m}^3/\text{ha}) \quad = \Sigma\, V_u$$
$$VA \quad (\text{mk/ha}) \quad = \Sigma\, VA_u$$

Sampling in proportion to the basal area is carried out with a set of circular sample plots having the same plot centre and plot radii which are functions of tree diameters. The angle gauge is the instrument for selecting those trees which belong to the plot.

According to the basic principle the proportion between the importance of a tree and the sample plot area is constant. Therefore the cumulative estimate of basal area (or volume, etc.) can be determined by counting the number of trees on the sample plot.

Table 1. Illustration of tree and sampling characteristics when sampling in proportion to basal area, tree number, volume and value having basal area factor $q = 1$ and plot radius $r = 10{,}00$ m for trees with $d = 20$ cm.

Taulukko 1. Puu- ja näytetunnukset, kun näyte mitataan suhteessa pohjapinta-alaan, puiden lukumäärään, kuutiomäärään ja arvoon. Pohjapinta-alan kerroin $q = 1$ ja koealan säde $r = 10{,}00$ m puille, joiden läpimitta $d = 20$ cm.

Tree characteristics *Puutunnukset*					Sampling in proportion to *Näyte suhteessa*										
					basal area *pohjapinta-alaan*					tree number *puulukuun*		volume *kuutiomäärään*		value *arvoon*	
Tree *Puu*	d, cm d²	g cm²	v m³	va mk	r, *m* *a*, m²	N_u trees/ha *kpl/ha*	B_u m²/ha	V_u m³/ha	VA_u mk/ha	r, *m* *a*, m²	trees per ha *kpl/ha*	r, *m* *a*, m²	m³/ha	r, *m* *a*, m²	mk/ha
1	10	78,5	0,039	0,78	5,0	127,32	1	4,97	99	10,00	31,83	3,84	8,43	1,92	675
	100				79					314		46		12	
2	15	176,7	0,121	4,84	7,5	56,59	1	6,85	274	10,00	31,83	6,76	8,43	4,78	675
	225				177					314		143		72	
3	20	314,2	0,265	21,20	10,0	31,83	1	8,43	675	10,00	31,83	10,00	8,43	10,00	675
	400				314					314		314		314	
4	25	490,9	0,492	49,20	12,5	20,37	1	10,02	1 002	10,00	31,83	13,63	8,43	15,23	675
	625				490					314		584		729	
5	30	706,9	0,747	82,17	15,0	14,15	1	10,57	1 163	10,00	31,83	16,79	8,43	19,68	675
	900				707					314		886		1 217	

4. SAMPLING IN PROPORTION TO TREE NUMBER

Sampling in proportion to tree number means that each tree enumerated on the plot contributes an equal number of trees to the tree stock estimate.

The sampling density will be determined in advance, as the basal area factor is determined when sampling in proportion to the basal area. For example, all trees having d = 20 cm are sampled by a circle r = 10 m. The problem is to determine r for other sizes of trees in order to sample them in proportion to the tree number.

If the sample plot size of r = 10 m for trees having d = 20 cm is considered to serve the purpose of the survey, this size of a tree contributes a number of trees to the estimate of tree stock number per ha as follows:

$$\frac{A}{a} = \frac{10\,000}{\pi 10^2} = 31{,}83 \text{ trees per ha}$$

Plot size (x) and plot radius for a tree having a diameter other than d = 20 cm is calculated as follows:

$$\frac{A}{a} = 31{,}83; \quad x = \frac{10\,000}{31{,}83} = 314{,}158 \text{ m}^2; \quad r = 10 \text{ m}$$

Plot size is therefore equal for all sizes of trees. Sampling is carried out by a fixed radius plot and each tree enumerated gives 31,83 trees per ha to the estimate of tree stock number.

Each sample tree characteristic is multiplied by $\frac{A}{a} = 31{,}83$ in order to enable the estimate of the tree stock characteristic per ha to correspond to the unit values achieved when sampled in proportion to basal area (Illustrations in table 1).

5. SAMPLING IN PROPORTION TO VOLUME

Sampling in proportion to volume means that each tree enumerated on the plot contributes an equal volume to the tree stock estimate.

As above, all trees having d = 20 cm are sampled by a plot of r = 10 m. A tree d = 20 cm and v = 0,265 m³ contributes a volume to the tree stock estimate per ha as follows:

$$\frac{A}{v} \times v_{d = 20 \text{ cm}} = \frac{10\,000}{\pi 10^2} \times 0{,}265 \text{ m}^3 = 8{,}43 \text{ m}^3/\text{ha}$$

A tree of any other size and enumerated on the plot should contribute a volume of 8,43 m³/ha to the tree stock estimate.

Plot size (x) and radius for a tree d = x cm are calculated as follows:

$$\frac{A}{x} \times v_{d = x \text{ cm}} = 8{,}43 \text{ m}^3/\text{ha}$$

An example: d = 25 cm, v = 0,492 m³. Plot size and radius are:

$$x = \frac{10\,000 \times 0{,}492}{8{,}43} = 584 \text{ m}^2; \quad r = 13{,}63 \text{ m}$$

Each sample tree characteristic is multiplied by $\frac{A}{a}$ in order to enable the estimate of tree stock characteristic per ha to correspond to the unit values achieved when sampled in proportion to basal area (Illustrations in table 1).

The exact volumes of the trees are not known in advance. However, the order of magnitude of the volumes can be calculated and plot sizes determined as functions of diameter at breast height.

6. SAMPLING IN PROPORTION TO VALUE

As in the case of volume:
Tree d = 20 cm, va = 21,20 mk.

$$\frac{A}{a} \times va_{d = 20 \text{ cm}} = \frac{10\,000}{\pi 10^2} \times 21{,}20 \text{ mk} = 675 \text{ mk/ha}.$$

Plot size and radius for a tree d = 25 cm; va = 49,20 mk are

$$x = \frac{10\,000 \times 49{,}20}{675} = 729 \text{ m}^2; \quad r = 15{,}23 \text{ m}$$

Illustrations are presented in table 1.

For practical applications, the magnitude class of volumes and plot sizes are determined as functions of diameter at breast height.

To illustrate, the unit values of volume and value given by each tree enumerated are 8,43 m³/ha and 675 mk/ha, which correspond to the fixed radius of 10 m for trees having d = 20 cm. In order to simplify the calculations in practice, the unit values can be chosen in units such as 10 m³/ha and 700 mk/ha.

7. SAMPLING BY ANGLE GAUGE IN PROPORTION TO TREE NUMBER, VOLUME AND VALUE

Sampling by angle gauge is carried out by adjusting the angle gauge in such a way that the desired plot size is achieved. If the distance from the notch to the vertical line passing through the plot centre is used as an adjustable characteristic, the procedure, illustrated here for the case of sampling in proportion to volume and with d′ = 2 cm, d = 25 cm, r = 13,63 m, is as follows:

$$\frac{d'}{r'} = \frac{d}{r}; \quad \frac{2}{r'} = \frac{25}{1\,363}; \quad r' = 109{,}04 \text{ cm}$$

For the trees presented in table 1, the value of r′ are:

tree	*d*, cm	number	Sampling in proportion to		
			B	*V*	*VA*
			r' in cm		
1	10	200,00	100,00	76,80	38,40
2	15	133,33	100,00	90,13	63,73
3	20	100,00	100,00	100,00	100,00
4	25	80,00	100,00	109,04	121,84
5	30	66,67	100,00	111,93	131,20

If the sampling is carried out by the simple stick and notch relascope, the sample plot radii and angle gauge characteristics are determined in advance and r′ and d′ are calibrated to give the angle needed for each diameter of tree.

8. ANGLE GAUGE SAMPLING IN PROPORTION TO BASAL AREA IN REPEATED MEASUREMENTS

There has been some discussion about the possibility of using angle gauge techniques on sample plots to be re-measured. The method has so far been considered either impossible or lacking a secure theoretical basis.

On the other hand, its use for increment estimations on the basis of radial and height increment measurements has been described and it has been succesfully used for this purpose (Kuusela 1966, Kuusela and Salminen 1969). The theory can be applied equally well in the cases of repeated measurements. Increment estimation covers a time period »backwards» and repeated measurements »forward in time».

An angle gauge plot is established and measured at the beginning of a period. At the end of a period of years the same unit trees are measured and the increment is calculated as the difference of the initial volume at the beginning of the period and the final volume at the end of the period, taking into account the possible drain from the unit trees and possible ingrowth of trees over breast height on the plot area.

Table 2. Angle gauge sampling in repeated measurements. Basal area factor $f = 1$; period between measurements 5 years.
Taulukko 2. Kulmanäyte toistuvassa koealamittauksessa. Pohjapinta-alakerroin $f = 1$; mittausten väli 5 vuotta.

Initial unit trees and ingrowth — *Alkupuusto ja kynnyskasvu*													New plot — *Uusi koeala*		
at the beginning of period — *jakson alussa*						at the end of period — *jakson lopussa*									
Tree number *Puun n:o*	G_{u0} m²/ha	d_0 cm	N_{u0} trees per ha *kpl/ha*	v_0 m³	V_{u0} m³/ha	Tree number *Puun n:o*	d_5 cm	g_5 m²	G_{u5} m²/ha	v_5 m³	V_{u5} m³/ha	N_{u5} trees per ha *kpl/ha*	G_u m²/ha	N_u trees per ha *kpl/ha*	V_u m³/ha
1	1	7,1	252,58	,011	2,78	1	7,6	,0045	1,14	,014	3,53		1	220,04	3,08
2	1	15,3	54,39	,137	7,45	2	16,5	,0214	1,16	,167	9,08		1	46,77	7,81
3	1	11,7	93,01	,062	5,77	3	12,6	,0125	1,16	,078	7,25		1	82,20	6,41
4	1	9,0	157,19	,029	4,56	4 X	9,4	,0069	1,08	,033	5,19		1	144,10	4,76
5	1	20,5	30,30	,260	7,88	5	22,1	,0384	1,16	,323	9,79		1	26,07	8,42
6	1	17,8	40,19	,203	8,16	6	19,3	,0293	1,18	,252	10,12		1	34,18	8,61
7	1	16,4	47,34	,152	7,20	7	17,8	,0249	1,18	,195	9,23		1	40,19	7,84
8	1	17,1	43,54	,170	7,40	8	18,4	,0266	1,16	,214	9,32		1	37,61	8,05
9	1	22,3	25,60	,322	8,24	9	24,0	,0452	1,16	,409	10,47		1	22,10	9,04
10	1	14,9	57,35	,132	7,57	10	16,1	,0204	1,17	,173	9,40		1	49,12	8,50
11	1	13,2	73,07	,085	6,21	11 X	13,8	,0150	1,10	,098	7,16		1	66,86	6,55
12	1	16,9	44,58	,183	8,16	12	18,3	,0263	1,17	,234	10,43		1	38,02	8,90
13	1	15,5	53,00	,141	7,47	13	16,7	,0219	1,16	,178	9,43		1	45,65	8,13
14	1	14,0	64,96	,095	6,17	14	15,1	,0179	1,16	,118	7,67		1	55,84	6,59
15	1	15,7	51,65	,157	8,11	15	16,9	,0224	1,16	,195	10,07		1	44,68	8,71
Initial stock *Alkupuusto*	15		1 089		103,13		Final stock *Loppupuusto*		15,12		115,80	859			
							Drain X *Poistuma*		2,18		12,35	230			
				Ingrowth *Kynnyskasvu*		16	1,4		1	,0005	3,25	6 496	1	6 496,12	3,25
						17							1	31,83	9,26
						18							1	64,04	5,96
											Final stock *Loppupuusto*		15	838	115,31
											Drain X *Poistuma*		2	211	11,31

In this procedure the plot sizes which were used at the beginning of the period are also used at the end of the period. This procedure minimizes the variance of the estimates based on the repeated measurements.

Of course, two independent angle gauge plots having the same centre point can be measured at the beginning and at the end of the period and calculate the increment as a difference of the two estimates taking into account the possible drain of trees which would belong to the plot at the time of the second measurement. Because new trees may enter into the plot at the second measurement on the basis of their diameter increment this increases the variance of the estimates compared with the estimates based on the same unit trees.

With regard to the procedure, the tree characteristics measured and calculated at the beginning of the period are marked by sub-symbol 0. The tree and unit tree characteristics are:

d_0 = diameter at breast height, cm
v_0 = volume of tree, m³
G_0 = unit basal area, m²/ha; if $f = 1$, $G_0 = 1$ m²/ha
N_{u0} = unit number of trees per ha
V_{u0} = unit volume, m³/ha.

Estimates of tree stock characteristics, basal area B_0, number of trees N_0 and volume V_0, all per ha, are sums of the corresponding unit values.

The results of the initial measurements are illustrated in table 2. The initial tree stock estimates are:

B_0 = 15 m²/ha
N_0 = 1 089 trees per ha
V_0 = 103,13 m³/ha

After 5 years the same unit trees are again measured. Their characteristics are marked by the sub-symbol 5. Unit trees which have been cut or have died during the period between the two measurements are marked by (x) in table 2 (trees 4 and 11). They comprise the estimate of drain.

Characteristics at the end of the period are:

d_5 = diameter at breast height, cm
g_5 = cross sectional area, m²
G_{u5} = unit basal area = $N_{u0} \times g_5$, m²/ha
v_5 = volume of tree, m³
V_{u5} = unit volume = $N_{u0} \times v_5$, m³/ha
N_{u5} = unit number of trees per ha = N_{u0}.

Tree stock characteristics are calculated as described above (table 2).

Increment of the unit trees during the period is:

increment = final stock — initial stock + drain

If there are trees which have grown over breast height during the period and belong into the angle gauge plot at the end of the period, they are called ingrowth and their characteristics will be added to the increment of the original unit trees in order to obtain the estimate of the total increment in the plot stock. In table 2, tree 16 is an example of ingrowth.

Results from table 2 are as follows:

N original unit trees	final stock	+ 859	trees per ha		
	initial stock	—1 089	»		
	drain	+ 230	»		
	increment	0	trees per ha	0	per year
ingrowth		+6 496	»	1 299	»
	total increment	6 496	trees per ha	1 299	per year
G original unit trees	final stock	+15,12	m²/ha		
	initial stock	—15,00	»		
	drain	+ 2,18	»		
	increment	2,30	m²/ha	0,46	per year
ingrowth		1,00	»	0,20	»
	total increment	3,30	m²/ha	0,66	per year
V original unit trees	final stock	+115,80	m³/ha		
	initial stock	—103,13	»		
	drain	+ 12,35	»		
	increment	25,02	m³/ha	5,00	per year
ingrowth		3,25	»	0,65	»
	total increment	28,27	m³/ha	5,65	per year

If two independent angle gauge measurements are used, the results from table 2 are:

N	final stock	+ 838			
	initial stock	—1 089			
	drain	+ 211			
	increment	— 40	trees per ha	—5	per year
	ingrowth	+6 496	»	1 299	»
	total increment	6 456	trees per ha	1 291	per year
G	final stock	+14	m²/ha		
	initial stock	—15	»		
	drain	+ 2	»		
	increment	1	m²/ha	0,20	per year
	ingrowth	1	»	0,20	»
	total increment	2	m²/ha	0,40	per year
V	final stock	+115,31	m³/ha		
	initial stock	—103,13	»		
	drain	+ 11,31	»		
	increment	23,49	m³/ha	4,70	per year
	ingrowth	3,25	»	0,65	»
	total increment	26,74	m³/ha	5,35	per year

REFERENCES

BITTERLICH, W. 1948. Die Winkelzählprobe. Allg. Forst- u. Holzwirtsch. Ztg., p. 4—5.

KUUSELA, K. 1966. A basal area-mean tree method in forest inventory. Seloste: Pohjapinta-ala-keskipuumenetelmä metsäninventoinnissa. Commun. Inst. For. Fenn. 61 (2): 1—32.

— & SALMINEN, S. 1969. The 5th National Forest Inventory in Finland. General design, instructions for field work and data processing. Commun.Inst.For.Fenn. 69 (4): 1—72.

ZÖHLER, F. 1978. Fundamentale Stichprobenkonzepte der Forstinventur I. Allg.Forstztg. p. 180—185.

SELOSTE

Puuston koealamittauksille perustuvan arvioinnin keskeisimpiä ongelmia on aikaansaada menetelmä, jossa puita mitataan suhteessa niiden merkitykseen halutun tuloksen kannalta. Koska yksityisen puun mittaamisen kustannukset ovat likimain riippumattomia puun koosta ja arvosta, niin suhteessa arvioinnin kustannuksiin edullisin on menetelmä, jossa jokainen mitattu puu on yhtä tärkeä tuloksen kannalta. Jos ensisijainen tavoite on puuston runkotilavuus, niin sanottu periaate merkitsee sitä, että jokaisen mitatun puun tulisi antaa yhtä suuri tilavuus hehtaaria kohti riippumatta puun koosta.

Menetelmän kenttäkelpoisuuden kannalta näyttää ongelma olevan edullisimmin ratkaistavissa kulmamittarilla eli relaskoopilla (Bitterlich 1948, vrt. myös Kuusela 1966, Kuusela ja Salminen 1969). Kulmamittarin yleisen teoreettisen soveltuvuuden on ehkä selvimmin tajunnut Zöhrer (1978). Tältä pohjalta lähtien esitetään käsillä olevassa julkaisussa menetelmä, jolla ongelma voidaan ratkaista kentällä.

Menetelmässä käytetyt puuston tunnukset ovat (Kuusela 1966):

d = rungon läpimitta rinnankorkeudella kuoren päältä
g = läpimittaa vastaava rungon poikkileikkauspinnan ala
v = rungon kuorellinen tilavuus
va = puun esim. kantohinnan mukainen arvo
N = puuston runkoluvun arvio hehtaaria (ha) kohti
G = puuston pohjapinta-alan arvio hehtaaria kohti
V = puuston runkotilavuuden arvio hehtaaria kohti
VA = puuston arvon arvio hehtaaria kohti.

Koealan muoto kulmamittaria käytettäessä on ympyrä, jonka koko on riippuvainen puun tunnuksista. Menetelmän kuvauksessa käytetään seuraavia tunnuksia:

r = koealaympyrän säde
a = koealan koko
A = metsän pinta-alan yksikkö, 1 ha
f = pohjapinta-alakerroin; kun $f = 1$, niin yksi luettu puu antaa puuston pohjapinta-alaa 1 m²/ha
p = ympyräkoealojen keskipiste
d' = yksinkertaisen varsi- ja hahlokulmamittarin hahlon leveys
r' = kulmamittarin varren pituus.

Esitettävissä vaihtoehdoissa kulmamittaria käytetään arvioitaessa puustoa siten, että arvioinnin kannalta tärkein tunnus on joko puuston runkoluku, pohjapinta-ala, runkotilavuus tai kantohinta-arvo.

Kun tärkein tunnus on pohjapinta-ala, niin kulmamittarin varsi on kaikille puille pituudeltaan vakio. Jokainen luettu puu antaa pohjapinta-alakertoimen mukaisen määrän pohjapinta-alaa puuston pohjapinta-alan arvioon. Läpimitaltaan tai täsmällisemmin sanottuna poikkileikkauspinta-alaltaan erilaisille puille on oma ympyräkoealan kokonsa.

Kun runkoluku, tilavuus tai arvo on tärkein tunnus, niin vastaavasti kulmamittarin ja hahlon suhde määritetään siten, että kukin luettu puu antaa joko yhtä suuren runkoluvun, tilavuuden tai arvon hehtaaria kohti. Käytännössä tämä voi tapahtua siten, että jokaista läpimittaa olevalle puulle on oma kulmamittarin varren pituutensa, joka antaa halutun yksikkötunnuksen (Taulukko 1).

Kun tärkein arvioitava tunnus on runkoluku, niin ympyräkoelan koko on kaikille puille sama. Kun tärkein tunnus on pojapinta-ala, niin ympyräkoeala on sitä suurempi mitä suurempi on puun läpimitta. Suhteessa puun läpimittaan pienen ja suuren puun ympyräkoealojen kokoero suurenee, kun tärkein tunnus on tilavuus. Suurin on kokoero, kun tärkein tunnus on arvo.

Kun otetaan huomioon työmenekki ja kustannukset, niin suoritettaessa arviointi suhteessa runkolukuun, on ilmeisestikin edullisempaa käyttää koealan säteen mittaa kuin kulmamittaria.

Suoritettaessa arviointi suhteessa pohjapinta-alaan on kulmamittarin käyttö kustannusten kannalta edullisin vaihtoehto. Silloinkin kun kuutiomäärä on tärkein tunnus, on kustannusten kannalta todennäköisesti edullisinta käyttää kulmamittaria suhteessa pohjapinta-alaan.

Kun tärkein tunnus on puuston arvo, niin kulmamittarin käyttäminen suhteessa puiden arvoon näyttäisi kustannusten kannalta edulliselta. Menetelmää varten tarvitaan puiden arvon funktio, jossa läpimitta on riippumaton tunnus. Kun kulmamittarin hahlon leveys on vakio, niin jokaista läpimittaa olevalle puulle on oma mittarin varren pituutensa. Käytännössä arvioinnin suorittaja oppii nopeasti arvioimaan, mikä on eri läpimittaa olevien puiden likimääräinen etäisyys keskipisteestä, luettavaksi tulevien puiden läpimitta mitataan, mittarin hahlo asetetaan vastaavan varren pituuden kohdalle ja tähtäämällä havaitaan, onko puu luettava. Rajapuut tarkistetaan mittanauhalla. Menetelmä näyttää edulliselta esim. silloin, kun tavoitteena on puuston kantohinta-arvon arvioiminen.

Taulukossa 2 on esitetty, miten kulmamittausta suhteessa pohjapinta-alaan voidaan käyttää, kun koeala mitataan kahteen kertaan 5 vuoden pituisen jakson alussa ja lopussa.

ON THE CONSTRUCTION OF TAPER CURVES BY USING SPLINE FUNCTIONS

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Seloste

RUNKOKÄYRÄN MUODOSTAMINEN SPLINI-FUNKTIOLLA

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LAHTINEN, A. & LAASASENAHO, J. 1979. On the construction of taper curves by using spline functions. Seloste: Runkokäyrän muodostaminen splini-funktiolla. Commun. Inst. For. Fenn. 95 (8): 1—63.

The theme of the present paper is the construction of the taper curve by using the interpolating cubic spline on the basis of several diameter measurements. Some attention has also been given to the interpolating parabolic spline. The properties of the cubic spline are analysed theoretically in relation to the taper curve. They depend essentially on so-called initial conditions. It is shown that these conditions can be determined by estimating the diameter of the stem or the first or second derivative of the actual taper curve at two given points. This estimation can be performed by interpolation so that no additional measurements are needed. Information on the effect of the place and nature of estimation is obtained by error analysis.

The theoretical results have been confirmed and sometimes also expanded by practical experiments using a representative sample tree material of 1864 spruces. The taper curves of all trees were constructed in different ways and their behaviour was examined numerically and in some cases also by forming their graphs. These investigations confirmed that the interpolating cubic spline is capable of producing a taper curve which has all the desired qualities. It is possible to devise for any application an effective data processing system which can be used without mathematical knowledge.

Tutkimuksessa tarkastellaan runkokäyrän muodostamista, kun puusta on mitattu useita läpimittoja. Päähuomio on kuutiollisen interpolaatiosplinin käytössä, mutta myös parabolista interpolaatiospliniä käsitellään jonkin verran. Teoreettisesti tutkitaan kuutiollisen splinin ominaisuuksia runkokäyräkäyttöä ajatellen. Erityisesti osoitetaan, että ns. alkuehdot, jotka oleellisesti vaikuttavat splinin ominaisuuksiin, voidaan määrätä estimoimalla puun läpimittaa tai todellisen runkokäyrän ensimmäistä tai toista derivaattaa kahdessa annetussa pisteessä. Estimointi voidaan suorittaa interpoloimalla, jolloin ylimääräisiä mittauksia ei tarvita. Virheanalyysin avulla tutkitaan estimoinnin suorituspaikan ja -tavan merkitystä.

Teoreettisesti saatuja tuloksia varmennetaan ja täydennetään kokeellisesti käyttäen 1864 rungon kuusikoepuuaineistoa. Näille puille on muodostettu runkokäyriä eri tavoilla, ja saatujen käyrien ominaisuuksia on tutkittu numeerisesti sekä joissain tapauksissa myös graafisesti. Tutkimukset osoittavat, että kuutiollisen interpolaatiosplinin avulla voidaan muodostaa runkokäyrä, jolla on kaikki tarvittavat ominaisuudet. Sen jokaista käyttötarkoitusta varten voidaan muodostaa tehokas tietojenkäsittelysysteemi, jota voidaan käyttää tarvitsematta matemaattista tietämystä.

Helsinki 1980. Valtion painatuskeskus

FOREWORD

This paper presents a mathematical model of the taper curve of a tree. Joint research by a mathematician and forest scientist has made it possible to take both theoretical and practical aspects into account to a considerable extent. The views of the writers have been brought together by close collaboration to form a unified presentation.

The writers have carried out the numerous practical tests and their numerical and statistical analyses with the help of the generosity of the Computing Centre, University of Helsinki. The financial support of the Foundation for Research of Natural Resources in Finland is gratefully acknowledged. Professor Kullervo K u u s e l a and Docent Pertti H a r i have read the entire manuscript and made many valuable comments. Timo L a u r i n e n, M.A. has checked the language of the manuscript.

Helsinki, December 1979

Aatos Lahtinen *Jouko Laasasenaho*

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1. INTRODUCTION

For a thorough investigation of form and volume of tree stem we have to measure the diameter of the tree at several heights. The diameters are usually taken at some standardized intervals or from prescribed proportional heights. The aim of the work may be, for example, a volume function. The determination of volumes of sample trees is then carried out by means of several accurately, preferably cross-wise, measured diameters. For a precise examination of the tree growth, e.g. the development of marketable assortments of a tree, we have to make a so-called stem analysis on it, and then the development of tree is often depicted by a graph, too (cf. Ilvessalo 1965, p. 126).

The total volume of a stem is usually evaluated piecewise by Huber's or Simpson's formula (cf. e.g. Ilvessalo 1965, p. 84). When we divide a stem into lumber assortments, the positions of the least acceptable measures of different lumber assortments on it must be found out. Diameters between the measurements are usually estimated by linear or parabolic interpolation. A parabola can also be used for determining the volume.

By Huber's formula we generally obtain too small volumes, especially at the neiloidic lowest part of the stem, even with abbreviated measuring intervals. Simpson's formula is more accurate. Nevertheless the double weights of every second diameter in the repeated Simpson's formula may cause bias in the results. However, the results given by these formulae are generally considered sufficiently accurate in relation to the errors and error tolerances of diameter measurements.

We cannot obtain a continuous derivative for every point by a piecewise linear or parabolic interpolation because the slope of the curve is liable to sudden changes at the seam points of subsequent components. Recently also such taper curve methods have been introduced in which the first derivative becomes continuous all over the stem (Kilkki *et al.* 1978). However, the topic involves such intricate problems that until now there is no generally accepted technique for defining the taper curve on the basis of sectional measurement of the stem. The development of scientific data processing has made it possible to construct and apply highly sophisticated methods on this line.

Since the beginning of 1976, the authors of the present paper have been working on a general system of computer programs for the construction and use of taper

curves based on diametrical observations on the stem. Most attention was paid to application of the so-called interpolating cubic spline for our purpose (cf. e.g. B ö h m e r 1975). In this procedure, the taper curve is approximated on each interval of adjacent measurements by a cubic polynomial and the adjoining polynomials are tied together so that their second derivatives have the same values at the junction point. Hence, the resulting taper curve is not only continuous but has also continuous first and second derivatives. At the measuring points it has the measured diameter values. Since the interpolating cubic spline also has a minimum curvature property, it appears to meet the requirements set on a mathematical model of a taper curve quite adequately.

Besides interpolation also other methods can be used to characterize a cubic spline. T i e t z e and P o f a h l (1979) have quite recently considered a case where a very large number of measurements is available and constructed a taper curve using a cubic spline determined by the least squares method. This spline has only a relatively moderate number of components despite the large amount of measurements.

Attempts to prepare taper curves with interpolating cubic splines have also been made by B. S l o b o d a (1976). In his approach to the problem S l o b o d a made use of the so-called natural spline, which is a cubic spline specified by setting the second derivatives equal to zero at the utmost measuring points. However, especially at the butt end of a tree, the second derivative of the actual taper curve is not zero. For this reason we have tried in the present work to construct spline functions that would suit better for taper curve. We have theoretically considered different ways of determining spline functions and then investigated the properties of the resulting taper curves also in practice by means of a large sample of tree material. In addition we have formed some views on the effect of the number and placement of measurements on the adequacy of these taper curves. Our target has been a reliable program library which could be used without knowledge of the underlying mathematics.

2. SAMPLE TREE MATERIAL

In practical tests we used the sample tree material collected for other aims by the Finnish Forest Research Institute between 1968 and 1972 (cf. Laasasenaho & Sevola 1971). For the present purpose we took only spruce stems out of this material on the assumption that the resulting methods could probably be adapted for other tree species.

Localities (95) of this material were chosen among the survey tracts of the Finnish National Forest Inventory by random sampling. Sample plots selected for the collection of material were spaced along the tract at intervals of 200 m. Plots outside forestry land were omitted. From any tract at most 26 sample plots were used for collecting of material. At most five trees objectively chosen by relascope were measured on each sample plot.

For diameter measurement the standing sample trees were mostly climbed up. Tree height was recorded to the nearest dm. Diameters were measured at the following proportional heights from ground: 1, 2½, 5, 7½, 10, 15, 20, 30, 40, 50, 60, 70, 80 and 90 per cent. Moreover, the diameters at 1,3 and 6,0 m were registered. The diameters were measured to the nearest mm by crosswise calipering.

The material covers the whole of Finland and illustrates the distribution of spruce into DBH-classes in relation to the basal area. The distribution of these sample trees into diameter- and length-classes is presented in Table 1.

Average stem form, as described by the spline functions, is shown in Figure 1 (p. 41). At each proportional height the curve represents the mean of diameters at the corresponding level in our spruce material. The relations of diameters on different per cent heights are approximately the same for all stems regardless of the size of the tree. The shape of taper curve of an individual tree may greatly depart from the average one, which fact can also be seen from Figure 1. We discovered in our material 471 such specimens where at least one diameter was reported larger than the nearest lower measured diameter.

The large amount of irregular diameter sequences — a quarter of our material — certainly calls for some comment. At least part of them must be due to unavoidable errors in measurements, the presence of which cannot be totally disregarded even when the material has been measured and checked carefully. But there is more to it. When the diameters on a tree are measured at distances short enough, the resulting sequence is not necessarily monotonically decreasing with the increase of height. This phenomenon is chiefly caused by boughs. The leading shoot in a tree may have a regular appearance, but at any whorl of branches the stem is liable to bulge out. The stem does not stop swelling even if the boughs are self-pruned out later on.

However, the purpose of the present paper is not to investigate this unimportant variation in trunk thickness. This would not even be feasible on the basis of our material, although with short trees the intervals between measurements are small, especially at the butt end. Nevertheless, the existence of such irregularities in actual taper curves is a good property in the sense that it helps to spot deficiencies in the construction of taper curves.

On the whole we can conclude that this sample tree material meets very well the demands of our investigation in relation to the measuring and selection. Its measurements give an adequate description of the actual taper curve, and the material can be considered very representative.

Table 1. Distribution of sample trees by diameter and height classes.
Taulukko 1. Koepuiden jakaantuminen läpimitta- ja pituusluokkiin.

d cm	Tree height, m — *Puun pituus, m*																	Total *Yhteensä*
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	
	Number of trees — *Puiden lukumäärä*																	
1	3	2																5
3		31	5															36
5		26	44	5														75
7			57	45	6													108
9			11	57	45	8	1											122
11			4	33	66	42	15											160
13			2	6	48	57	48	5										166
15				5	14	38	53	37	9									156
17					5	29	51	40	24	5								154
19				1	5	17	34	41	36	11	3							148
21						3	22	53	37	25	8							148
23							10	25	43	24	27	5						134
25							6	11	22	30	27	10						106
27							5	6	16	26	23	17	4					97
29								1	15	21	25	17	5	1				85
31							1	2	7	3	16	10	9	1				49
33									1	6	8	12	3	3	1			34
35							1		4	2	3	7	3	2				22
37											4	4	10	6	2			26
39											2	4	1	4	1			12
41											1		4	3				8
43												1	1	1	1			4
45														1	2	1		4
47												1			1			2
49																		
51																		
53												1			1			2
55																		
57																		
59																		
61																	1	1
Total — *Yhteensä*	3	59	123	152	189	194	247	221	214	153	147	89	40	22	9	1	1	1 864

3. CUBIC SPLINES

This chapter contains a short introduction to interpolating cubic splines. It concentrates on the properties which we need in this research or which are necessary for understanding some aspects of the results. A larger and more detailed presentation of cubic splines can be found in A h l b e r g *et al.* 1967 and B ö h m e r 1974, to which we also refer for the proofs of several known results which are only stated here.

In the first section we give the definition of the interpolating cubic spline and present an outline of its construction with first derivatives at mesh points. It appears that the spline is unique only on some additional conditions which we call initial conditions. We give the usual form of initial conditions and state when these conditions determine the spline uniquely.

In the second section we introduce Thomas's algorithm, the most efficient way of getting the first derivatives needed in the construction of the spline.

The third section presents two essential properties of interpolating cubic splines. The first property means in effect that if s_f is the cubic spline interpolating a given function f in a mesh Δ, then the difference $s_f - f$ can be made arbitrarily small by choosing a sufficiently large Δ. The second is the so-called minimum curvature property which can be used in an alternative definition of the spline and which has played a great part in the development of the theory of splines.

In section four we show that the initial conditions can be chosen in a much more general way than that presented in the first section.

Some natural ways to determine admissible initial conditions are presented in section five.

The sixth section contains some elementary remarks concerning the effect of errors occurring in practical calculations.

Finally, in section seven we give another common method of constructing an interpolating cubic spline. It involves the use of second derivatives at mesh points.

31. Definition and construction

We begin with some definitions and notations. Let N be the set of natural numbers, R the set of real numbers and R^n the set of n-triples, $r = (r_1, \ldots, r_n)$, $r_i \in R$, $i = 1(1)n$. Let $[a,b]$ be a closed interval in R and Δ a mesh of points called knots, $\Delta = \{x_1, \ldots, x_n\} \subset$

$[a,b]$, $a = x_1 < x_2 < \ldots < x_n = b$. We denote $h = b-a$, $h_i = x_{i+1}-x_i$. The number $\|\Delta\| = \max\{h_i | 1 \leq i \leq n-1\}$ is called the mesh gauge. Let $f\colon [a,b] \to R$ be a given function. If f is a polynomial of degree not exceeding n, we denote $f \in \Pi_n[a,b]$, and if f has continuous derivatives up to the order n, we denote $f \in C^n[a,b]$.

Definition 31.1. A function $s_r\colon [a,b] \to R$ is called the spline of a given vector $r \in R^n$ in Δ if

1) $s_r/[x_i, x_{i+1}] \in \Pi_3[x_i, x_{i+1}]$, $i = 1(1)n-1$,

2) $s_r \in C^2[a, b]$,

3) $s_r(x_i) = r_i$, $i = 1(1)n$.

If r is formed from a function f by setting $r_i = f(x_i)$, $i = 1(1)n$, then s_r is denoted by s_f and called the spline of f in Δ.

The function s_r is in fact the *interpolating cubic spline* of r in Δ but we shall use the shorter name because we do not use here other kinds of splines. The spline of r in Δ is thus a twice continuously differentiable function which takes prescribed values r_i at knots x_i and is a cubic polynomial between knots. We can get an expression for the spline by determining these cubic polynomials and joining them together so that they have same values up to the second derivatives at common knots. This can be done by using Hermitian interpolation. If $\Delta = \{x_1, \ldots, x_n\}$ and $r \in R^n$ are given, we denote

$$\delta r_i = (r_{i+1}-r_i)/h_i. \tag{31.1}$$

Proposition 31.2. A polynomial $q_i \in \Pi_3[a,b]$, $i \in \{1, \ldots, n-1\}$ has under conditions

$$q_i(x_j) = r_j,\ Dq_i(x_j) = m_j,\ j = i, i+1 \tag{31.2}$$

a unique representation

$$q_i(x) = \frac{-2\delta r_i + m_{i+1} + m_i}{h_i^2}(x-x_i)^3 + \frac{3\delta r_i - m_{i+1} - 2m_i}{h_i}(x-x_i)^2 + m_i(x-x_i) + r_i. \tag{31.3}$$

Moreover, $D^2 q_i(x_{i+1}) = D^2 q_{i+1}(x_{i+1})$ if and only if

$$\varrho_{i+1} m_i + 2m_{i+1} + \lambda_{i+1} m_{i+2} = d_{i+1}, \tag{31.4}$$

where

$$\begin{aligned} \varrho_{i+1} &= h_{i+1}/(h_i + h_{i+1}), \\ \lambda_{i+1} &= 1-\varrho_{i+1}, \\ d_{i+1} &= 3(h_i \delta r_{i+1} + h_{i+1}\delta r_i)/(h_i + h_{i+1}). \end{aligned} \tag{31.5}$$

This proposition can be verified by direct calculation (B ö h m e r 1974, p. 20). The representation of the spline can now be formed as follows. We demand that (31.4) is valid at knots x_i, $i = 2(1)n$—1. Thus we get a system of equations

$$\begin{aligned} &\varrho_2 m_1 + 2m_2 + \lambda_2 m_3 = d_2 \\ &\qquad\qquad \vdots \\ &\varrho_{n-1} m_{n-2} + 2m_{n-1} + \lambda_{n-1} m_n = d_{n-1}. \end{aligned} \tag{31.6}$$

If the vector $m = (m_1, \ldots, m_n)$ is solved from (31.6) and substituted into (31.3) we get a spline s_r in the sense of Definition 31.1 by setting

$$s_r/[x_i, x_{i+1}] = q_i, \qquad i = 1(1)n-1.$$

As the system (31.6) has n unknowns and only n—2 equations, its solution cannot be unique. Thus the resulting spline is not unique without additional specifications. It is clear that an effective use of the spline is not possible without uniqueness.

Thus we have to find suitable additional conditions. A natural solution is to choose four initial values $\lambda_1, d_1, \varrho_n, d_n$ in some convenient way and form two additional equations

$$\begin{aligned} &2m_1 + \lambda_1 m_2 = d_1 \\ &\varrho_n m_{n-1} + 2m_n = d_n. \end{aligned} \tag{31.7}$$

If we now demand that the solution of (31.6) is also a solution of (31.7), we get a system of n equations and n unknowns

$$Am = d, \tag{31.8}$$

where $m = (m_1, \ldots, m_n)^T$, $d = (d_1, \ldots, d_n)^T$ and

$$A = \begin{bmatrix} 2 & \lambda_1 & 0 & \ldots & 0 & 0 & 0 \\ \varrho_2 & 2 & \lambda_2 & \ldots & 0 & 0 & 0 \\ 0 & \varrho_3 & 2 & \ldots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \ldots & 2 & \lambda_{n-2} & 0 \\ 0 & 0 & 0 & \ldots & \varrho_{n-1} & 2 & \lambda_{n-1} \\ 0 & 0 & 0 & \ldots & 0 & \varrho_n & 2 \end{bmatrix} \tag{31.9}$$

If $\det A \neq 0$, then (31.8) has a unique solution and therefore the resulting spline is also unique. However, this condition is difficult to use in practice and no more convenient condition which is both necessary and sufficient is available. Therefore we choose for the basis of later considerations the following result which uses a sufficient but not necessary condition (A h l b e r g *et al.* 1967, p. 61).

Proposition 31.3. Let a mesh $\Delta = \{x_1, \ldots, x_n\} \subset [a,b]$ and a vector $r = (r_1, \ldots, r_n) \in R^n$ be given. There exists a unique spline s_r of r in Δ satisfying initial conditions (31.7) if $\lambda_1 < 4$, $\varrho_n < 4$ and $d_1, d_n \in R$. On an interval $[x_i, x_{i+1}]$ the spline s_r has the representation (31.3), where $m = (m_1, \ldots, m_n)^T$ is the solution of (31.8).

The initial conditions are usually given using either first or second derivatives at the end points of the interval (A h l b e r g *et al.* 1967, p. 14; B ö h m e r 1974, p. 22). If g_i' is the estimate of the first derivative at x_i, $i = 1,n$, then (31.7) takes the form

$$2m_1 = 2g_1', \quad 2m_n = 2g_n'. \tag{31.10}$$

If g_i'' is the estimate of the second derivative at x_i, $i = 1,n$, then (31.7) takes the form

$$\begin{aligned} 2m_1+m_2 &= 3\delta r_1-\tfrac{1}{2}h_1g_1'' \\ m_{n-1}+2m_n &= 3\delta r_{n-1}+\tfrac{1}{2}h_{n-1}g_n''. \end{aligned} \tag{31.11}$$

Clearly the conditions of Proposition 31.3 are satisfied in both cases. The spline determined using the values $g_1'' = g_n'' = 0$ in (31.11) is called *the natural spline*. It can also be defined by using an extremal property instead of end conditions (see Proposition (33.2)).

Later on, in section 35, we present other, more general, initial conditions.

32. Thomas's algorithm

A tridiagonal system of linear equations

$$\begin{aligned} b_1x_1 \;+c_1x_2 \qquad\qquad\qquad &= e_1, \\ a_{i+1}x_i+b_{i+1}x_{i+1}+c_{i+1}x_{i+2} &= e_{i+1} \quad i = 1(1)n-2, \\ a_nx_{n-1}+b_nx_n \qquad &= e_n, \end{aligned} \tag{32.1}$$

can very efficiently be solved by the following *Thomas's algorithm*.

Algorithm 32.1. Let $q_0 = u_0 = 0$, and define the numbers p_i, u_i, $i = 1(1)n$ and q_i, $i = 1(1)n-1$ by the relations

$$p_i = a_iq_{i-1}+b_i, \quad q_i = -\frac{c_i}{p_i}, \quad u_i = \frac{e_i-a_iu_{i-1}}{p_i}. \tag{32.2}$$

Calculate then the numbers $x_1,\ldots,x_n$ recursively by the relations

$$x_n = u_n, \quad x_{n-i} = q_{n-i}x_{n+1-i}+u_{n-i}, \quad i = 1(1)n-1. \tag{32.3}$$

If the system (32.1) has a unique solution, then it is given by Thomas's algorithm provided that the numbers p_i, $i = 1(1)n$ are all different from zero (Y o u n g 1971, p. 441). Notice that the latter condition is not always fulfilled. For example, the system

$$x_1+x_2 = 2, \quad x_1+x_2+x_3 = 3, \quad x_2+x_3 = 2$$

has a unique solution $x_1 = x_2 = x_3 = 1$, but it is not given by Thomas's algorithm because $p_2 = 0$ and the algorithm breaks down at that stage. For matrices with dominant main diagonal Thomas's algorithm is stable in the sense that errors rapidly damp out. This happens because then $|q_i| < 1$.

The system (31.8) of linear equations needed in the calculation of the spline is clearly tridiagonal, i.e. of the type (32.1) where

$$\begin{aligned} &b_i = 2,\ i = 1(1)n, \\ &a_i > 0,\ c_i > 0,\ a_i + c_i = 1,\ i = 2(1)n-1. \end{aligned} \tag{32.4}$$

The question is how to choose initial values c_1 and a_n so that (31.8) can be solved with Thomas's algorithm.

Proposition 32.2. Suppose that the coefficients of the linear system (32.1) satisfy the conditions (32.4). If $c_1 < 4$ and $a_n < 4$, then (32.1) has a unique solution which is given by Thomas's algorithm.

Proof. By Proposition 31.3 the system (32.1) has a unique solution. Thus it suffices to prove that $p_i \neq 0$, $i = 1(1)n$. Clearly $p_1 = 2 > 0$ and $q_1 = -\frac{1}{2}c_1 > -2$. We show by induction that $p_i > 0$ and $-\frac{1}{2} < q_i < 0$ when $i = 2(1)n-1$. With these values of i we have

$$\begin{aligned} &p_i = a_i q_{i-1} + 2(a_i + c_i) = 2c_i + (2 + q_{i-1})a_i, \\ &q_i = -\frac{c_i}{2c_i + (2 + q_{i-1})a_i} \end{aligned} \tag{32.5}$$

With the value $i = 2$ we have $2 + q_1 > 0$, whence $p_2 > 2c_2 > 0$ and $0 > q_2 > -c_2/2c_2 = -\frac{1}{2}$. The statement is thus valid if $i = 2$. By using (32.5) we can similarly show that if the statement is valid on value $i-1$, then it is also valid on the value i. Thus the statement is valid on values $i = 2(1)n-1$. Finally also $p_n \neq 0$. In fact, $p_n = a_n q_{n-1} + 2 > 0$, if $a_n \leq 0$ because $q_{n-1} < 0$, and $p_n > -\frac{1}{2}a_n + 2 > 0$, if $0 < a_n < 4$ because $q_{n-1} > -\frac{1}{2}$. The proposition is proved.

It has to be noticed that the condition $c_1 < 4$, $a_n < 4$ is the same as in Proposition 31.3 and is not a necessary one.

33. Two properties of splines

The spline has many favourable properties rendering it suitable for use in approximation. In this section we present two of these which support for their own part the use of the spline in our special problem. Let us start with the convergence. Suppose that $f\colon [a,b] \to R$ is a given function and we want to approximate it with a prescribed accuracy by using interpolation. To be more specific, let $\{\Delta_n\}_1^\infty$ be a sequence of meshes in $[a,b]$ with $\lim_{n\to\infty} \|\Delta_n\| = 0$ and let f_n be an approximation of f which interpolates f at the knots of Δ_n. Any prescribed accuracy can then be obtained

if the function f_n can be chosen in such a way that $\lim_{n\to\infty} f_n(x) = f(x)$ for every $x \in [a,b]$. This is no trivial demand. It is well-known that if f_n is the Lagrangian interpolating polynomial of f, then f_n does not always converge to f even if f has derivatives of all order (B ö h m e r 1974, p. 12; R u n g e 1901). If, however, f_n is the spline of f in Δ_n, then the convergence takes place on some moderate regularity conditions. From such results we mention the following one (A h l b e r g *et al.* 1967, p. 66).

Proposition 33.1. Let $f \in C^1[a,b]$ and let $\{\Delta_k\}$ be a sequence of meshes on $[a,b]$ with $\lim_{k\to\infty} \|\Delta_k\| = 0$. Let s_k be the spline of f in Δ_k satisfying the initial conditions

$$\begin{aligned} 2m_{k,1} \qquad\quad &+\lambda_{k,1}m_{k,2} = d_{k,1} \\ \varrho_{k,n}m_{k,n_k-1} &+2m_{k,n_k} = d_{k,n_k}. \end{aligned} \tag{33.1}$$

If

$$\inf_k (4-\lambda_{k,1}) > 0, \quad \inf_k (4-\varrho_{k,n_k}) > 0 \tag{33.2}$$

and

$$\sup_k |d_{k,1}| < \infty, \quad \sup_k |d_{k,n_k}| < \infty, \tag{33.3}$$

then $\lim_{k\to\infty} s_k(x) = f(x)$ uniformly on $[a,b]$.

The second property which we shall shortly present is the so-called *minimum curvature property*. It has had a profound effect on the development of the general theory of splines. We have no direct use of this property in our paper but it appears to be connected with the natural properties of the form of a tree and thus speaks for the spline as an approximation of the taper curve. We mention here only the first form of this result, presented by H o l l o d a y 1957. More sophisticated versions can be found e.g. in A h l b e r g *et al.* 1967 and B ö h m e r 1974.

Proposition 33.2. Let $\Delta = \{x_1,\ldots,x_n\}$ be a given mesh on $[a,b]$ and $r \in R^n$. Then of all functions $f \in C^2[a,b]$ with $f(x_i) = r_i$, $i = 1(1)n$, the natural spline of r in Δ minimizes the integral

$$\int_a^b |D^2 f(x)|^2 dx. \tag{33.4}$$

This is called the minimum curvature property because the integral (33.4) is often a good approximation to the integral of the square of the curvature for a curve $y = f(x)$. It is also closely related to the minimization of potential energy of a deflected beam (S o k o l n i k o f f 1946, p. 293).

The natural spline is defined by the initial conditions (31.11) with $g_1'' = g_n'' = 0$. Also other initial conditions can be used to get similar results (cf. e.g. A h l b e r g *et al.* 1967, p. 81).

34. The continuation of splines

In the first section of this chapter we defined the spline uniquely by giving two additional conditions concerning first derivatives in two first and two last mesh points. We shall now show that the additional conditions can be given also at other mesh points. This is based on the following continuation property.

Proposition 34.1. Let $\Delta = \{x_1,\ldots,x_n\}$ be a given mesh and let $\Delta_1 = \{x_i | i = k(1)l,\ k < l\}$ be a subset of Δ. Let $r = (r_1,\ldots,r_n) \in R^n$. If $s_1 : [x_k,x_l] \to R$ is a spline of $(r_k,\ldots,r_l)$ in Δ_1, then there exists a unique spline s of r in Δ with $s/[x_k,x_l] = s_1$.

Proof. It is sufficient to consider the case where $1 < k < l < n$. Since the values $r = (r_1,\ldots,r_n)$ are given, the spline s is determined by the first derivatives $m = (m_1,\ldots,m_n)$ at mesh points. They satisfy the equations (31.6)

$$\varrho_{i+1}m_i + 2m_{i+1} + \lambda_{i+1}m_{i+2} = d_{i+1}, \quad i = 1(1)n-2.$$

Since $s/[x_k,x_l] = s_1$ and s_1 is known, the derivatives $m_k,\ldots,m_l$ are known. For the solution of the remaining derivatives we get from (31.6) two systems of equations. The derivatives $m_1,\ldots,m_{k-1}$ satisfy equations

$$\begin{aligned}
&\varrho_2 m_1 + 2m_2 + \lambda_2 m_3 = d_2\\
&\qquad\qquad\vdots\\
&\varrho_{k-2}m_{k-3} + 2m_{k-2} + \lambda_{k-2}m_{k-1} = d_{k-2}\\
&\varrho_{k-1}m_{k-2} + 2m_{k-1} = d_{k-1} - \lambda_{k-1}m_k\\
&\varrho_k m_{k-1} = d_k - 2m_k - \lambda_k m_{k+1}.
\end{aligned} \tag{34.1}$$

It is easy to see that the determinant of the coefficient matrix has the value

$$D = \prod_{j=2}^{k} \varrho_j \neq 0$$

because every $\varrho_j \neq 0$. Thus (34.1) has a unique solution $m_1,\ldots,m_{k-1}$. The remaining derivatives $m_{l+1},\ldots,m_n$ satisfy equations

$$\begin{aligned}
\lambda_l m_{l+1} &= d_l - 2m_l - \varrho_l m_{l-1}\\
2m_{l+1} + \lambda_{l+1}m_{l+2} &= d_{l+1} - \varrho_{l+1}m_l\\
\varrho_{l+2}m_{l+1} - 2m_{l+2} + \lambda_{l+2}m_{l+3} &= d_{l+2}\\
&\vdots\\
\varrho_{n-1}m_{n-2} + 2m_{n-1} + \lambda_{n-1}m_n &= d_{n-1}.
\end{aligned} \tag{34.2}$$

The determinant of the coefficient matrix has the value

$$D = \prod_{j=l}^{n-1} \varrho_j \neq 0$$

because every $\lambda_j \neq 0$. Thus (34.2) has a unique solution $m_{l+1},\ldots,m_n$. Now all the derivatives $(m_1,\ldots,m_n)$ have been determined uniquely and thus the spline s exists and is unique. The proposition is proved.

Any spline can now be continued outside its domain of definition simply by giving additional points of interpolation and values at those points. If the original spline has been determined using initial conditions (31.7), the resulting spline has in fact been determined by initial conditions at interior mesh points. This observation makes it possible to choose the initial conditions more freely. Because all additional specifications do not determine the spline uniquely we introduce the following definition.

Definition 34.2. Let a mesh $\Delta = \{x_1,\ldots,x_n\} \subset [a,b]$ and a vector $r \in R^n$ be given. The equations

$$\begin{aligned} \mu_1 m_k + \nu_1 m_{k+1} &= \gamma_1 \\ \mu_2 m_l + \nu_2 m_{l+1} &= \gamma_2, \end{aligned} \tag{34.3}$$

are called *admissible* or *admissible initial conditions*, and the quantities $\mu_i, \nu_i, \gamma_i \in R$, $i = 1, 2$, and $k, l \in \{1,\ldots,n-1\}$ *admissible initial values* if there exists a unique spline of r in Δ satisfying conditions (34.3).

For example, (31.10) and (31.11) are admissible initial conditions, and also (31.7) if $\lambda_1 < 4$, $\varrho_n < 4$. More generally, we have the following result:

Proposition 34.3. Let $\Delta = \{x_1,\ldots,x_n\}$ be a mesh on the interval $[a,b]$ and let $r \in R^n$. Suppose that $k, l \in \{1,\ldots,n-1\}$; $k \leq l$ and $\lambda_1, \varrho_n, d_1, d_n \in R$. If either $k < l$ and $\lambda_1 < 4$, $\varrho_n < 4$ or $k = l$ and $\lambda_1 \varrho_n \neq 4$, then the equations

$$\begin{aligned} 2m_k + \lambda_1 m_{k+1} &= d_1 \\ \varrho_n m_l + 2m_{l+1} &= d_n \end{aligned} \tag{34.4}$$

are admissible initial conditions.

This proposition follows directly from Propositions 31.3 and 34.1. The construction of the spline by using (34.4) goes as follows. First we determine the derivatives $m_1,\ldots,m_n$ satisfying (31.6) and (34.4). The derivatives $m_k,\ldots,m_{l+1}$ are solved from the system

$$\begin{aligned} 2m_k + \lambda_1 m_{k+1} &= d_1 \\ \varrho_{i+1} m_i + 2m_{i+1} + \lambda_{i+1} m_{i+2} &= d_{i+1} \qquad i = k(1)l-1 \\ \varrho_n m_l + 2m_{l+1} &= d_n \end{aligned} \tag{34.5}$$

by using Thomas's algorithm as stated in 32. The other derivatives $m_1,\ldots,m_{k-1}$ and $m_{l+2},\ldots,m_n$ can then be obtained from the recursion formulae (cf. (34.1) and (34.2))

$$m_{k-i} = (d_{k+1-i} - 2m_{k+1-i} - \lambda_{k+1-i} m_{k+2-i})/\varrho_{k+1-i}, \qquad i = 1(1)k-1 \tag{34.6}$$

and

$$m_{l+1+i} = (d_{l+i} - 2m_{l+i} - \varrho_{l+i} m_{l+i-1})/\lambda_{l+i}, \qquad i = 1(1)n-l-1. \tag{34.7}$$

The polynomials of the spline can now be formed by using representation (31.3).

35. Some choices of initial values

In practice the determination of the initial values is often difficult. One common reason is that the values of the function f, which has to be approximated, are known only at discrete points. In this section we present some natural methods of choosing initial values and examine the conditions on which they are admissible. Because the spline is twice continuously differentiable, the additional information can be derived from three different sources; from the values of the function, from the values of first derivatives or from the values of second derivatives. We deal with each case separately. The situation is the usual, on an interval $[a,b]$ there is given a mesh $\Delta = \{x_1,\ldots,x_n\}$ and a vector $r \in R^n$. If the additional information is given at a point y_j and $y_j \in [x_i,x_{i+1}]$ we denote

$$\alpha_i = (y_j - x_i)/h_i.$$

Proposition 35.1. Suppose that the points $y_1, y_2 \in [a, b] \setminus \Delta$ and $g_1, g_2 \in R$. If $y_1 \in (x_k, x_{k+1})$ and $y_2 \in (x_l, x_{l+1})$ and $y_1 < y_2$, then the equations

$$(35.1)\qquad \begin{aligned}(1-\alpha_k)m_k - \alpha_k m_{k+1} &= \frac{1}{\alpha_k(1-\alpha_k)}\frac{g_1 - r_k}{h_k} + \frac{\alpha_k(2\alpha_k-3)}{(1-\alpha_k)}\,\delta r_k,\\ (1-\alpha_l)m_l - \alpha_l m_{l+1} &= \frac{1}{\alpha_l(1-\alpha_l)}\frac{g_2 - r_l}{h_l} + \frac{\alpha_l(2\alpha_l-3)}{(1-\alpha_l)}\,\delta r_l,\end{aligned}$$

are admissible initial conditions to the spline s_r with

$$(35.2)\qquad s_r(y_i) = g_i, \quad i = 1,2.$$

Proof. If $k = l$ we see by a direct calculation that (35.1) has a unique solution $\{m_k, m_{k+1}\}$. Thus we get a unique spline on the interval $[x_k, x_{k+1}]$. The admissibility follows now from Proposition 34.1. So we suppose that $k < l$. Because y_1 and y_2 are not mesh points we have $0 < \alpha_i < 1$, $i = k, l$. Therefore we can divide the former equation in (35.1) by $\frac{1}{2}(1-\alpha_k)$ and the latter by $-\frac{1}{2}\alpha_l$. The resulting equations are of the form (34.4) with

$$\lambda_1 = -\frac{2\alpha_k}{1-\alpha_k} < 0, \qquad \varrho_n = 2\,\frac{\alpha_l - 1}{\alpha_l} < 0$$

and $d_1, d_n \in R$. These are admissible initial values by Proposition 34.3. Finally we see by direct calculation that the spline s_r determined by (35.1) satisfies the conditions (35.2). The proposition is proved.

This result means that the spline s_r of r in Δ becomes uniquely determined if we choose two different points y_1, y_2 which are not mesh points, choose values $g_1, g_2 \in R$, and impose the condition (35.2), $s_r(y_i) = g_i$, $i = 1,2$. The initial conditions take then the form (35.1).

Next we shall examine if the same result is valid when the condition (35.2) is replaced by the statement that the first derivative of the spline has a given value

at two given points. We have already had such a result. In fact, if the points are end points of the interval, this leads to equations (31.10) which are admissible.

Proposition 35.2. Suppose that the points $y_1, y_2 \in [a,b]$ and $g_1', g_2' \in R$. If $y_1 \in [x_k, x_{k+1}]$, $y_2 \in [x_l, x_{l+1}]$ and $y_1 < y_2$, then the equations

$$\begin{aligned}(\alpha_k-1)(3\alpha_k-1)m_k+\alpha_k(3\alpha_k-2)m_{k+1} &= g_1'+6\alpha_k(\alpha_k-1)\delta r_k,\\ (\alpha_l-1)(3\alpha_l-1)m_l+\alpha_l(3\alpha_l-2)m_{l+1} &= g_2'+6\alpha_l(\alpha_l-1)\delta r_l\end{aligned} \tag{35.3}$$

are admissible initial conditions to the spline s_r with

$$Ds_r(y_i) = g_i', \quad i = 1,2, \tag{35.4}$$

provided that one of the following conditions is valid

a) $l > k+1$ and

$$\alpha_k \in [0,\tfrac{1}{3}] \cup (1-\frac{1}{\sqrt{3}},1], \qquad \alpha_l \in [0,\frac{1}{\sqrt{3}}) \cup [\tfrac{2}{3},1], \tag{35.5}$$

b) $l = k+1$ and (35.5) is valid on the exception that the conditions

$$\alpha_k \in \{\tfrac{1}{3},1\} \text{ and } \alpha_l \in \{0,\tfrac{2}{3}\} \text{ are not both valid}$$

c) $l = k$ and either $\alpha_k \in (\frac{1}{3},1)$ or $\alpha_l \neq (\alpha_k-\frac{2}{3})/(2\alpha_k-1)$.

Proof. If c) is valid, we see by direct calculation that (35.3) has a unique solution $\{m_k, m_{k+1}\}$. Thus we get a unique spline on the interval $[x_k, x_{k+1}]$. The admissibility follows now from Proposition 34.1. Suppose then that $k < l$. If $\alpha_k \notin \{\frac{1}{3},1\}$ and $\alpha_l \notin \{0,\frac{2}{3}\}$, then we can divide the former equation by $\frac{1}{2}(\alpha_k-1)(3\alpha_k-1)$ and the latter by $\frac{1}{2}\alpha_l(3\alpha_l-2)$. The resulting equations are of the form (34.4) with

$$\lambda_1 = 2\frac{\alpha_k(3\alpha_k-2)}{(\alpha_k-1)(3\alpha_k-1)}, \qquad \varrho_n = 2\frac{(\alpha_l-1)(3\alpha_l-1)}{\alpha_l(3\alpha_l-2)}$$

and $d_1, d_n \in R$. We see easily that $\lambda_1 < 4$ and $\varrho_n < 4$ if

$$\alpha_k \in [0,\tfrac{1}{3}) \cup (1-\frac{1}{\sqrt{3}},1), \qquad \alpha_l \in (0,\frac{1}{\sqrt{3}}) \cup (\tfrac{2}{3},1]. \tag{35.6}$$

Suppose now that $\alpha_k \in \{\frac{1}{3},1\}$ and α_l satisfies (35.6). The equations (35.3) take the form

$$\begin{aligned}2m_{k+1} &= d_1\\ \varrho_n m_l+2m_{l+1} &= d_n.\end{aligned}$$

These are admissible with indices $k+1$ and l. Similarly, if $\alpha_l \in \{0,\frac{2}{3}\}$ and α_k satisfies (35.6), the equations (35.3) are equivalent to the equations

$$\begin{aligned}2m_k+\lambda_1 m_{k+1} &= d_1\\ 2m_l &= d_n,\end{aligned}$$

which are admissible with indices k and l—1. If then $\alpha_k \in \{\frac{1}{3},1\}$ and $\alpha_l \in \{0,\frac{2}{3}\}$, the equations (35.3) are equivalent to the equations

$$2m_{k+1} = d_1, \qquad 2m_l = d_n. \tag{35.7}$$

These are admissible if $l > k+1$. These facts show that the equations (35.3) are admissible if one of the statements a), b), or c) is valid. Finally we see by direct calculation that if the spline s_r is determined by using admissible initial conditions (35.3), then s_r satisfies conditions (35.4). The proposition is proved.

The spline s_r of r in Δ can thus be uniquely determined by requiring that its first derivative has given values at two given points only if some additional conditions are fulfilled. Proposition 35.2 gives some sufficient conditions. We state a simple case separately.

Corollary 35.3. Suppose that $g_i' \in R$, $i = 1,2$ and $1 \leq k < l \leq n$. Then the equations

$$m_k = g_1', \qquad m_l = g_2'. \tag{35.8}$$

are admissible initial conditions for the spline s_r of r in Δ with

$$Ds_r(x_k) = g_1', \qquad Ds_r(x_l) = g_2'.$$

More specifically, if we take $k = 1$, $d = n$, we get the equations (31.10).

We shall now consider the use of second derivatives in initial values.

Proposition 35.4. Let $y_1,y_2 \in [a,b]$ and $g_1'',g_2'' \in R$. If $y_1 \in [x_k,x_{k+1}]$, $y_2 \in [x_l,x_{l+1}]$ and $y_1 < y_2$, then the equations

$$\begin{aligned} (4-6\alpha_k)m_k+(2-6\alpha_k)m_{k+1} &= 6(1-2\alpha_k)\delta r_k - h_k g_1'', \\ (4-6\alpha_l)m_l + (2-6\alpha_l)m_{l+1} &= 6(1-2\alpha_l)\delta r_l - h_l g_2'' \end{aligned} \tag{35.9}$$

are admissible initial conditions for the spline s_r with

$$D^2 s_r(y_i) = g_i'', \qquad i = 1,2 \tag{35.10}$$

when one of the following conditions is valid

a) $l > k+1$ and

$$\alpha_k \in [0,\tfrac{2}{3}], \qquad \alpha_l \in [\tfrac{1}{3},1], \tag{35.11}$$

b) $l = k+1$ and (35.11) is valid with the exception that $(\alpha_k,\alpha_l) \neq (\frac{2}{3},\frac{1}{3})$,
c) $l = k$.

Proof. If $k = l$, we see by direct calculation that (35.9) has a unique solution $\{m_k,m_{k+1}\}$. Thus we get a unique spline on the interval $[x_k,x_{k+1}]$. By Proposition 34.1 the equations are now admissible. So we can suppose that $k < l$. If $\alpha_k \neq \frac{2}{3}$ and $\alpha_l \neq \frac{1}{3}$, we can divide the former equation by $(2-3\alpha_k)$ and the latter by $(1-3\alpha_l)$. The resulting equations are of the form (34.4) with

$$\lambda_1 = \frac{2-6\alpha_k}{2-3\alpha_k}, \qquad \varrho_n = \frac{4-6\alpha_l}{1-3\alpha_l}$$

and $d_1, d_n \in R$. We see easily that $\lambda_1 < 4$ and $\varrho_n < 4$ if

$$\alpha_k \in [0,\tfrac{2}{3}), \qquad \alpha_l \in (\tfrac{1}{3},1]. \tag{35.12}$$

Suppose now that $\alpha_k = \frac{2}{3}$, $\alpha_l \in (\frac{1}{3},1)$. The equations (35.9) are equivalent to the equations

$$\begin{aligned} 2m_{k+1} &= d_1 \\ \varrho_n m_l + 2m_{l+1} &= d_n, \end{aligned}$$

which are admissible with indices $k+1$ and l. If $\alpha_k \in [0,\frac{2}{3})$ and $\alpha_l = \frac{1}{3}$, then the equations (35.9) are equivalent to the equations

$$\begin{aligned} 2m_k + \lambda_1 m_{k+1} &= d_1 \\ 2m_l &= d_n, \end{aligned}$$

which are admissible with indices k and $l-1$. If then $\alpha_k = \frac{2}{3}$ and $\alpha_l = \frac{1}{3}$, the equations (35.9) take the form

$$2m_{k+1} = d_1, \qquad 2m_l = d_n,$$

which gives admissible initial conditions if $l > k+1$. These facts show that the equations (35.9) are admissible if one of the conditions a), b), or c) is valid. Finally we see by direct calculation that if the spline s_r is determined by admissible initial conditions (35.9), then s_r satisfies conditions (35.10). The proposition is proved.

This result is very similar to Proposition 35.2. We shall again state a simple special case separately.

Corollary 35.5. Suppose that $g_i'' \in R$, $i = 1,2$ and $1 \leq k \leq l \leq n-1$. Then the equations

$$\begin{aligned} 2m_k + m_{k+1} &= 3\delta r_k - \tfrac{1}{2}h_k g_1'' \\ m_l + 2m_{l+1} &= 3\delta r_l + \tfrac{1}{2}h_l g_2'' \end{aligned} \tag{35.13}$$

are admissible initial conditions to the spline s_r with

$$D^2 s_r(x_k) = g_1'', \qquad D^2 s_r(x_{l+1}) = g_2''. \tag{35.14}$$

If we take $k = 1$, $l = n-1$ in Corollary 35.5, we get the equations (31.11).

In these results both equations needed in the admissible initial conditions have been formed according to the same principle. This is of course not necessary. We could equally well form the first equation according to one principle and the second equation according to another. One only has to be careful that the two resulting equations form an admissible pair.

36. Error analysis

Let f be a given function and s_f the spline of f in a mesh Δ. Several results concerning the magnitude of the difference $|f(x)-s_f(x)|$ are known (cf. A h l b e r g *et al.* 1967; B ö h m e r 1974; H a l l & M e y e r 1976). The estimates of this difference are usually based on the derivatives of f. Therefore these results are of little use when we only know the values of f at mesh points. If, however, the function f belongs to a mathematical model of a real phenomenon, then it is possible to assess the properties of the spline approximation s_f with the known properties of the situation. These kinds of arguments will be used later on when we consider the use of the spline as a taper curve of a given tree. On the other hand, such a connection usually brings more errors. In fact, the function values at mesh points as well as the initial values are then usually results of measurements or even estimates, and are not exact. In this section we describe how the effect of such errors on the spline can be obtained.

Let $[a,b] \subset R$ be a interval with length h and let $\Delta = \{x_1,\ldots,x_n\}$ be a mesh in $[a,b]$. Let $f\colon [a,b] \to R$ be a given function. Suppose that at the points x_i we use numbers r_i instead of values $f(x_i)$. Denote $e_i = r_i - f(x_i)$, $i = 1(1)n$. Let the initial conditions be given using one of the results of the preceding section and let the numbers g_i or g_i' or g_i'' used be approximations of the exact values $f(y_i)$ or $Df(y_i)$ or $D^2f(y_i)$ respectively with error e_{n+i}, $i = 1,2$. We naturally suppose that the initial conditions are admissible.

The problem is the effect that these errors may have to the spline values. While not trying to establish any general estimates of spline errors, we intend to point out how these can be calculated in any specific case. This procedure is essentially the same as the method of constructing the spline.

We begin by the effect of errors e_j on the derivative vector m. If the matrix equation of derivatives is $Am = d$, we denote by $d(e_j) = (d_1(e_j),\ldots,d_n(e_j))^T$ and by $\mu(e_j) = (\mu_1(e_j),\ldots,\mu_n(e_j))^T$ the errors in d and m caused by e_j, $j = 1(1)n+2$. The errors e_j have no effect on the coefficient matrix A. From the expression of the vector d we get $d(e_j)$. The error $\mu(e_j)$ is the solution of the equation

$$A\mu(e_j) = d(e_j) \tag{36.1}$$

and its components are multiples of e_j, $\mu_i(e_j) = e_{i,j}e_j$, $e_{i,j} \in R$. The total effect of errors e_j, $j = 1(1)n+2$ to m_i is then μ_i. We set

$$\mu_i = \mu_{xi}+\mu_{yi}, \qquad i = 1(1)n,$$

where

$$\mu_{xi} = \sum_{j=1}^{n} e_{i,j}e_j, \qquad i = 1(1)n$$

is the effect of errors in interpolation and

$$\mu_{yi} = e_{i,n+1}e_{n+1}+e_{i,n+2}e_{n+2}, \qquad i = 1(1)n$$

is the effect of initial value errors.

After the derivative error we can turn to the spline. Denote the error of the spline at a point $x \in [x_i,x_{i+1}]$ by $\varepsilon_i(x)$ and set

$$\varepsilon_i = \varepsilon_{xi}+\varepsilon_{yi},$$

where ε_{xi} is caused by the errors in interpolation and ε_{yi} by those in inital values. We define a new variable y by $y = (x—x_i)/h_i$ and a polynomial $p_{i,j}$ by

$$p_{i,j}(y) = (e_{i+1,j}+e_{i,j})y^3—(e_{i+1,j}+2e_{i,j})y^2+e_{i,j}y. \tag{36.2}$$

Then we see from (31.3) that for $i = 1(1)n$

$$\varepsilon_{xi}(y) = h_i \sum_{j=1}^{n} p_{i,j}(y)e_j—(2y^3—3y^2)e_{i+1}+(2y^3—3y^2+1)e_i, \tag{36.3}$$

and

$$\varepsilon_{yi}(y) = h_i(p_{i,n+1}(y)e_{n+1}+p_{i,n+2}(y)e_{n+2}) \tag{36.4}$$

and thus

$$\varepsilon_i(y) = h_i \sum_{j=1}^{n+2} p_{i,j}(y)e_j—(2y^3—3y^2)e_{i+1}+(2y^3—3y^2+1)e_i. \tag{36.5}$$

An upper bound for the error ε_i on $[x_i,x_{i+1}]$ is then obtainable by determining the maximal absolute values $P_{i,j}$ of the coefficients of e_j, $j = 1(1)\ n+2$. This is easy because these coefficients belong to $\Pi_3[0,1]$ as functions of y. Thus we get upper bounds

$$|\varepsilon_i(x)| \leq \sum_{j=1}^{n+2} P_{i,j}e_j, \qquad x \in [x_i,x_{i+1}], \qquad i = 1(1)n—1, \tag{36.6}$$

which are in practice more useful than the exact formulae (36.5).

Suppose then that we do an elongation $x' = ax$ on the axis where the interval $[a,b]$ lies. Let us agree that in the continuation all the dotted quantities belong to the transformed situation. Thus we have a new interval $[a',b']$ with length $h' = ah$ and with a mesh $\Delta' = \{x'_1,\ldots,x'_n\}$, $x'_i = ax_i$. If the original errors are intact, i.e. $e'_j = e_j$, $j = 1(1)n+2$, what is the effect of the transformation on final errors?

Let us again start with the derivative errors. According to (31.5)

$$\varrho'_i = \varrho_i,\ \lambda'_i = \lambda_i \text{ and } d'_i = \frac{1}{a}d_i, \qquad i = 2(1)n—1.$$

Suppose that the initial conditions are given in the form (34.4) so that the initial values have been obtained by approximating the values of D^kf, $k = 0,1$ or 2 at given points. From the results of 35 we see that $\lambda'_1 = \lambda_1$ and $\varrho'_n = \varrho_n$ but

(36.7) $$d'_j = \alpha^{k-1} d_j, \qquad j = 1,n$$

By the linearity of (36.1) we see then that the new derivative errors μ'_{xi}, μ'_{yi} are related to the old ones by the formulae

(36.8) $$\mu'_{xi} = \frac{1}{\alpha}\mu_{xi},\ \mu'_{yi} = \alpha^{k-1}\mu_{yi}, \qquad i = 1(1)n.$$

If the error of the spline is taken at a point $x' = \alpha x$, $x' \in [x'_i, x'_{i+1}]$ and if we denote $y' = (x' - x'_i)/h'_i$, then $y' = y$. From the expressions of μ_{xi}, μ_{yi} and the polynomial $p_{i,j}$ we see that

$$p'_{i,j}(y') = p'_{i,j}(y) = \frac{1}{\alpha} p_{i,j}(y) \qquad i = 1(1)n, j = 1(1)n$$

(36.9)

$$p'_{i,j}(y') = \alpha^{k-1} p_{i,j}(y) \qquad i = 1(1)n, j = n+1, n+2.$$

Thus

(36.10) $$\varepsilon'_{xi}(y') = \varepsilon'_{xi}(y) = \varepsilon_{xi}(y)$$

but

(36.11) $$\varepsilon'_{yi}(y') = \varepsilon'_{yi}(y) = \alpha^k \varepsilon_{yi}(y).$$

Consequently, we see that errors due to interpolation errors are invariant in the elongation of $[a,b]$. The errors due to the starting information errors are invariant only if the initial values are formed by using approximations of function values as in Proposition 35.1. If the initial values are formed with first or second derivatives as in Propositions 35.2 or 35.4, the errors become multiplied by the first or second power of the elongation ratio.

37. Another construction

In the preceding sections we have used a construction of interpolating cubic spline which is based on the first derivatives at mesh points. In the last section of this chapter we want to mention another popular construction method. This method uses second derivatives at mesh points and is based on the following analogue of Proposition 31.2.

Proposition 37.1. A polynomial $q_i \in \Pi_3[a,b]$, $i \in \{1,\ldots,n\}$ has under conditions

(37.1) $$q_i(x_j) = r_j, \qquad D^2 q_i(x_j) = M_j, \qquad j = i, i+1$$

a unique representation

(37.2) $$q_i(x) = \frac{M_{i+1} - M_i}{6h_i}(x - x_i)^3 + \frac{M_i}{2}(x - x_i)^2 + \left(\delta r_i - h_i \frac{M_{i+1} + 2M_i}{6}\right)(x - x_i) + r_i.$$

Moreover, $Dq_i(x_{i+1}) = Dq_{i+1}(x_{i+1})$ if and only if

$$\lambda_{i+1}M_i+2M_{i+1}+\varrho_{i+1}M_{i+2} = D_{i+1}, \tag{37.3}$$

where λ_{i+1} and ϱ_{i+1} are as in (31.5) and

$$D_{i+1} = \frac{6}{h_i+h_{i+1}}(\delta r_{i+1}-\delta r_i).$$

The proposition can be verified by direct calculation (B ö h m e r 1974, p. 22).

Now we can proceed as after Proposition 31.2. Instead of (31.6) we now get a system

$$\begin{aligned} &\lambda_2 M_1 \quad +2M_2 \quad +\varrho_2 M_3 \quad = D_2 \\ &\quad\vdots \\ &\lambda_{n-1}M_{n-2}+2M_{n-1}+\varrho_{n-1}M_n \quad = D_{n-1}. \end{aligned} \tag{37.4}$$

If the numbers $M_1,\ldots,M_n$ are solved from (37.4) and substituted into (37.2) we get a spline s_f in the sense of definition 31.1 by setting

$$s_f|[x_i,x_{i+1}] = q_i$$

just as in section 31. In order to achieve uniqueness we need two auxiliary conditions which can be set in the same way as before. Thus the following counterpart of Proposition 34.2 is valid.

Proposition 37.2. Let $\Delta = \{x_1,\ldots,x_n\}$ be a mesh on the interval $[a,b]$ and let $r = (r_1,\ldots,r_n) \in R^n$. Suppose that $k,l \in N$, $1 \leq k < l < n$ and $\lambda_1,\varrho_n,d_1,d_n \in R$. If $\lambda_1 < 4$ and $\varrho_n < 4$, then there exists a unique interpolating cubic spline s_r of r in Δ satisfying conditions

$$\begin{aligned} 2M_k \; &+ \lambda_1 M_{k+1} = d_1 \\ \varrho_n M_l \; &+ 2M_{l+1} \; = d_n. \end{aligned} \tag{37.5}$$

The result is also valid when $k = l$, if $\lambda_1\varrho_n \neq 4$. On an interval $[x_i,x_{i+1}]$ s_r has the representation (37.2), where $(M_1,\ldots,M_n)$ is the solution of systems (37.4) and (37.5).

The proof is quite similar to the proof given for Propositions 31.3 and 34.2 and will be omitted (cf. A h l b e r g *et al.* 1967, p. 61).

Similarly, all the results which have been introduced for the spline using first derivatives have analogues for splines constructed by using second derivatives. This is also true for the choice of initial values needed in (37.5).

Because we do not use this way of construction we shall omit the details (cf. A h l b e r g *et al.* 1967; B ö h m e r 1974).

4. POLYNOMIAL SPLINES

Cubic spline is a special case of *polynomial spline*. In this chapter we shall present some aspects of the use of polynomial splines as a taper curve. Our conclusion is that it is sufficient to consider only *parabolic splines* in addition to cubic splines. For this purpose, we shall briefly describe the construction of a parabolic spline.

41. The significance of degree

The cubic spline consists of cubic polynomials which are joined together so that the resulting function is twice continuously differentiable. This principle can also be used to form more general functions, so called polynomial splines, from polynomials of arbitrary degree.

A polynomial spline of degree n consists of polynomials of degree at most n which are joined together so that the resulting function is $(n-1)$-times continuously differentiable. Thus the cubic spline is a polynomial spline of degree three. A presentation of polynomial splines is to be found e.g. in A h l b e r g *et al.* (1967). Here we are only interested to know which polynomial splines can be expected to give a reasonable taper curve.

Polynomial splines of even degree are in general more difficult to use than the ones of odd degree. It may even happen that a polynomial spline of even degree interpolating in a given mesh does not exist. On the other hand, the difficulty of constructing polynomial splines increases very rapidly as the degree increases. The simplest non-trivial polynomial spline of odd degree is the cubic spline. It is also the polynomial spline most commonly examined and used. It is easy to construct and it has many favourable properties as we have seen. Polynomial splines of higher odd degree are much more difficult to construct and their properties do not seem to be directly connected with the taper curve (cf. A h l b e r g *et al.* 1967, ch. V).

Polynomial splines of even degree are much less used than the ones of odd degree. The polynomial spline of degree two, the so-called parabolic spline, seems to be the only one worth considering in this connection. It can be constructed even more simply than the cubic spline and its unique existence can be shown. On the other hand, it appears that its properties are not connected with our situation as closely as the properties of the cubic spline. There is also another possible disadvantage.

We have fixed meshes with which it is preferable that the polynomials used in the spline should be able to imitate the behaviour of the real taper curve on the whole subinterval. As the form of the stem changes rapidly near the ground, the parabolas may not give a sufficiently good approximation.

We conclude that the cubic spline is our main instrument in constructing the taper curve but the parabolic spline is also worth some attention. For this reason, a short introduction to the construction of a parabolic spline will be given in the next section.

42. Parabolic spline

The interpolating parabolic spline can be formed according to two different systems. In the first case the procedure is analogous to that of cubic splines in the sense that the function is composed from parabolas which are joined together at interpolating points. In the second case the joining takes place at points which are situated between interpolating points. These different ways of construction give rise to different properties in the resulting spline. We consider here only the first case. The notation will be the same as in the chapter three.

Definition 42.1. A function $s_r\colon [a,b]\to R$ is called the parabolic spline of a given vector $r \in R^n$ in a mesh $\Delta = \{x_1,\ldots,x_n\} \subset [a,b]$ if

1) $s_r/[x_i,x_{i+1}] \in \Pi_2[x_i,x_{i+1}], \qquad i = 1(1)n-1,$

2) $s_r \in C^1[a,b],$

3) $s_r(x_i) = r_i, \qquad i = 1(1)n.$

If r is formed from a function f by setting $r_i = f(x_i)$, $i = 1(1)n$, then s_r is denoted by s_f and called the parabolic spline of f in Δ.

The function s_r is in fact *the interpolating parabolic spline* of r in Δ. It is a continuously differentiable function which takes prescribed values r_i at knots x_i and is a parabola between knots. We can get an expression of the spline by determining these parabolas and joining them together so that they have the same values up to the first derivatives at common knots.

Proposition 42.2. Let $\Delta = \{x_1,\ldots,x_n\}$ and $r \in R^n$ be given. A polynomial $q_i \in \Pi_2[a,b]$, $i \in \{1,\ldots,n-1\}$ has under conditions

$$q_i(x_j) = r_j, \qquad j = i,i+1, \qquad Dq_i(x_i) = m_i \tag{42.1}$$

a unique representation

$$q_i(x) = \frac{\delta r_i - m_i}{h_i}(x-x_i)^2 + m_i(x-x_i) + r_i. \tag{42.2}$$

Moreover $Dq_i(x_{i+1}) = Dq_{i+1}(x_{i+1})$ if and only if

$$m_i + m_{i+1} = 2\delta r_i. \tag{42.3}$$

This proposition can be verified by direct calculation, which will be omitted. The representation of the parabolic spline can now be formed by demanding that (42.3) is valid at knots x_i, $i = 2(1)n—1$. We get a system of equations

$$m_i + m_{i+1} = 2\delta r_i, \qquad i = 1(1)n—1. \tag{42.4}$$

If the vector $m = (m_1,\ldots,m_n)$ is solved from (42.4) and substituted into (42.2) we get a parabolic spline s_r in the sense of Definition 42.1 by setting

$$s_r/[x_i,x_{i+1}] = q_i, \qquad i = 1(1)n—1.$$

Since the system (42.4) has n unknowns and $n—1$ equations its solution cannot be unique without *one* additional condition called initial condition. (*Two* initial conditions are needed for the construction of cubic spline.) We say that an initial condition is *admissible* if it together with (42.4) determines a parabolic spline uniquely. Admissible initial conditions can be formed according to the principles used for cubic splines in 35. Only one possibility is considered here.

Proposition 42.3. Let $\Delta = \{x_1,\ldots,x_n\}$ be a given mesh on $[a,b]$, let $r \in R^n$, $y \in [a,b] \setminus \Delta$ and let $g \in R$. If $y \in (x_k,x_{k+1})$ and $\alpha = (y—x_k)/h_k$, we denote

$$\mu_k = \frac{1}{\alpha(1—\alpha)} \left(\frac{g—r_k}{h_k} — \alpha^2\delta r_k\right). \tag{42.5}$$

Then

$$m_k = \mu_k \tag{42.6}$$

is an admissible initial condition for the parabolic spline s_r with

$$s_r(y) = g. \tag{42.7}$$

Proof: The derivatives $m_1,\ldots,m_n$ satisfy the equations (42.4) and (42.6). By direct calculation we see that the system has a unique solution which is given by the algorithm

$$\begin{aligned} &m_k = \mu_k \\ &m_{k-i} = 2\delta r_{k-i} — m_{k-i+1}, \qquad i = 1(1)\ k—1, \\ &m_{k+i} = 2\delta r_{k+i-1} — m_{k+i-1}, \qquad i = 1(1)\ n—k. \end{aligned} \tag{42.8}$$

These values determine a parabolic spline uniquely. By direct calculation we see that also (42.7) is valid. The proposition is proved.

A parabolic spline can now be constructed as follows. When Δ,r,y and g are given as in Proposition 42.3, the initial value μ_k can be evaluated by using (42.5). Then the derivatives $m_1,\ldots,m_n$ are solved by (42.8). The result is substituted into (42.2), which gives the representation of the parabolic spline.

Our study of parabolic splines is at the moment of preparatory nature. Therefore, instead of analysing the properties of these splines theoretically, we only make some practical experiments to study their suitability for the taper curve. It is, however, instructive to pay some attention to the behaviour of errors. Because of the construction used, the parabolic spline differs in this respect from the cubic spline. It is sufficient to consider the effect of initial value error. Other errors have essentially the same behaviour but their treatment is not quite so simple.

Let us suppose that we have the situation of Proposition 42.3. At a point $y \in [x_k, x_{k+1}]$ there is given an intial value g with error Δg. If we denote $\alpha = (y - x_k)/h_k$, we see by (42.5) and (42.6) that the quantity μ_k has now an error

$$\Delta\mu_k = (\alpha(1-\alpha)h_k)^{-1}\Delta g. \tag{42.9}$$

By (42.8) the derivatives m_i have then errors

$$\Delta m_i = (-1)^{|i-k|}\Delta\mu_k, \qquad i = 1(1)n. \tag{42.10}$$

If $x \in [x_i, x_{i+1}]$ and we denote $x^* = (x - x_i)/h_i$, we get from (42.2) that the error of parabolic spline at the point x is

$$\Delta s(x) = (-1)^{|i-k|}\frac{h_i x^*(1-x^*)}{h_k\alpha(1-\alpha)}\Delta g. \tag{42.11}$$

This shows that the magnitude of the error varies periodically on the whole interval $[a,b]$ so that on each subinterval $[x_i, x_{i+1}]$ it has the same behaviour multiplied by the length h_i. The dependence on the situation of the initial point is similarly periodic on the whole interval. Thus the behaviour of error is essentially the same on the whole interval and does not depend on the subinterval on which the initial point is chosen. From sections 32 and 55 we see that the error of the cubic spline behaves quite differently.

The best choise of the initial point is the midpoint of any subinterval. The maximum error is always on the midpoints of subintervals and thus

$$|\Delta s(x)| \leq \frac{h_i}{h_k}|\Delta g|, \qquad x \in [x_i, x_{i+1}], \qquad i = 1(1)n-1. \tag{42.12}$$

Finally we remark that (42.11) shows the error to be invariant in an elongation on the x-axis where the interval $[a,b]$ lies.

5. CUBIC SPLINE AS TAPER CURVE

As was said earlier, our main object is to examine the suitability of interpolating cubic or parabolic spline for the taper curve of an individual tree. In this chapter we shall consider the things we must pay attention to in using the cubic spline. The use of the parabolic spline is quite analogous and its details are therefore omitted.

After the introduction, sections two and three will discuss what we have to take into account in the construction of a taper curve by using cubic spline.

In section four we shall decide on what principles the properties of the taper curve are estimated. Section five deals with the contribution of error analysis.

Finally, in section six we shall give short descriptions of the FORTRAN-programs we have formed for the construction and use of cubic splines.

51. Introduction

Theoretically it is evident that the cubic spline can be used as a taper curve. In fact, it is reasonable to suppose that the actual taper curve of a tree is twice continuously differentiable. If initial values are now chosen as in section 35, Proposition 33.1 implies that the cubic spline approximates the actual taper curve at any prescribed accuracy as long as there is a sufficient number of interpolating points. In practice, however, the situation is somewhat different. There are only some diameters measured at certain heights at disposal and the taper curve has to be formed using only this information. No possibility of making the mesh thicker in accordance with Proposition 33.1 exists. Thus it is an open question whether the cubic spline forms a sufficiently good approximation in a given fixed mesh. It also remains to select sufficiently good way of constructing the cubic spline for that purpose.

We choose the representation of the cubic spline which uses first derivatives. All necessary information has been presented in chapter 3. We only have to adapt it to the present situation. In the same connection, we write FORTRAN-programs which are capable of performing all the necessary actions needed in the construction and use of cubic splines. The essential parts are written in the form of independent subroutines so that diversified operations are possible.

We shall use the expression taper spline to mean a taper curve formed by a spline function. If necessary, we shall specify the nature of the spline function by speaking about a cubic taper spline, parabolic taper spline etc.

52. The determination of initial values

The most difficult problem in the construction of a spline is here, and in general, the determination of initial values in a satisfactory way. We start the exposition by pointing out the possible alternatives. As a basic form of initial conditions we take the equations presented in (34.4) divided by two. The problem is then how to choose the initial values ZA_i, $i = 1(1)4$ and initial indices k,l in the equations

$$\begin{aligned} m_k + ZA_1 m_{k+1} &= ZA_2 \\ ZA_3 m_l + \quad m_{l+1} &= ZA_4. \end{aligned} \tag{52.1}$$

Section 35 presents three different possibilities of choosing initial values ZA_i. We consider each of them in turn and start with the use of additional function values. This seems to be the most natural way in this connection.

According to Proposition 35.1 extra diameters g_1 and g_2 can be given at two different heights y_1 and y_2 provided that they are not interpolating points. If k and l are initial indices and we denote as usually $\alpha_k = (y_1 - x_k)/h_k$, $\alpha_l = (y_2 - x_l)/h_l$, we get from (35.1) the expressions of initial values

$$\begin{aligned} ZA_1 &= -\frac{\alpha_k}{1-\alpha_k}, \\ ZA_2 &= \frac{1}{\alpha_k(1-\alpha_k)^2}\frac{g_1 - r_k}{h_k} + \frac{\alpha_k(2\alpha_k - 3)}{(1-\alpha_k)^2}\delta r_k, \\ ZA_3 &= -\frac{1-\alpha_l}{\alpha_l}, \\ ZA_4 &= -\frac{1}{\alpha_l^2(1-\alpha_l)}\frac{g_2 - r_l}{h_l} - \frac{2\alpha_l - 3}{1-\alpha_l}\delta r_l. \end{aligned} \tag{52.2}$$

There are two possibilities in the choice of initial diameters g_1 and g_2. Either we can use two suitable measurements in the initial values instead of using them in interpolation, or we can from the measurements somehow generate two approximations which we use as initial diameters. The properties of the cubic spline seem to indicate that in general it is better to use all the measurements in the interpolation if even a moderate way of generating approximations of initial diameters is available. The most natural way is to use interpolating polynomials for the values g_1 and g_2. Practical experiments will show whether it gives sufficiently accurate results.

Two contrary factors affect the choice of initial indices. The approximation of initial diameters mentioned above is most accurate in the middle of the stem. Near the ground the approximation is most inaccurate because of the rapid tapering of the stem. In fact, we know of no adequate exposition of this tapering. On the other hand, the minimum curvature property together with the error analysis of section 55

makes the choice of initial values at the ends of the stem preferable. We intend to solve this problem by experimental evidence.

The third choice, even if of lesser importance, concerns the placing of initial points y_1 and y_2 on the intervals $[x_k,x_{k+1}]$ and $[x_l,x_{l+1}]$. The quantities α_k and α_l express this situation. The diameter error in y_1 has a coefficient $\alpha_k^{-1}(1-\alpha_k)^{-2}$. This has minimum value when $\alpha_k = \frac{1}{3}$. Similarly, the coefficient of diameter error in y_2 has minimum value when $\alpha_l = \frac{2}{3}$. In practice it is more important to know the points at which the approximate diameters g_1 and g_2 are most accurate. In the absence of such information y_1 and y_2 can be chosen somewhere near the midpoints of intervals.

It is also possible to use first derivatives in the construction of initial values. This is stated in Proposition 35.2. In this case we have essentially the same problems as in the use of extra diameters. The greatest difference is that the first derivatives are never available as direct information in the case of a taper curve. We always have to use approximative derivatives generated from known diameters. The approximation is most easily done by an interpolating polynomial. It is to be expected that the error may be larger than when approximating diameters. We do not, however, know the exact values of derivatives and therefore the suitability of this method must be assessed by the properties of the taper curve it produces for the sample trees.

The remarks on the choice of initial indices k and l made in connection with initial diameters are still valid. On the other hand, the placement of initial points on the intervals $[x_k,x_{k+1}]$, $[x_l,x_{l+1}]$ is now different. Initial points may now coincide with interpolating points but they cannot be arbitrary points inside the interval. It must be remembered, however, that the conditions of proposition 35.2 which essentially say that $\alpha_k \notin [0{,}33,\ 0{,}43]$, $\alpha_l \notin [0{,}57,\ 0{,}67]$ are not always necessary. For example, let $\{1, 5, 10, 20, 40, 60, 80, 100\}$ be a mesh on the interval $[0{,}100]$. The points 2,5 and 90 give now admissible initial conditions even if $\alpha_k = 0{,}375$. Nevertheless, the existence of possible limitations makes the use of first derivatives slightly more complicated than the use of diameters.

As for the third possibility, the use of second derivatives by Proposition 35.4, we can repeat what was said on the use of first derivatives. Now the excluded values of α_k and α_l lie on the intervals $[0{,}67,\ 1]$ and $[0,\ 0{,}34]$. There is, however, one additional feature. The original form of the minimum curvature property as presented in Proposition 33.2 states that the natural spline is in this sense distinguished from other splines. It has fixed initial values, the second derivative vanishes at end points, and there is thus no problem in forming the initial values. Therefore the natural spline deserves attention in practical experiments. In fact, after starting our research we found that some experiments of this kind have already been made (cf. S l o b o d a 1976).

Finally we remark that initial information can, of course, be estimated in several ways, and the use of a simple interpolating parabola, especially on the butt, may not always be the best choice.

53. The construction of the taper spline

When we have got admissible initial conditions by some method or other the construction of the corresponding cubic taper spline is relatively simple. It begins by the determination of the first derivatives at mesh points. This is done as presented at the end of section 34 by using Thomas's algorithm together with formulae (34.6) and (34.7) if necessary. After this the representation of the cubic spline between two adjacent interpolating points can be formed by using (31.3).

One problem still remains. What is the effect of the placement of interpolating points on the accuracy of the resulting taper curve? In other words, suppose that we can afford n measurements for constructing a cubic taper spline. At what heights should the measurements be made in order to get as good a taper curve as possible with an interpolating cubic spline of n points?

We have not succeeded in finding any adequate solution to this problem. Consequently, we present only some general comments on the subject. It is usually favourable to have meshes with equal subintervals. However, the stem tapers so fast near the ground that a cubic polynomial cannot match it very long. Therefore it seems that we should use rather short distances between interpolating points near the ground in order to have a reasonable approximation. Since we have a fixed number of interpolating points, we have to use greater distances between interpolating points situated higher up.

54. The criteria of suitability

When we have found the possible ways of constructing cubic splines, we can start the investigation of the suitability of splines for taper curve. This presupposes the existence of a sufficient number of accurate measurements based on a representative sample of trees.

The sample tree material we use has already been presented in chapter 2. Now we must decide how to measure the suitability of different splines for taper curve. The ideal method would be the comparison of diameters given by taper spline to the true ones at every height of sample trees. This is, however, impossible in practice. Even in our excessive material the diameter of each tree has been measured only at 14 different heights. In addition, comparison is sensible only at those points which have not been used in the construction of the spline in question. This is too minute a corpus for drawing any reliable conclusions. Therefore we must base the conclusions also on other properties of trees which the taper curve must reproduce correctly.

The most important thing is that we get the right volume. So our first requirement is that the taper spline should give the total volume and suitable chosen partial volumes of a stem with sufficient accuracy. In determining volumes we suppose that the cross-sections of stems are always circles. Volumes can then be evaluated

as volumes of solids of revolution using the well-known formulae. We do not know the exact volumes of sample trees. Therefore we must compare the results given by spline to the results given by some other reliable method.

Our comparison volumes are formed by a method where the volumes are evaluated piecewise using the solids of revolution of interpolating parabolas. The integration is performed near the ground exactly and in the upper parts by using Simpson's formula. The following table shows the essentials of this method (cf. also Laasasenaho 1976). The numbers show the percentage of tree height.

Interval	Interpolating points			Way of integration
stump— 2,5	1	2,5	5	exact
2,5— 5	2,5	5	7,5	»
5 — 10	5	7,5	10	Simpson's rule
10 — 20	10	15	20	» »
20 — 40	20	30	40	» »
40 — 60	40	50	60	» »
60 — 80	60	70	80	» »
80 —100	80	90	100	» »

It is clear that this method is not exact. Especially the interpolating parabolas are not able to match the real taper curve near the ground. The resulting values are therefore perhaps slightly too high near the ground. Another source of error is the approximative integration used from 5 per cent upwards. It is known that for any function $f \in C^4(a,b)$

$$\int_a^b f(x)dx = S(f;a,b) - \frac{1}{2\,880}(b-a)^5 f^{(4)}(\xi),$$

where $S(f;\ a,b)$ is the approximative value of the left side given by Simpson's rule and $\xi \in [a,b]$ (cf. Davis & Rabinowitz 1975, p. 45). In practice ξ is unknown. Because the integrands are squares of parabolas in our case, Simpson's rule is not exact. In addition, the possible errors in measurements of sample trees have variable effects on the results because all weights are not equal in Simpson's rule. We may, however, say that even if this model of comparison does not give exact volumes, the errors are relatively small apart from some extreme cases.

Another essential demand is that a good taper curve should imitate the form of the stem with sufficient accuracy. This is necessary, for example, in dividing the stem into different classes of lumber. In practice the investigation of this is based on two things. Firstly, the taper curve should be decreasing in the trees where the measured diameters form a monotonically decreasing sequence. Secondly, partial volumes should be approximately right. This guarantees that the tapering is not too fast and that trees with increase in the sequence of measured diameters have a reasonable taper curve, too. It is also necessary to investigate that the taper curve given by the spline is decreasing, because many approximations good in other re-

spects do not have this property. As an example we can present the following result called Tonelli's Theorem (cf. Luenberger 1969, p. 123).

Let $f \in C(a,b)$. Suppose we seek the polynomial $p \in \Pi_n(a,b)$ that best approximates f in the sense of minimizing $\max_{a \leq t \leq b} |f(t)-p(t)|$. If p_0 is such a polynomial, then $|f(t)-p_0(t)|$ achieves its maximum at at least $n+2$ points in $[a,b]$.

Since our splines are composed of polynomials they may have similar oscillation properties as Tonelli's Theorem states.

Now we can state the criteria we use in judging the suitability of splines for taper curve. A good taper curve must give with sufficient accuracy

1) total volume,
2) partial volumes at per cent intervals [stump, 5], [5, 10], [10, 20], [20, 40], [40, 60], [60, 80], [80, 100],
3) diameters at measured points not used in the construction of the splines.

In addition a good taper curve must decrease if the interpolating diameters form a decreasing sequence.

In the first two statements accuracy means being in accordance with the comparison model. In the fourth statement we may allow some misbehaviour because this may also happen in reality (cf. chapter 2).

55. Consequences of error analysis

In section 36 we developed a formula giving the maximum error of a cubic spline on an interval $[x_i,x_{i+1}]$. It was

$$\varepsilon_i = \sum_{j=1}^{n+2} P_{i,j} e_j.$$

In the case of a taper spline the quantity e_j is the error of diameter at point x_j, $j = 1(1)n$ and e_{n+1}, e_{n+2} are errors in initial information, e.g. in diameters, at initial points. A coefficient $P_{i,j}$ indicates the maximum effect of error source e_j on the interval $[x_i,x_{i+1}]$. It can be evaluated as stated in the section 36.

In this section, we shall consider these maximum errors in some cases where the cubic spline is used as a taper curve. Our intention is to discuss the stability properties of the cubic spline, the placement of initial points and the significance of the nature of initial information. We suppose for all cases that the diameters are measured at eight per cent heights 1, 5, 10, 20, 40, 60, 80 and 100. The corresponding cubic spline is constructed by using either diameters or first derivatives or second derivatives at two initial points.

In the first case we evaluate the coefficients $P_{i,j}$ by using initial diameters. When the diameters are taken at the heights of 2,5 and 90 per cent we get the following set-up where e.g. ,1598E—4 means the number $0{,}1598 \cdot 10^{-4}$ etc.

Set-up 51.

Situation of error source	Maximum effect on the error of taper curve on subintervals						
	1—5	5—10	10—20	20—40	40—60	60—80	80—100
2,5	,1001E+1	,3878E+0	,2737E+0	,1830E+0	,4885E—1	,1244E—1	,1458E—2
90	,1598E—4	,1523E—3	,1700E—2	,1918E—1	,7664E—1	,2874E+0	,1073E+1
1	,1000E+1	,9467E—1	,6683E—1	,4467E—1	,1193E—1	,3036E—2	,3560E—3
5	,1000E+1	,1106E+1	,5341E+0	,3570E+0	,9531E—1	,2426E—1	,2845E—2
10	,3881E—1	,1000E+1	,1135E+1	,5307E+0	,1417E+0	,3607E—1	,4230E—2
20	,3489E—2	,3323E—1	,1000E+1	,1119E+1	,2009E+0	,5115E—1	,5999E—2
40	,3956E—3	,3768E—2	,4207E—1	,1000E+1	,1001E+1	,1327E+0	,1556E—1
60	,1079E—3	,1028E—2	,1147E—1	,1295E+0	,1000E+1	,1000E+1	,5673E—1
80	,3796E—4	,3616E—3	,4037E—2	,4556E—1	,1820E+0	,1070E+1	,1000E+1
100	,1998E—5	,1903E—4	,2125E—3	,2398E—2	,9580E—2	,3593E—1	,1000E+1

The set-up shows e.g. that an error of one diameter unit at the initial point 90 per cent causes an error of at most 0,01918 units on interval [20, 40].

If the initial diameters are at the heights of 30 and 50 per cent, then the corresponding set-up is

Set-up 52.

Situation of error source	Maximum effect on the error of taper curve on subintervals						
	1—5	5—10	10—20	20—40	40—60	60—80	80—100
30	,6278E+1	,2432E+1	,1712E+1	,1094E+1	,1283E+0	,1094E+1	,4297E+1
50	,1532E+1	,5921E+0	,4005E+0	,1283E+0	,1094E+1	,4297E+1	,1610E+2
1	,1000E+1	0	0	0	0	0	0
5	,2019E+1	,1000E+1	0	0	0	0	0
10	,2904E+1	,1533E+1	,1000E+1	0	0	0	0
20	,4901E+1	,1924E+1	,1734E+1	,1000E+1	,1604E—1	,1368E+0	,5372E+0
40	,4424E+1	,1710E+1	,1165E+1	,1000E+1	,1000E+1	,3135E+1	,1222E+2
60	,1915E+0	,7401E—1	,5007E—1	,1604E—1	,1000E+1	,2919E+1	,9222E+1
80	0	0	0	0	0	,1000E+1	,2393E+1
100	0	0	0	0	0	0	,1000E+1

The stability properties of the cubic spline can clearly be seen in these set-ups. Let us denote the whole interval by $[0,h]$ and the initial points by y_1 and y_2. The most important property is that the cubic spline is stable on the interval $[y_1,y_2]$. This means that the effect of any error decreases as the distance from the error source increases. On the other hand, the cubic spline is unstable outside the interval $[y_1,y_2]$. The effect of each error e_j increases on the interval $[0,y_1]$ when we approach the point 0 and on the interval $[y_2,h]$ when we approach the point h. In these stability concepts we also include that the cubic spline has the minimum curvature property, but only on the interval between initial points (cf. Proposition 33.2 and the remark after it). According to these facts the initial points should be at end points 0 and h or at least near them.

From Set-up 52 we see in addition that if $y_1 \in [x_k, x_{k+1}]$, $k > 1$, and $y_2 \in [x_l, x_{l+1}]$, $l < n-1$, then the interpolating diameter error e_i takes effect only to the left from the point x_i when $i = 1(1)k-1$ and to the right from the point x_i when $i = k+1(1)n$. This phenomenon is sometimes useful. It may e.g. happen that the measurement at an extreme point x_1 or x_n is unreliable or tends to have a negative influence on the spline. Then the situation may be improved by choosing the initial points so that this inconvenient point does not affect the major part of the spline. It must be noticed, however, that the instability of the spline outside the interval $[y_1, y_2]$ may cause unpredictable behaviour in the neighbourhood of the inconvenient point. Therefore this expedient must be used with care.

Using these set-ups we can estimate the accuracy of the cubic taper spline of eight points. The sample trees have been measured with the accuracy of 1 mm. If we suppose that this is the maximum error of diameters at the interpolating or initial points, then we get the following upper bounds of taper function errors in millimetres.

Set-up 53.

Initial points		Upper bound of the taper function error on subintervals (mm)						
y_1	y_2	1—5	5—10	10—20	20—40	40—60	60—80	80—100
2,5	90	3,05	2,63	3,07	3,44	2,77	2,66	3,17
30	50	23,25	9,27	6,07	3,24	3,24	12,59	45,77

The stability of the first spline and the unstability of the second can clearly be seen. It must be remembered, however, that the actual errors may be much smaller than the aforementioned upper bounds.

Let us then consider the alternative where the initial values are formed by using first derivatives. The stability properties remain unchanged. Similarly, the effect of errors in interpolating diameters remains essentially the same. Thus it is sufficient to concentrate on the effect of errors in initial derivatives. We give the coefficients $P_{i,j}$ in two cases. The initial heights are 2,5 and 90 per cent in the first and 1 and 100 per cent in the second case. As stated in 36 these coefficients depend linearly on the height of the tree. In the following set-up this height is 13,8 m which is the average height of our sample trees.

Set-up 54.

Situation of error source	Maximum effect on the error of taper curve on subintervals						
	1—5	5—10	10—20	20—40	40—60	60—80	80—100
2,5	,4594E+3	,1780E+3	,1257E+3	,8403E+2	,2259E+2	,6363E+1	,3013E+1
90	,1059E+0	,1993E—1	,3845E+0	,4571E+1	,1831E+2	,6870E+2	,2564E+3
1	,9555E+1	,3703E+1	,2614E+1	,1747E+1	,4677E+0	,1236E+0	,2719E—1
100	,1087E—2	,6854E—2	,7449E—1	,8392E+0	,3352E+1	,1257E+2	,4693E+2

This table reveals that when the initial points coincide with interpolating points, the maximum effect of initial errors is much smaller than in other cases. Comparisons around other interpolating points give the same result.

It is, however, to be remembered that the total maximum error is the product of the maximum effect and initial error. Thus, if the approximation of first derivatives is fairly accurate at some specific point, it can give the least total error whether the approximation is taken at an interpolating point or not.

A drawback of the use of first derivatives is that it makes it difficult to estimate the accuracy of initial values. In fact, this estimation is only possible if we know the true derivatives. Even when the measurements give some idea of the diameter at an arbitrary point, they do not give sufficient hints on the values of first derivatives at any point. Thus we cannot produce any analogue to Set-up 53 to show the maximum taper function error in a »usual» situation.

A third possibility is to construct the initial values using second derivatives. The remarks made for the use of first derivatives apply here too, except for the placement of initial points. Now there is no essential difference in the effect of initial derivative error when the initial point is an interpolating point or near it. We present an example of the effect of initial value errors even though we have no direct use for it. Now the coefficients depend on the square of the tree height. We use again the average height, 13,8 m, of our sample trees.

Set-up 55.

Situation of error source	Maximum effect on the error of taper curve on subintervals						
	1—5	5—10	10—20	20—40	40—60	60—80	80—100
2,5	,2889E+3	,1120E+3	,7905E+2	,5283E+2	,1410E+2	,3592E+1	,4211E+0
90	,2116E+0	,1481E+1	,1621E+2	,1827E+3	,7298E+3	,2737E+4	,1022E+5

It would be convenient to conclude with a remark on the comparison of these three different ways of choosing initial information in the light of error analysis. However, as we have noticed, we cannot present any analytical results because we do not have the true values of first and second derivatives. We experimented with individual trees supposing that the cubic spline, if we use all measurements in interpolation, represents the true taper curve. In this way we got some reasonable 'real' values of the derivatives. Nevertheless, these experiments gave no clear indication of one method being better or worse than others. The possible preference of one method must therefore be based on the analysis of taper curves of all sample trees.

56. Programs

For the numerical treatment of the sample tree material, computers were used. We constructed FORTRAN-programs suitable for this purpose, and we also formed programs for the most common uses of the cubic taper splines. The essential parts

have been written as independent subroutines, and a short account of these will be given here. We suppose throughout that the stem begins at the point 0 and ends at the last interpolating point x_n. If the first interpolating point exceeds 0, then the taper curve on the interval $[0,x_1]$ is formed by extrapolating the polynomial of the interval $[x_1,x_2]$. We use diameters as the values on interpolating points.

We start with the programs needed in the construction of the taper curve and especially with the evaluation of initial values. This evaluation can be performed in three ways.

Subroutine INITIA

Given initial points and respective diameters, the subroutine forms initial values ZA_i, $i = 1(1)4$ and initial indices satisfying equation (52.1). The evaluation is performed by formulae (52.2).

Subroutine INIDE 1

The subroutine constructs interpolating parabolas through given points and evaluates their first derivatives at initial points. After this the subroutine calculates the initial values and indices using formulae (35.3).

Subroutine INIDE 2

The subroutine constructs interpolating parabolas through given points and evaluates their second derivatives at initial points. After this the subroutine calculates the initial values and indices using formulae (35.9).

When we use one of these subroutines we get the coefficients of the cubic spline at two stages.

Subroutine DERFIR

Given initial values ZA_i, $i = 1(1)4$ and initial indices k and l satisfying (52.1), the subroutine evaluates the first derivatives of the cubic spline at mesh points. The calculation is based on Thomas's algorithm and formulae (34.6) and (34.7) (cf. section 34).

Subroutine SPLINE

Given first derivatives at mesh points, the subroutine forms the coefficients of the polynomials of the cubic spline by using formula (31.3).

The initial diameters needed in the subroutine INITIA can be approximated by interpolating polynomials with the following subroutine.

Subroutine AITKEN

Given interpolating points and values at those points, the subroutine calculates the value of the Lagrangian interpolating polynomial through those points at a given point. The calculation is based on Aitken's algorithm (cf. Henrici 1964, p. 206).

The second group contains the subroutines constructed for the use of the cubic taper spline. Some of them have also been used in the investigation of the suitability of different cubic splines for taper curve. All subroutines of this group presuppose that the taper curve of the tree is given by a cubic spline $s = s(x)$ whose representation is known.

Subroutine DIAMET

The subroutine evaluates the diameter of the stem at a given height. It determines at first which polynomial of the spline has to be used and evaluates then the diameter with Horner's rule (cf. Henrici 1964, p. 51).

Subroutine THICKN

The subroutine evaluates the lowest height h_z at which the stem has a given diameter z. It determines at first the lowest mesh interval (x_k,x_{k+1}) on which $s(x_k) \geq z > s(x_{k+1})$. Then it determines with Newton's method the lowest height $y \in (x_k,x_{k+1})$ at which $s(y) = z$. This procedure is complicated by the possibility of bulges in the taper curve. The value y is accepted for the answer h_z.

In this subroutine it is supposed that since $s(x_i) \geq z$ for every $i \leq k$, then also $s(x) \geq z$ for every $x \leq x_k$. This may not be true in some exceptional situations. The subroutine can easily be modified so that this additional assumption is unnecessary. The revised subroutine would, however, require much more computer time.

Subroutine VOLUME

The subroutine calculates the volume of a stem between given heights a and b. It is supposed that the stem is a solid of revolution and so the volume V is evaluated with the formula

$$V = \frac{\pi}{4} \int_{\alpha}^{\beta} s^2(x)dx. \tag{56.1}$$

Here $\alpha = \max(0,a)$ and $\beta = \min(b,x_n)$. The coefficient $\frac{1}{4}$ is needed because the taper curve $s = s(x)$ is formed by using diameters and not radii.

Subroutine MANTLE

The subroutine calculates the area of the mantle of a stem between given heights a and b. It is supposed that the stem is a solid of revolution and the area A is thus evaluated by using the formula

$$A = \pi \int_{\alpha}^{\beta} s(x)\sqrt{1+(\tfrac{1}{2}Ds(x))^2}\,dx. \tag{56.2}$$

Here $\alpha = \max(0,a)$ and $\beta = \min(b,x_n)$. The coefficient $\frac{1}{2}$ is needed because the taper curve $s = s(x)$ is formed by using diameters and not radii. The elliptic integral in (56.2) is calculated approximately by using the Romberg rule (cf. Davis & Rabinowitz 1975, p. 327) because it cannot in general be evaluated exactly.

Finally we have two subroutines which we have written for the investigation of the suitability of the cubic spline for taper curve.

Subroutine COMPAR

The subroutine compares the diameters given by the cubic spline with the given ones by using Horner's rule (cf. Henrici 1964, p. 51).

Subroutine DECREA

The subroutine investigates the monotonicy of the cubic spline $s = s(x)$ on the interval $[0,x_n]$. It considers each mesh interval $[x_i, x_{i+1}]$, $i = 1(1)n-1$ separately and gives the subintervals of $[x_i, x_{i+1}]$ on which the cubic spline is

1) monotonically decreasing
2) monotonically increasing
3) constant.

6. RESULTS

We examined the suitability of interpolating splines for taper curves by applying the principles of section 54 to the whole sample tree material (cf. ch. 2). In addition we judged the qualities of taper splines by the graphs the splines produced for some special trees.

The results of analyses of total and partial volumes of sample trees were tabulated by diameter and height classes. The parts of the taper splines where the curves were increasing were found out. The means and dispersions of their locations, lengths and maximum values of the increase were evaluated by diameter classes. We also compared the diameters given by the taper splines with the measured ones at the points not used in the construction of splines. The means and dispersions of the possible differences were tabulated by diameter classes.

In this chapter we present conclusions which can be deduced from this large material. From the numerical results mentioned above we present for considerations of space only summaries of the most significant ones. Unless otherwise mentioned, the results do not depend on the size of the tree. The essentials of numerical results have been collected in Tables 2 and 3 (p. 45 and 46).

In section one we shall describe the form which the cubic spline gives for the average tree and consider the cubic, natural and parabolic splines of exceptional trees by means of an extreme case. In section two we shall deal with the effect of different initial conditions on the properties of cubic taper splines. In section three we shall briefly compare the volumes given by cubic and parabolic taper splines with the volume given by the comparison model. Finally, the accuracy of taper splines in relation to the number and place of measurements will be discussed in section four.

61. On the form of taper splines

We already know the construction methods and general properties of splines from the theoretical considerations of the previous chapters. These expositions, however, were not sufficient to show whether the splines could reproduce the natural form of trees. Consequently, we studied this problem, in addition to the numerical test results, by forming the graphs of taper splines for some special trees. We were especially interested in the average tree and, on the other hand, in trees with an exceptional sequence of measured diameters.

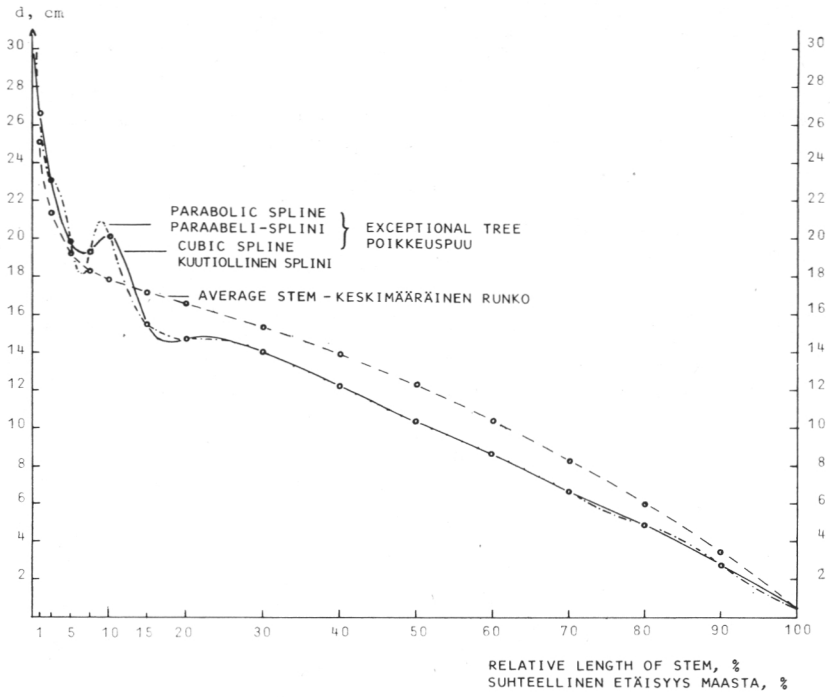


Fig. 1. The form of the average stem by cubic spline and the parabolic and cubic taper splines of an exceptional tree.

Kuva 1. Keskimääräisen puun runkokäyrä kuutiollisella splinillä ja erään poikkeuspuun runkokäyrä kuutiollisella ja paraabeli-splinillä.

The average spruce was defined to be a spruce whose height and diameters on relative heights were the means of the corresponding quantities of all sample trees. The cubical taper spline of this average tree was constructed by using all known diameters. The initial points were situated at the heights of 3,5 and 95 per cent and the initial diameters were taken from parabolas interpolating at points $2\frac{1}{2}$, 5 and $7\frac{1}{2}$ per cent and, respectively, at 80, 90 and 100 per cent. In practice this was done by using subroutine AITKEN (cf. 56). The resulting average taper spline is shown in Figure 1. The curve of this spline is quite regular with a rapid decrease at the butt. It is so natural that other methods using the same information could hardly give a better form to the taper curve.

The shapes of taper curves of individual trees may differ considerably from that of the average tree. Especially, as we already have remarked, they do not always decrease as evenly.

A concrete view on the ability of cubic and parabolic splines to form a reasonable taper curve can be obtained using an exceptional tree. At the upper half of this special tree the diameters are steadily monotonic but at the butt they vary rather irregularily, which can be seen from the following set-up:

per cent height:	1	2,5	5	7,5	10	15	20	30
d_i, cm	26,6	23,1	19,8	19,3	20,1	15,5	14,7	14,0

When the measurement intervals are not equal and there are both large and small differences between subsequent diameters, it is difficult to determine an adequate taper curve. The curves of parabolic and cubic taper splines can be seen in Figure 1.

We can see from the graph that the parabolic spline cannot describe the taper curve of such exceptional trees in a natural way. The initial condition (cf. 42) for this parabolic spline was chosen from among several tested alternatives. The initial height was 35 per cent and the initial diameter was taken from parabola interpolating at the heights of 30, 40 and 50 per cent. In the middle part of the stem the curve of the parabolic spline almost coincides with the curve of the cubical spline but in the end parts it oscillates more than the curve of the cubical spline. The oscillation is especially large in and below the exceptional part of the tree (5—10 per cent). This is due to the stiffness of the parabolic spline, the maximum degree of its partial polynomials being only two.

The curve of the cubic taper spline is clearly better. The initial conditions for this spline were determined as for the average tree. The sudden increase of the diameter at the height of 10 per cent causes an oscillation in this spline between the heights of 15 and 30 per cent so that the diameter at 22 per cent exceeds the one at 18 per cent by 0,29 cm. This oscillation is, however, relatively small due to the stability of the cubic spline. On the other hand, it appears that in such extreme cases the oscillation of cubic spline cannot be completely avoided. We tried e.g. to apply the idea of section 55 and raise the lower initial point over the exceptional part but then the unstability of the cubic spline below the initial point caused considerable oscillation in the butt. This also confirms that it is quite natural to place the initial points in the proximity of the lowest and highest points of measurement.

For this exceptional tree, the natural spline (cf. 31) produces a taper curve which is in the main part of the stem nearly the same as that given by the cubic spline in Figure 1. The greatest difference is again in the butt. At ground level the discrepancy between curves was 1,08 cm but at the height of 4 per cent it was no more than 0,5 mm. The same is also true in general. The accuracy of the natural taper spline suffers most in the proximity of the lowest measurement, but it rapidly increases with the height if a sufficient number of measurements are available. In the next section we shall show that the second derivative varies a great deal in the butt from tree to tree. For example, the second derivative of the cubic taper spline at the height of 1 per cent is 0,0284 for the average tree and 0,00454 for the exceptional tree treated above. This means that we cannot except any constant value of derivatives to give satisfactory initial values for all trees. A better result can be expected when the derivatives are chosen separately for each tree. These assumptions were confirmed by experiments we made by using the whole sample tree material. We return to this in the next section.

If we compare the three types of taper splines considered, we notice that the exceptional tree was given the most natural form by the cubic spline with estimated initial diameters. The natural spline was almost as good but the parabolic spline was clearly weaker due to its greater oscillation. Thus the cubical spline seems to be worth the greatest attention as we proceed.

The volume obtained with cubic spline for the exceptional tree of Figure 1 exceeds by 1 per cent the comparison volume of this tree (cf. 54). For the difficult interval from 10 to 20 per cent the cubic taper spline yields a volume which is 3,6 per cent larger than that obtained by Simpson's formula in the comparison model. For other intervals the differences are from —0,1 to 0,5 per cent. Because the exact volume is, of course, an enigma, it is difficult to draw any reliable conclusions about these differences between the respective models.

An examination of the cubic taper splines of Figure 1 reveals that the splines consist on each subinterval only of very regular parts of the cubic polynomial components. This might have been expected because of the minimum curvature property of cubic splines. If there is no oscillation in the measured diameters or if the oscillation is small, no undue oscillation will occur in the cubic taper spline provided that the initial conditions are properly chosen.

Some information on the average forms of taper splines can also be obtained from Tables 2 and 3. The differences of partial volumes in regard to comparison model and the diameter errors at comparison points can give some idea of the average behaviour of the graphs of taper splines. Especially the oscillation properties in Table 2 are useful in estimating how natural taper splines are.

If we determine cubic, natural and parabolic taper splines for all sample trees in the same way as for the exceptional tree of Figure 1 and consider the form of these curves by the amount of oscillation they have, the opinion about their relative preference remains the same as in the case of the single exceptional tree. In fact, from the cubical taper splines 42,5 per cent had increasing parts, when the corresponding amount for natural taper splines was 49,7 per cent, and 80,7 per cent for parabolic taper splines. In all cases the majority of increasing parts were situated below the height of 20 per cent, the proportions being 84 per cent for cubical, 89 per cent for natural and 72 per cent for parabolic taper spline. Thus the parabolic taper spline has absolutely and relatively more oscillation in the middle part of the stem than the other taper splines.

In analysing the oscillations of cubical taper splines we noticed that the sequence of measurements was unmonotonic for 25,3 per cent of all sample trees. Thus the cubic spline has caused increase only for 17,2 per cent of trees. In addition, the increasing parts were short and the increase was only seldom over 1 mm. The irregularity and the short distances between measurements at the butt caused the accumulation of the increasing parts between the heights of 5 and 20 per cent (79 per cent of increasing parts). For small trees the large top diameter (0,8 cm)

caused often unmonotonicity in the top (7 per cent of all trees). As the actual taper curve of every tree has unmonotonic parts due to the branch whorls this slight oscillation of cubic taper curve does not significantly reduce its utility.

62. The effect of initial conditions

In sections 35 and 52 we considered different ways of placing the initial points, of determining the initial indices k and l, and the initial values ZA_i, $i = 1(1)4$. In addition we noticed in section 55 that the heights of initial points affect the stability of the resulting cubic spline to a great extent. These theoretical considerations alone, however, are not sufficient to decide the preferable ways of choosing initial heights and values for cubic taper splines. Consequently, we compared the following ways of giving the initial information:

— second derivatives equaling zero
— actual diameters
— diameters from interpolating parabolas
— first derivatives from interpolating parabolas
— second derivatives from interpolating parabolas.

The comparison was made for different pairs of initial points at a mesh of eight per cent heights (1, 5, 10, 20, 40, 60, 80 and 100) using all 1 864 sample trees. The most essential numerical results of these comparisons have been collected in Tables 2 and 3.

In Table 2 we see for the first three stated ways the effect of initial information and initial heights on the accuracy of total and partial volumes as well as on the oscillation of cubic taper splines. For the latter purpose, the taper spline of every tree was examined by the test program in order to find out whether it was increasing at some intervals. If such an interval was detected, its length and position were registered together with the increase of taper spline on this interval. Our sample trees included 49 specimens whose measurements at the used mesh already formed an unmonotonic sequence. However, in other respects these stems had a rather regular form. In fact, when the taper splines of these stems were formed by using the values of interpolating parabolas at the heights of 7,5 and 90 per cent as initial diameters, only three trees had increase in two parts of the taper spline, and all the remaining 46 trees only in one part. In addition, the mean value of the maximum increase was 0,3 cm and the average length of an increasing part was 6,2 per cent of tree height. Thus we can see that the results are not so much affected by the presence of these trees. Considering the total and partial volumes we must bear in mind the restrictions of the corresponding comparison volumes. We shall return to this topic in section 63.

In Table 3 we can see the mean values and standard deviations of errors of taper splines at comparison points, when the three last ways of choosing initial information are used at some reasonable initial heights.

Table 2. Main results of analysis of taper curves produced by different choices of initial values and points of interpolation.

Taulukko 2. Eri alkuarvo- ja interpolaatiopistevalinnoilla muodostettujen splini-runkokäyrien analyysien tärkeimmät tulokset.

Initial values - *Alkuarvot*			Per cent differences (ΔV) of spline and test model *Splinillä ja vertailumallilla saatujen tilavuuksien prosentuaaliset erot (ΔV)*																Monotonicy-analysis *Monotoonisuus-analyysi*							
			Total volumes *Kokonaistilavuudet*			Partial volumes - *Osatilavuudet*													2) I-tr.	3) LE	4) INC	Distribution of intervals with increase along the tree in % *Epämonotoonisuutta sisältävien välien prosent. jakauma rungolla*					
						Means - *Keskiarvot*							St. deviations - *Hajonnat*													
Method *Menetelmä*	Lower *Alempi*	Upper *Ylempi*	1) $\lvert\Delta V\rvert \leq 1$	Aver. *keskiarvo*	$S_{\Delta V}$	0-5	5-10	10-20	20-40	40-60	60-80	80-100	0-5	5-10	10-20	20-40	40-60	60-80	80-100	%	%	cm	0-5	5-10	10-15	15-20	20-90	90-100
Splines of 8 points (1, 5, 10, 20, 40, 60, 80 and 100 %) - *8 pisteen splinit (1, 5, 10, 20, 40, 60, 80 ja 100 %)*																										
D_S^2 =0.	2,5	90	53	0,47	1,52	7,6	-3,3	2,4	-1,9	0,8	-0,2	4,0	5,9	3,1	3,6	3,6	3,5	5,3	17	63,8	3,7	0,4	0	54	43	1	1	0
real diam.-*tod. läpimitat*	2,5	90	59	-0,08	1,42	-1,1	0,4	-0,4	0,2	0,1	0,4	0,2	1,3	3,1	3,5	3,7	3,5	5,4	1,1	35,7	2,9	0,2	17	33	16	13	8	14
Aitken	2,5	90	56	0,13	1,51	5,2	-2,3	1,6	-1,2	-0,3	4,9	-27,4	5,1	2,8	3,4	3,5	3,4	5,5	16	85,9	2,9	0,3	0	30	24	1	1	43
with points-*pisteillä*	(1,5,10)	(60,80,100)																										
D_S^2 =0.	7,5	90	56	-0,2	1,48	-3,3	1,3	-1,2	0,7	-0,1	0,1	3,9	3,8	2,5	3,0	3,5	3,5	5,3	17	12,7	4,7	0,1	3	13	15	42	26	1
real diam.-*tod. läpimitat*	7,5	90	53	-0,02	1,58	-0,3	0	-0,1	0	0,1	0,3	0,2	6,4	0	3,7	3,7	3,5	5,4	1,1	35,6	2,7	0,2	20	33	15	10	8	13
Aitken	7,5	90	56	-0,13	1,49	-2,3	0,9	-0,8	0,5	0,1	-0,1	5,0	3,9	2,4	2,8	3,4	3,4	5,1	14,5	9,8	4,2	0,1	11	18	13	35	16	8
with points-*pisteillä*	(5,10,20)	(60,80,100)																										
D_S^2 =0.	15	70	55	0,19	1,54	1,1	-0,6	0,3	-0,4	0,6	-1,3	14	5,6	2,8	2,6	3,2	3,4	4,9	19	15,2	2,4	0,2	35	25	5	5	1	29
real diam.-*tod. läpimitat*	15	70	54	0,14	1,61	0,4	-0,2	0	-0,1	0,2	0	8,1	9,7	4,9	0	4,0	3,6	0,2	42	57,4	2,9	0,5	20	32	17	4	6	21
Aitken	15	70	56	0,08	1,55	1,3	-0,7	0,4	-0,4	0,3	0,2	1,1	5,9	2,9	2,5	3,1	3,3	5,1	17	20,9	2,4	0,3	26	25	7	3	0	38
with points-*pisteillä*	(10,20,40)	(40,60,80)																										
D_S^2 =0.	30	50	52	0,18	1,70	4,8	-2,1	1,4	-0,9	-1,0	8,6	-33	8,7	4,1	2,9	2,8	3,2	7,7	34	92,2	3,5	0,8	9	25	19	0	1	46
real diam.-*tod. läpimitat*	30	50	37	1,84	4,05	0,2	0,2	-0,1	0	0	2,2	105	15,3	7,0	5,6	0	0,1	21,5	291	89,5	5,1	1,6	14	21	10	5	24	26
Aitken	30	50	53	0,12	1,68	-0,4	0,1	-0,2	0	0,1	0,3	10	8,8	4,2	3,3	2,9	3,4	8,0	52	58,2	3,0	0,5	21	29	12	1	9	28
with points-*pisteillä*	(20,40,60)	(20,40,60)																										
D_S^2 =0.	20	90	53	0,06	1,62	1,0	-0,5	0,2	-0,3	0,3	0	4,0	8,5	4,1	3,1	2,8	3,4	5,2	17	39,6	2,6	0,4	27	47	26	0	0	0
real diam.-*tod. läpimitat*	30	90	45	0,03	2,09	0,1	0,2	-0,2	0	0,1	0,4	0,2	14,2	6,6	5,3	0	3,6	5,4	1,1	65,7	3,1	0,7	24	37	17	8	7	6
Aitken	30	90	53	-0,17	1,63	0,3	-0,2	0	0	-0,7	5,1	-27	8,6	4,2	3,2	2,9	3,2	5,5	16	79,6	2,6	0,4	15	23	11	0	0	50
with points-*pisteillä*	(20,40,60)	(60,80,100)																										
D_S^2 =0.	1	100	53	0,36	1,52	6,1	-2,7	1,9	-1,6	0,8	-0,6	3,9	5,4	2,9	3,4	3,5	3,4	5,1	17	56,9	3,4	0,3	0	53	42	1	1	3
Spline of 8 points ($2\frac{1}{2}$, $7\frac{1}{2}$, 15, 30, 50, 70, 90 and 100 %) - *8 pisteen splini ($2\frac{1}{2}$, $7\frac{1}{2}$, 15, 30, 50, 70, 90 ja 100 %)*																										
Aitken	5	80	80	-0,1	0,82	-1,4	0,4	-0,3	0,4	-0,2	0	0,2	3,4	1,1	1,1	1,2	1,3	1,9	5,3	42,6	3,1	0,1	0	1	37	29	1	31
with points-*pisteillä*	($2\frac{1}{2}$,$7\frac{1}{2}$,15)	(50,70,90)																										
Spline of 6 points ($2\frac{1}{2}$, 10, 30, 50, 70 and 100 %) - *6 pisteen splini ($2\frac{1}{2}$, 10, 30, 50, 70 and 100 %)*																										
Aitken	5	80	40	-1,11	1,39	-0,4	5,1	-5,9	-1,5	0,5	-0,5	-1,9	4,0	4,2	4,8	1,4	1,3	2,0	21	20,6	6,8	0,2	1	1	0	11	87	0
with points-*pisteillä*	($2\frac{1}{2}$,10,30)	(50,70,100)																										
Spline of all points - *Kaikkien pisteitten splini*																										
Aitken	3,5	95	97	-0,14	0,42	-1,1	-0,1	-0,1	0	0	0,1	0,3	1,1	0,4	0,6	0,7	0,6	0,9	1,9	42,5	2,5	0,1	5	34	28	17	9	7
with points-*pisteillä*	($2\frac{1}{2}$,5,$7\frac{1}{2}$)	(80,90,100)																										

1) The per cent amount of trees with total volume error less than 1 %. — *Korkeintaan yhden %:n kokonaistilavuusvirheen omaavien puiden prosentuaalinen lukumäärä.*

2) The per cent amount of trees with increase in taper curve. — *Runkokäyrältään epämonotoonisten puiden prosentuaalinen lukumäärä.*

3) Mean per cent proportion of length with increase in taper curve in unmonotonic trees. — *Runkokäyrissä ylöspäin paksunevien osien puittain laskettujen prosentuaalisten pituuksien keskiarvot epämonotoonisilla puilla.*

4) Mean maximum increase in an interval with increase. — *Ylöspäin paksunevien osien loppu- ja alkuläpimittojen erojen keskiarvot.*

Table 3. The mean per cent errors and standard deviations of some eight points taper splines at comparison points, and the mean per cent differences and standard deviations of the resulting total volumes in relation to the comparison model. Initial values have been evaluated by estimating diameters or derivatives with interpolating parabolas (see Table 2).

Taulukko 3. Kahdeksan pisteen splineillä, joiden alkuarvot on laskettu interpolaatioparaabeleilta estimoitujen läpimittojen tai derivaattojen avulla, vertailupisteissä saatujen ja mitattujen läpimittojen erojen sekä splinillä saadun ja vertailutilavuuden prosentuaalisten erojen keskiarvot ja hajonnat (ks. taulukko 2).

Initial values — *Alkuarvot*				Comparison points — *Vertailupisteet*							Aver. and st. dev. (%) of diff. in volumes *Tilavuuserojen keskiarvot ja hajonnat* (%)
				2,5	7,5	15	30	50	70	90	
Lower *Alempi*	Upper *Ylempi*			Mean errors ($\Delta\bar{d}$) and st. dev. (s), cm *Erojen keskiarvot* ($\Delta\bar{d}$) *ja hajonnat* (*s*), *cm*							
2,5	90	diameter	$\Delta\bar{d}$	1,05	—0,33	0,21	—0,16	0,05	0,02	—0,08	0,23
		läpimitta	*s*	1,13	0,42	0,43	0,39	0,30	0,30	0,41	1,51
2,5	90	1st der.	$\Delta\bar{d}$	2,03	—0,69	0,47	—0,32	0,09	0,00	—0,06	0,65
		1. der.	*s*	1,69	0,62	0,56	0,45	0,31	0,30	0,42	1,58
1	100	1st der.	$\Delta\bar{d}$	1,02	—0,31	0,21	—0,15	0,05	0,02	—0,08	0,22
		1. der.	*s*	1,11	0,42	0,43	0,39	0,30	0,30	0,42	1,51
2,5	90	2nd der.	$\Delta\bar{d}$	1,03	—0,32	0,21	—0,15	0,05	0,02	—0,08	0,22
		2. der.	*s*	1,12	0,42	0,43	0,39	0,30	0,30	0,41	1,51
1	100	2nd der.	$\Delta\bar{d}$	0,98	—0,30	0,20	—0,14	0,05	0,02	—0,07	0,20
		2. der.	*s*	1,09	0,41	0,42	0,38	0,30	0,30	0,42	1,50
7,5	90	diameter	$\Delta\bar{d}$	—0,20	0,13	—0,11	0,06	—0,01	0,03	—0,08	—0,23
		läpimitta	*s*	0,85	0,34	0,36	0,36	0,30	0,30	0,42	1,49
7,5	90	1st der.	$\Delta\bar{d}$	—0,14	0,11	—0,09	0,05	0,00	0,03	—0,07	—0,21
		1. der.	*s*	0,86	0,34	0,35	0,36	0,30	0,30	0,42	1,49
7,5	90	2nd der.	$\Delta\bar{d}$	—0,20	0,13	—0,11	0,06	—0,01	0,03	—0,08	—0,23
		2. der.	*s*	0,85	0,34	0,36	0,36	0,30	0,30	0,41	1,49
5	100	1st der.	$\Delta\bar{d}$	—0,18	0,13	—0,10	0,05	—0,01	0,03	—0,08	—0,23
		1. der.	*s*	0,85	0,34	0,35	0,36	0,30	0,30	0,42	1,49

We start the analysis of the first alternative with the natural spline. As we can see from Table 2, the initial conditions for this spline, second derivative equals zero at the extreme heights of 1 and 100 per cent, produce increasing parts in the taper curve for more than one half of the trees (56,9 per cent). This oscillation can also be detected by observing the differences of partial volumes compared with the comparison volumes.

In fact, an intial condition that the second derivative should equal zero is exactly valid only at the inflection point of the stem, because intervals with constant diameter hardly exist in any tree. As we can see from the taper spline of the average tree, this initial condition is liable to cause bias and oscillation in the resulting taper spline. This is especially the case if the lower initial height is 2,5 per cent. The taper spline is clearly better if we choose the second derivatives equal to zero at initial heights

of 7,5 and 90 per cent, even though the stable part of the spline is now shorter. Now the error in lower initial condition is essentially smaller and this weighs more than the decrease in stability. If we try to raise the lower initial height over 7,5 per cent, we get again worse results. However, the initial heights of 20 and 90 per cent make an exception. In this case, the initial conditions in question produce a taper spline which oscillates less than those obtained with alternative conditions (cf. Table 2). This can be explained by the average location of the inflection point just at the height of 20 per cent. This is, however, too high in view of the stability of the spline and, in addition, it varies considerably from tree to tree. Thus we can conclude that the use of a zero value of second derivative at a constant relative height is not very recommendable.

For a final view of this initial condition we formed an estimate of the values of second derivatives at the butt and top. This was done by constructing a cubical taper spline for all sample trees by using all measurements and initial diameters given by subroutine AITKEN at the heights of 3,5 and 95 per cent. In the following set-up the means and standard deviations of second derivatives of these taper splines at the heights of 1 and 100 per cent can be seen for some height classes.

	Height of tree, m										
	3	5	7	9	11	13	15	17	19	21	23
Per cent height 1											
2nd deriv. × 1 000	57,5	43,7	46,6	43,1	38,4	31,5	26,5	24,8	20,3	15,8	17,2
st. dev. × 1 000	223,0	90,5	71,2	40,2	40,2	27,8	22,3	19,9	20,4	12,9	13,2
Per cent height 100											
2nd deriv. × 10 000	2,7	0,8	0,3	0,2	—0,0	—0,1	—0,1	—0,1	—0,1	—0,1	—0,1
st. dev. × 10 000	2,5	1,1	0,7	0,5	0,4	0,3	0,2	0,2	0,2	0,2	0,1

At the height of 1 per cent the second derivative decidedly decreases as the height of the tree increases. The values of second derivatives at the top are small compared with those at the butt, but also there the derivatives are similarly correlated with the height of the tree. The dispersions of derivatives are larger for short trees than for tall trees. These dependencies on the height of the tree can be connected with the dependence of the absolute distances between the measurements on the height of the tree and with the constant value (0,8 cm) of top diameter.

The second method, the use of measurements as initial diameters reduces the number of partial polynomials by two and thus diminishes the flexibility of the spline. On the other hand, it increases the accuracy in the neighbourhood of initial points. The figures of Table 2 show that this method causes oscillation in the curve. Even though the taper splines constructed by this method have most accurate initial values, they are better than the other alternatives only for the initial heights of 2,5 and 90 per cent. In all other cases this method leads to the weakest result. It is true that mean errors of diameters at comparison points are relatively small, but the oscillation renders this property worthless. It is possible that this oscillation has

something to do with the corresponding property of the best polynomial approximations mentioned in section 54.

If we take the actually measured diameters as initial diameters, we prefer to use measurements at points which are extreme or nearest to extreme. Then the stability properties of the spline damp the oscillation most effectively. On the other hand, additional analyses on the points used as initial points in Table 2 showed that the taper curve as a rule improves, if all measurements are used in interpolation and initial diameters are determined by subroutine AITKEN, the initial heights being on second and last intervals. As a conclusion of the treatment of this method we can state that the use of measurements in initial diameters is not preferable. This is in accordance with the theoretical considerations of section 52.

In the third possibility the initial diameters are estimated by using interpolating parabolas. In practice the diameters are calculated by the subroutine AITKEN with interpolating points which can be seen in Table 2. As we remember, the stability properties of splines prefer initial points near the butt and top. If the initial heights are 2,5 and 90 per cent, then the diameter of the interpolating parabola is 1,05 cm too large at the former height. This produces oscillation in the taper spline as we can see from the differences in partial volumes in Table 2 and from the diameter errors in comparison points in Table 3. A considerably better taper spline is obtained by raising the lower initial height to 7,5 per cent and retaining the upper one at 90 per cent. The initial diameters are taken from parabolas interpolating at per cent points 5, 10 and 20 in the lower case and 60, 80 and 100 in the upper case. These initial conditions produce the best result of all the alternatives presented in Table 2. Only 9,8 per cent of the taper splines of all sample trees have unmonotonic parts. Thus the third possibility is clearly to be preferred.

It remains to be considered the last two cases where initial values are obtained by estimating the first or second derivatives at initial points. These approximative values are taken from interpolating parabolas by subroutines INIDE1 or INIDE2 (cf. 56). If taper splines are constructed in this way, their evaluated properties are in most cases approximately the same as for the taper splines with estimated initial diameters at the same heights (cf. Table 3). This is logical in the sense that both the diameters and the derivatives have been taken from the same parabolas. It is also in agreement with the error considerations of section 55. It must, however, be remarked that this is by no means an obvious result and its validity may be violated e.g. if the shape of the interpolating parabola differs from the shape of the stem. Because of the similarity of the results we included in Table 2 only taper curves with estimated initial diameters.

Greatest differences between the three interpolatory methods were discovered when the parabolas were constructed by using extreme points and the initial heights were 2,5 and 90 per cent. In this case the use of first derivatives as initial information caused clearly more biased oscillation at the butt end than the use of other

information. The use of second derivatives gave in this case practically the same results as the use of diameters (cf. Table 3).

We remember from theoretical considerations that if the initial conditions are formed by using first derivatives, the initial points cannot be chosen freely (Proposition 35.2). We also showed in the analysis of initial errors (cf. Set-up 54) that the effect of errors in first derivatives is smallest when the initial heights coincide with interpolating points. In Table 3 we have collected some results which for their own part show the effect of initial heights for taper splines. When the first derivatives were taken at the extreme points (1 and 100 per cent), the diameter errors at comparison points were even slightly smaller than in the case where initial diameters were estimated at the heights of 2,5 and 90 per cent. When the estimation of second derivatives took place at extreme points, the results also improved. The situation in the neighbourhood of initial heights of 7,5 and 90 per cent was different. When the estimation of first derivatives was pushed to the points of 5 and 100 per cent, the result was slightly weaker than before. This means, of course, that the estimate of the first derivatives is definitely worse at the height of 5 per cent than at 7,5 per cent. On the whole we can say that the estimation of derivatives is a preferable initial method.

We can conclude the treatment of the different initial methods by confirming that the use of interpolating parabolas in the determination of initial values is the most convenient method. It must be admitted, however, that even the best initial conditions of Table 2 have errors which produce a slight oscillation in the taper spline at the butt. It is more or less immaterial whether the interpolating parabola is used in estimating diameters or first or second derivatives because the resulting taper splines have nearly equal properties. In the present context we suppose that the first derivatives are estimated at an interpolating point or near it.

The taper splines of Table 3 were constructed by using 0,4 cm as the constant value of top diameter, because the results at comparison points of the upper half of the stem were then unbiased on the average. If the top diameter is 0,8 cm, then the taper splines of shorter trees have unmonotonicy in the upper part (cf. Table 2). In fact, then the mean diameter error of all sample trees at the height of 90 per cent was over 1 cm. The top diameter has also some effect on the volume differences between taper splines and comparison model. If we consider the taper spline with estimated initial diameters at the heights of 2,5 and 90 per cent, we can see from the mean values of per cent differences in total volumes presented in Tables 2 and 3 that the smaller top diameter gives a difference 0,1 per cent units bigger. If the initial points are 7,5 and 90 per cent, the result is the same even though the difference has a different sign.

Our considerations show that the nature of initial information does affect the monotonicy of the taper spline. The most monotonic curve was achieved by using interpolating parabolas in determining initial values. This method does not give sufficiently accurate initial values in the lowest part of the butt, but a reasonably

good initial value was obtained already on the second interval between measurements. When the eight point taper spline of Table 2 with initial diameters estimated by subroutine AITKEN at heights 7,5 and 90 per cent, but with the top diameter 0,4 cm, was constructed for trees on which the sequence of these eight measurements was monotonic (1 815 stems), then 6,9 per cent of taper splines had increasing parts. This increase always occurred on one interval below the height 30 per cent. The size of such trees was generally small, and the mean value of the maximum increase was only 0,06 cm.

We may conclude that the stability of the cubic taper spline is clearly dependent on the placement of initial points. The farther the initial points are from end points, the more unstable the spline is. This was already evident after the error analyses of section 55. Also the method on which the initial values are generated has a substantial effect on the form of the taper spline. In our experiments we got the closest resemblance to the actual taper curve by estimating the initial values with an interpolating parabola. The estimated quantity may be the diameter or first or second derivative because all these ways as a rule lead to similar results. The best discovered lower initial height was fairly near the ground, between second and third measurements. The best place for the upper initial height was near the top between the last actual measurement and the top. On these intervals the best place for the initial point is where the estimate of the initial value is most accurate. In estimating derivatives the extreme points seem to be the best choice. In the case of the first derivative this follows already from the error analysis.

63. Volume differences between splines and comparison model

As we have already pointed out, there exists no method that can give the exact volume of a stem even when the diameters have been measured at very short intervals. The reason is, of course, that we cannot accurately deduce how the actual taper curve behaves between measurements. If we had an accurate taper curve and if we supposed that the stem is a solid of revolution, then we could evaluate the exact volume by means of the known integration formula.

The last line of Table 2 shows the differences in volume between cubic taper splines based on all measurements and comparison model (cf. 54). The initial values of these splines have been produced by using the values of interpolating parabolas at the heights of 3,5 and 95 per cent as initial diameters. The mean value of per cent differences (—0,14) is statistically highly significant (risk less than 1 per cent). The difference is generated in the lowest interval of comparison, where the mean value of the per cent differences of partial volumes is —1,1. On the other parts of the stem the methods give on the average similar results but the dispersions reveal that they have differences also there.

We can form an opinion on the difference between cubic spline and Simpson's formula used in the comparison model above the butt by comparing the mean values and standard deviations of the five middlemost partial volumes (5—80 per cent). On the steadiest part of the stem (20—60 per cent) the mean differences are zero and standard deviations 0,6—0,7 per cent units. On the interval 5—10 per cent the standard deviation is only 0,4 but the volume given by Simpson's formula is 0,1 per cent larger. If we consider the volumes by partial intervals no obvious systematic differences between these methods are revealed, but the dispersion values show that a difference of 1 per cent is not very uncommon. If the total volume of the stem had been evaluated by Simpson's formula, the dispersion of volume differences would have been smaller than 0,42 per cent, the figure of Table 2.

The parabolic taper spline based on all measurements and the initial height of 35 per cent produces almost the same volumes as the comparison model. This was to be expected because these methods clearly resemble each other. The value given by the parabolic spline for the total volume was on the average 0,06 per cent smaller, the dispersion of differences being 0,22. Also this difference is statistically highly significant.

The mean values and deviations of per cent differences in partial volumes between parabolic spline and comparison model were

per cent interval	—5	5—10	10—20	20—40	40—60	60—80	80—100
per cent difference	—0,9	0	0	0	0	0,1	1,6
per cent st. dev.	1,4	0,1	0,1	0,1	0,1	0,8	6,5

The large dispersion of the last comparison interval reveals that the parabolic taper spline is not very stable at top. Nevertheless, in absolute terms, the differences are small. In most parts of the stem, the volume given by Simpson's formula was almost the same, as could have been expected. The oscillation of the parabolic spline pointed out in 61 shows, however, that even here there is some difference between these methods.

These considerations show already that one should pay close attention to the evaluation method of volumes in stem analyses. Any result which is considered accurate has certain error tolerances due to the choice of the evaluation method even when a considerable number of measurements is available. In principle all measured diameters should be treated as reliable and they should be weighted likewise in volume evaluation. According to the analysis of methods performed here, the volume given by the cubic spline falls nearest to the actual value, because the cubical taper curve is fairly stable and it can best approximate the form of the butt. In addition, it seems natural to suppose that the volumes evaluated by exact integration of splines are more accurate than the comparison volumes evaluated by numerical integration. The differences between the methods considered here are, however, small. For the use of taper splines, it is important that cubical splines give a reliable total volume even if there is some oscillation in the curve.

64. The number and placement of measurements

The planning of diameter measurements for the construction of taper curves of sample trees is based on the type and accuracy of information we want about the stems. Further, the number and placement of measurements depend on the method of construction of the taper curve and on the arrangement of the actual measuring. In most cases we ultimately want a taper curve which is sufficiently unbiased for defining the assortment of lumber and gives the most reliable estimation of the total stem volume. On the other hand, even a biased taper curve may give a fairly good estimate of the total volume. The taper curve methods cannot give the exact total solid volume because the irregularities of the bark and stem affect the diameters measured. The best estimates of this solid volume are achieved by using immersion measurements by Archimedes' principle.

The problem of placing the measurements can in theory be treated according to several principles. Concerning the accuracy of volume it seems natural to place the measurements so that the volumes between two adjacent levels of measuring are equal. The following arrangement shows the distribution of stem volume above the root collar as the function of the per cent height from the ground level (cf. Laasasenaho 1975, p. 8).

Height from ground level, %	5	10	20	40	60	80	100
The amount of volume up to this height, %	11	21	40	70	89	98	100

The distribution is similar in all length classes. On individual trees the height of the root collar causes variation in this distribution. The mean values of the per cent heights of the topmost root collar varied from 0,85 to 1,40 per cent by diameter classes. This per cent height seems to increase slightly with the length of the tree.

As we can see from the arrangement, one half of the total stem volume lies in the lowest quarter of length and only two per cent lies over the height of 80 per cent. Consequently, this principle leads to too few measurements on the upper part of the stem in regard to the accuracy of the taper curve, even though the top diameter is always available as a fixed quantity.

Another possible principle is to place the measurements so that the change in diameter between them is on the average the same. As we can see from the taper curve of the average tree in Figure 1, this means that on the butt the measurements should be made at very short intervals. Even this principle does not account for the irregularities of the actual taper curve which affect the accuracy of the results. In Table 4 we can see the mutual correlations of diameters measured at different heights. The inaccuracy of the butt can be seen clearly in these correlations, for example, the correlation of diameters at per cent heights 1 and 2,5 is 0,987, which is also the correlation between the heights of 10 and 40 per cent. In the top region the corre-

Table 4. Correlations between diameters of different per cent heights in the whole material.
Taulukko 4. Eri korkeuksilla olevien läpimittojen väliset korrelaatiot aineistossa.

Height (%) %-korkeus	1	2,5	5	7,5	10	15	20	30	40	50	60	70	80
2,5	,987												
5	,981	,994											
7,5	,979	,991	,998										
10	,977	,989	,996	,999									
15	,974	,986	,994	,997	,998								
20	,973	,983	,991	,995	,997	,999							
30	,969	,979	,987	,991	,993	,996	,998						
40	,964	,972	,981	,985	,987	,991	,993	,997					
50	,956	,963	,971	,976	,978	,983	,986	,992	,997				
60	,948	,953	,961	,965	,969	,973	,977	,984	,991	,996			
70	,934	,938	,946	,950	,954	,959	,963	,972	,980	,988	,994		
80	,918	,920	,927	,931	,935	,940	,945	,953	,963	,974	,982	,990	
90	,882	,881	,885	,889	,893	,898	,903	,911	,921	,932	,942	,955	,967

lations are weakest. This is partially due to the smaller limits of variation in these diameters. If we follow this principle, relatively few measurements are made in the middle part of the stem. It seems possible, however, to construct additional, hypothetical diameter values which effectively damp oscillations generated by the butt and top parts of the stem if the amount of measurements is too small.

As we remarked in section 53, the best placement of measurements for taper splines is a mathematical optimization problem, which does not seem easy to solve. Moreover, this problem should be treated separately for each species because even the average taper curves vary by species. Therefore we shall only consider the effect of the number and placing of measurements in the light of statistical analyses of the different taper splines constructed for our research.

In comparing the ways of determining initial values, the lowest measurement was made at the height of 1 per cent. This height is, however, still in the area of root collar where the variation of diameter is very strong. Therefore the per cent dispersion of volumes for the eight point cubic taper spline was about 1,5 per cent even when the initial values were constructed by the best alternative. When we transformed the taper spline so that each measurement was replaced by the nearest upper measurement in the complete set of measurements, the accuracy of resulting volume was considerably higher, as we can see in Table 2 ($S_{\Delta V} = 0{,}82$).

The accuracy of the taper spline, especially at the butt, depends on the way in which initial values are determined. The eight point taper spline is still slightly biased. This can be seen by considering the best spline found, which has initial diameters from interpolating parabolas at the heights of 7,5 and 90 per cent. The mean values and standard deviations of diameter errors of this spline at comparison points can be seen in Table 3. If the results are divided into diameter classes, it can be noticed that the mean values of errors are greater for larger than for smaller

trees but the direction of oscillation is the same in all classes. The corresponding average values of diameter errors for the aforementioned taper spline giving a good value estimate ($S_{\Delta V} = 0{,}82$) were

per cent height	1	5	10	20	40	60	80
mean values of errors; cm .	—2,58	0,40	—0,22	0,15	—0,06	0	—0,02
st. dev. of errors; cm	2,22	0,50	0,40	0,39	0,32	0,29	0,34

The lower initial diameter was evaluated at the height of 5 per cent from an interpolating parabola. It is clearly biased and causes oscillation in the curve, which can be also seen at other comparison points of the butt. The bias is especially large at the height of 1 per cent.

If we have to place seven diameter measurements at the relative heights of the stem in order to get a good estimate both of the taper curve and of the volume then the heights of the above arrangement are clearly not the best ones even though they give a good volume estimate. The upmost diameter (90 per cent) is too high especially for the volume. Also the lowest diameter (2,5 per cent) is slightly too high, its best place being probably just above the root collar, which means approximately the height of 2 per cent for the spruce.

In practice the placing of measurements is not based on any theoretical model and certain fixed intervals are used. On the butt the intervals are smaller, and higher up they all have the same absolute length. This means that the number of measurements and, thus, the relative accuracy of the resulting volume depends on the length of the tree. This system has been in general use, because the calculations are relatively simple.

When we use a computer and the spline technique presented in this paper we can choose the heights of diameter measurements freely as long as they are recorded. The accuracy of the resulting taper spline, however, depends on the form of the stem and on the placing of measurements as always in the case of taper curves. According to the general principles of approximation the intervals of measurements should preferably not be very uneven. Thus, for example, in the situation where we have two measurements on the butt near each other and the next one very far, the taper spline tends to oscillate because its partial polynomials are connected with derivative conditions.

The minimum number of measurements should be at least 7 if we want the volume error measured with dispersion to be less than 1 per cent. We carried out some experiments with five measurements, and Table 2 shows also the properties of one such taper spline. The mean value of its volume differences with comparison model is —1,1 per cent and the corresponding standard deviation is 1,39 per cent. The amount of oscillation is still reasonable but it is not distributed in the same way as with seven measurements. Thus, if we reduce the number of measurements, the dispersion and the probability of bias increase. A sparse set of measurements can be transformed into a thicker set by inducing additional hypothetical measurements e.g.

by using simultaneous equations models (K i l k k i *et al.* 1978) or by fitting general taper curve models through the known measurements and determining the additional diameters from this curve. Such thickening of a sparse set of measurements would make it possible to evaluate taper splines having all components apparently unbiased. Such a method would be a very useful extension of the spline technique but further research is necessary to elaborate it and to determine its actual potential.

7. CONCLUSIONS

The main object of our investigation was to construct taper curves by means of the interpolating cubic spline, when several diameters of the stem are known. The results obtained here warrant the following conclusions:

1. Theoretical properties of the spline are quite adequate for the taper curve. Especially the minimum curvature property of the spline adds stability to the curve.
2. The computational algorithms of the spline are efficient, so that this method needs relatively little computer time and capacity.
3. The use of the initial conditions presented in this paper enhances the suitability of cubic spline for taper curve.

The two initial conditions mentioned have a substantial influence on the behaviour of the taper spline. These initial conditions are determined by selecting two heights and requiring that either the spline function or its first or second derivative has given values at these heights. Since the cubic spline is stable between initial points, these points should be set close to the lowest and highest measurements. The best method found for defining initial values was clearly the use of an interpolating parabola. However, at the very butt of the stem the parabola is not flexible enough to give sufficiently accurate initial values, by which reason it is advisable to place the lower initial point on the second interval of measurements.

The spline does not require an even spacing of measured diameters and is thus a very supple method. Measuring points can be chosen rather freely as needed; it is even possible to choose them tree by tree. Because of the alternating form of the actual taper curve, at least 7 diameters must be measured at the stem in order to guarantee a standard deviation under one per cent in the volume estimate. As long as we have a fair number of measurements along the stem at our disposal, the taper spline can be considered unbiased, and it can be used as a taper curve for all purposes, e.g. for determining volumes and diameters. It seems also possible to use taper splines quite accurately in a sparse set of measurements by introducing additional diameters calculated with the aid of general taper curve models or simultaneous equations models. Special attention should then be paid to the monotonicy of the resulting curves.

By means of stem analyses we study the growth of a tree, and this involves the estimation of under-bark diameters at different points in time. The data we are then interested in include the development of volume and timber assortment. The taper curves of the tree at different ages must not intersect each other. In the spline technique the logical behaviour of curves can be secured by an appropriate choice of initial values to a great extent. The easiest solution is to relate the curves to each other with the help of initial values. For each phase of growth, the initial values are determined by means of diameters, taken, for example, at the middle of the second and the last but one interval. The initial diameters for the taper spline of the present time are determined by subroutine AITKEN. For the past time of interest the initial diameters are constructed by subtracting the mean of increments at the ends of the interval from the previous values, supposing that the number of measurements remains the same. In this method the initial diameters for each phase of growth are defined by means of the diameter and increment read from the taper curve of a posterior phase. In principle, the curves can of course also be defined in reverse order. The curves of different phases can be plotted e.g. by a computer printer on the same sheet, from which the logical form of curves can be seen, as well as possible measuring errors. For illustration of a such curve family see Figure 2. The curves were constructed by the spline technique and their graphs were drawn by a separate program (P e k k o n e n 1979).

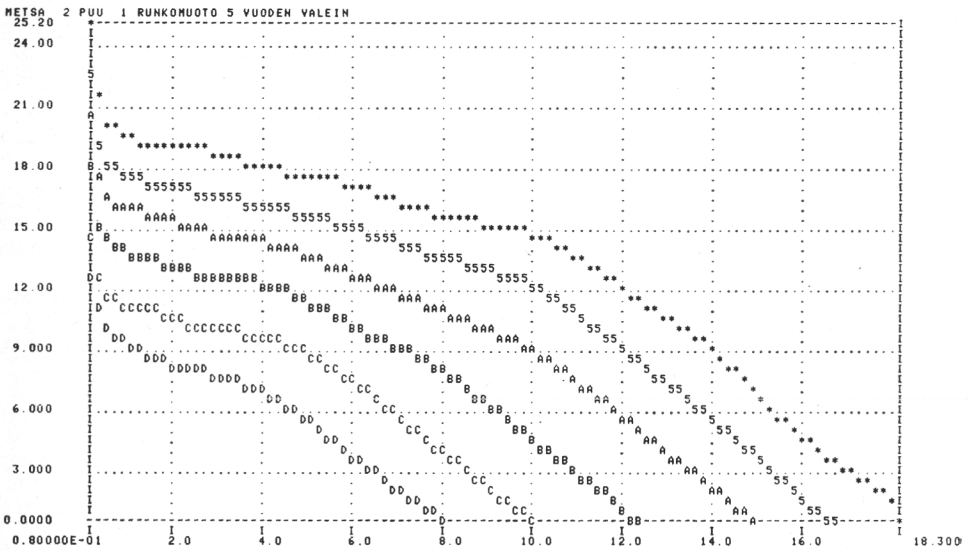


Fig. 2. Taper splines of a stem with five-years intervals produced by computer printer.
Kuva 2. Erään puun runkoanalyysin splini-runkokäyrät viiden vuoden välein tietokoneen rivikirjoittimella graafisesti tulostettuna.

In addition to ordinary purposes, say, the evaluation of volume and diameters, a taper curve is also suitable for calculating the area of the mantle of a tree, which is a point of interest in increment research (Wilson 1951, Laasasenaho 1978). The subroutine MANTLE mentioned in section 56 was constructed for this purpose.

Taper curve can be made either for an entire tree or for a part of it. The taper curve made for a stem section may be used to predict the taper curve outside this part. Such an extrapolation is needed for example in multi-process machines. Then diameters are only available from the section treated but for optimization of logging out we must have information on the remaining part of the trunk.

The diameter prediction is the more unsafe the farther we are from measurements. In the proximity of a sequence of measurements quite sound predictions can be obtained by a straightforward interpolation with e.g. subroutine AITKEN. If predictions are desired for stretches of several meters, we must resort to some taper curve for the tree. A solution offered by the spline technique could be the relative taper curve built on a fictional standard tree. Predictions could be made on the basis of this standard taper curve and the measuring data. Note that these methods generally require an estimate of the height of the tree in question. The accuracy of this process can be expected to increase steadily together with the amount of measuring data from the tree and stand. The process should be made versatile in view of the variable situations and its details should be confirmed by practical tests. Thus its further development must be left for a separate investigation.

Besides taper curves, the spline functions can obviously be used also for other fitting problems. Such a problem is for example the plotting of a graph for a stem frequency distribution series, that is, of a graph giving the number of trees in different diameter classes. The sum curve for the stem frequency distribution series could be described with the spline and this spline curve could then, in turn, give the stem frequency distribution series for any desired range of diameter classes. Curve fitting problems solvable with the spline technique can surely be found also outside the realm of forest survey.

8. SUMMARY

The object of our work has been to construct the taper curve of a tree on the basis of diameter measurements of the stem. We have chosen the most widely used function in the class of polynomial splines, the interpolating cubic spline, for the taper function. It is a twice continuously differentiable function which attains the diameter values at measuring points and which can be represented by a cubic polynomial between the measuring points. The properties of any polynomial spline depend quite decidedly on so-called initial conditions. Thus the succesful determination of suitable initial conditions is vital for the use of cubic spline as a taper curve.

We have theoretically considered the properties of interpolating cubic splines in relation to the taper curve. Especially we have contributed to the theory of initial conditions in case they are determined by estimating a natural property of the stem at two points. This property may be the diameter of the stem or the first or second derivative of the actual taper curve. We have also analysed the effect of errors in measurement or in estimation of initial conditions on the behaviour of the taper curve. These analyses have given information on the stability properties of the cubic spline and on the optimal determination of initial conditions.

The results of theoretical considerations have been confirmed and also sometimes expanded by practical experiments. We have had a large and representative sample tree material, 1 864 spruces, at our disposal. The diameters of each stem have been measured at 14 relative heights. In these experiments we have constructed taper curves for all sample trees in different ways and examined their behaviour analytically and in some cases also by forming their graphs. For comparison we experimented with another possible polynomial spline, the interpolating parabolic spline. This did not, however, weaken the preference of the cubic spline. We also tried to get some experimental information on the effect of the number and placing of measurements on the properties of the resulting interpolating spline.

The practical experiments confirmed that the essential factor in the determination of initial conditions is the choice of the two heights at which the relevant quantities are estimated. The best lower height appeared to be slightly above the stump, in the part where the tapering of the butt begins to be moderate. The best upper height was at or slightly below the top. The cubic splines giving the best taper curves were obtained by using initial conditions in which the estimation was performed

by parabolic interpolation at the abovementioned heights. The estimation of diameters or first or second derivatives led to almost similar taper curves. This interpolation method is also recommendable in that no additional measurements are needed. The inferiority of other initial methods and especially of other initial heights was mainly reflected by an increase of oscillation in the taper curve, the total volume estimate being in general still relatively accurate.

We also constructed computer programs for the determination and the most common uses of taper curve of a cubical spline. These programs can be linked together to form an effective automatic system which performs all the necessary operations as long as a sequence of diameter measurements and the height of the tree are given. At least seven measurements are needed for a relatively unbiased taper curve.

In conclusion we may confirm that the interpolating cubic spline is capable of producing a taper curve which has all the desidered qualities and which can be used easily in all applications. For all applications, too, it is possible to devise an effective automatic data processing system which can be used without any mathematical knowledge.

9. REFERENCES

AHLBERG, J. H., NILSON, E. N. & WALSH, J. L. 1967. The Theory of Splines and Their Applications. 284 p. Academic Press, New York and London.

BÖHMER, K. 1974. Spline-Funktionen. 340 p. B. G. Teubner. Stuttgart.

DAVIS, P. & RABINOWITZ, P. 1975. Methods of numerical integration. 451 p. Academic Press, New York—San Fransisco—London.

HALL, C. A. & MEYER, W. W. 1976. Optimal Error Bounds for Cubic Spline Interpolation. J. Appr. Theory 16: 105—122.

HENRICI, P. 1964. Elements of numerical analysis. 328 p. John Wiley & Sons, Inc. New York—London.

HOLLODAY, J. C. 1957. Smoothest curve approximation. Math. Tables Aids Computation 11: 233—243.

ILVESSALO, Y. 1965. Metsänarvioiminen. 400 p. Porvoo—Helsinki.

KILKKI, P., SARAMÄKI, M. & VARMOLA, M. 1978. A simultaneous equation model to determine taper curve. Seloste: Runkokäyrän määrittäminen simultaanisen moniyhtälömallin avulla. Silva Fenn. 12 (2): 120—125.

LAASASENAHO, J. 1975. Runkopuun saannon riippuvuus kannon korkeudesta ja latvan katkaisuläpimitasta. Summary: Dependence of the amount of harvestable timber upon the stump height and the top-logging diameter. Folia For. 233: 1—20.

— 1976. Männyn, kuusen ja koivun kuutioimisyhtälöt. Helsingin Yliopiston metsänarvioimistieteen laitos. Moniste. 1—89.

— 1978. Puun ja metsikön kasvusta ja kasvatuksesta. Metsä ja Puu 12: 12—14.

— & SEVOLA, Y. 1971. Mänty- ja kuusirunkojen puutavarasuhteet ja kantoarvot. Summary: Timber assortment relationships and stumpage value of Scots pine and Norway spruce. Commun. Inst. For. Fenn. 94 (3): 1—87.

LUENBERGER, D. 1969. Optimization by vector space methods. 326 p. John Wiley & Sons, Inc. New York—London—Sydney—Toronto.

PEKKONEN, T. 1979. Pistediagrammi-aliohjelmat. (PDP-tietokoneelle.) Metsäntutkimuslaitos, Matemaattinen osasto. Moniste. 1—7.

RUNGE, C. 1901. Über empirische Funktionen und die Interpolation zwischen äquidistanten Ordinaten. Z. Math. u. Physik 46: 224—243.

SLOBODA, B. 1976. Spline und Bitterlich'sche Interpolation bei der Widergabe der Baumschaftform. Discourse at I.U.F.R.O.-Conference, Oslo.

SOKOLNIKOFF, T. S. 1946. Mathematical Theory of Elasticity. 373 p. McGraw-Hill, New York.

TIETZE, B. & POFAHL, U. 1979. Die Konstruktion von Schaftformkurvenfunktionen mittels lokalangepasster Spline-Funktionen. Beiträge für die Forstwirtschaft 1: 30—33.

WILSON, F. G. 1951. Control of growing stock in even-aged stands of conifers. Journal of Forestry 49: 692—695.

YOUNG, D. 1971. Iterative solution of large linear systems. 570 p. Academic Press, New York and London.

SELOSTE

Tutkimuksen kohde ja menetelmä

Tutkimuksessa tarkastellaan runkokäyrän muodostamista, kun rungosta on mitattu läpimittoja useilta korkeuksilta. Työssä tutkitaan splini-funktion ja erityisesti kuutiollisen interpolaatiosplinin soveltuvuutta runkokäyrän kuvaamiseen. Kuutiollinen splini on yleisimmin käytetty funktio ns. polynomisplinien luokassa, ollen kahdesti jatkuvasti derivoituva funktio, joka saa mittauspisteissä annetut arvot ja jota mittauspisteiden välissä kuvataan kolmannen asteen polynomilla. Splini-funktion ratkaisemisessa tarvittavan kahden lisäehdon erilaiset ratkaisutavat sekä niiden soveltuvuus runkokäyrän laskentaan olivat tutkimuksen pääkohde. Parabolisen splinin teoriaa ja tarkkuutta tutkittiin myös jonkin verran.

Teoreettisten tarkastelujen ja kehitelmien lisäksi menetelmiä testattiin laajoin tietokoneanalyysein koepuuaineistolla. Analyyseissä pyrittiin selvittämään myös muita runkokäyrän tarkkuuteen vaikuttavia tekijöitä, kuten mittauspisteiden lukumäärää ja sijoitusta. Koepuut, joilla menetelmiä testattiin, on kerätty valtakunnan metsien inventoinneissa käytetyiltä trakteilta maan eri osista. Testaukset suoritettiin kuusen rungoilla ja niitä oli kaikkiaan 1 864 kappaletta (ks. taulukko 1). Koepuista oli läpimitat mitattu 14 suhteelliselta korkeudelta, tyvellä tiheämmin ja pääosalla runkoa 1/10 korkeuksilta.

Tutkimuksen teoreettiset tarkastelut

Kuutiollisen interpolaatiosplinin määritelmää, yksikäsitteistä muodostamista sekä ominaisuuksia, kuten konvergenssia mittausverkkoa tihennetäessä ja minimikaarevuutta selostetaan kappaleessa 3. Kappaleessa osoitetaan, että yksikäsitteisen splinin (kaava 31.3, s. 10) määrittämisessä tarvittavat kaksi lisäehtoa (kaava 31.7, s. 11) voidaan sijoittaa myöskin muualle kuin tavallisesti käytettyihin ulommaisiin mittauspisteisiin. Systemaattisesti tutkitaan lisäehtojen muodostamista, kun käytettävissä on arvio rungon läpimitasta, 1. tai 2. derivaatasta kahdessa annetussa pisteessä. Lopuksi kappaleessa selvitetään interpolaatio- ja alkuarvovirheen vaikutuksen määräämistä ja esitetään kuutiollisen splinin muodostaminen mittauspisteissä annettujen toisten derivaattojen avulla.

Kappaleessa neljä todetaan kuutiollisen splinin olevan erikoistapauksen yleisemmästä polynomisplinistä ja päätellään, että runkokäyrän muodostamisessa kannattaa kokeilla vain parabolista ja kuutiollista spliniä. Tämän jälkeen selostetaan lyhyesti paraabelisplinin muodostamista ja teoreettista virhekäyttäytymistä.

Runkokäyrän muodostamista kuutiollista spliniä käytettäessä sekä runkokäyrän hyvyyden arvioimista tutkitaan kappaleessa viisi. Analysoitavat alkuarvojen (kaava 52.1, s. 30) erilaiset muodostamisvaihtoehdot ovat:

a) 2. derivaatta = 0
b) todellinen läpimitta
c) interpolaatioparaabelilla estimoitu läpimitta
d) » » 1. derivaatta
e) » » 2. »

Virheanalyysien avulla pyritään selvittämään näiden keskinäistä paremmuutta sekä alkuarvopisteiden sijoitusta.

Runkokäyrän antamia kokonais- ja osatilavuuksia verrataan toisella tavalla muodostetun, ns. vertailumallin, vastaaviin arvoihin, koska tarkkoja tilavuuksia ei ole saatavissa. Lisäksi runkokäyrän hyvyyttä arvioidaan splinin muodostamisessa pois jätettyjen mittauspisteiden läpimittojen ja runkokäyrän monotoonisuuden avulla. Lopuksi kappaleessa kuusi esitellään lyhyesti testausta ja käyttöä varten muodostetut tietokoneohjelmat.

Testiaineistolla saadut tulokset

Koepuuaineiston avulla varmistettiin teoreettisesti saatuja tuloksia sekä pyrittiin selvittämään kysymyksiä, joihin teorian avulla ei saatu varmoja vastauksia. Runkokäyrän muotoa tutkittiin yksittäisten puiden runkokäyrän kuvaajien avulla (ks. kuva 1) sekä koko aineistolla tehdyillä analyyseillä.

Kokeet osoittivat paraabelisplinin kuutiollista huonommaksi. Kuutiollisen splinin alkuarvojen määritystapa vaikutti selvästi splinin monotoonisuuteen. Parhaaksi alkuarvojen määritystavaksi osoittautui interpolaatioparaabelin käyttö sekä parhaiksi alkuarvojen määrityspisteiksi hiukan tyven yläpuolella sekä lähellä latvaa olevat pisteet. Läpimittojen ja derivaattojen estimointi tuottivat suunnilleen samoja tuloksia.

Alkuarvojen määritystapa-analyysien keskeiset tulokset nähdään taulukosta kaksi. Taulukossa kolme nähdään interpolaatioparaabelia ja eräitä parhaita alkuarvopisteitä käytettäessä saatujen seitsemästä osavälistä muodostettujen splinien tarkkuutta vertailupisteissä. Taulukosta kaksi nähdään myöskin splinin ja vertailumallin antamien rungon kokonais- ja osatilavuuksien prosentuaalisten erojen keskiarvot ja hajonnat, kun mittauspisteitä rungolta on 7, 5 tai 14 sekä latva. Rungon tilavuuden ennusteen jäännöshajonta jää alle yhden prosentin, jos mittauspisteitä on vähintään 7 ja ne sijoitetaan siten, että runkokäyrä saadaan kutakuinkin harhattomaksi. Mikäli mittauksia on vähemmän, systemaattisen virheen mahdollisuus kasvaa nopeasti, jollei sopivia lisäpisteitä voida muodostaa jollain yleisillä runkokäyrämalleilla.

Yhteenvetona kappaleessa 7 todetaan splinin vastaavan teoreettisilta ominaisuuksiltaan runkokäyrälle asetettavia vaatimuksia. Mikäli alkuarvot määrätään runkokäyrälle tutkimuksessa löydettyjä sopivia ehtoja käyttäen, saadaan splinin minimikaarevuuden ansiosta stabiili runkokäyrä. Menetelmä ei vaadi tasaisia mittausvälejä, joten se on joustava laskentamenetelmä. Splinin jokaista käyttötarkoitusta varten voidaan muodostaa tutkimuksessa luotuja ohjelmia käyttäen tehokas tietojenkäsittelysysteemi, jota voidaan käyttää tarvitsematta matemaattista tietämystä. Lopuksi kappaleessa mainitaan eräitä sovellutusmahdollisuuksia.

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