Swedish University of Agricultural Sciences
Faculty of Forestry
Uppsala, Sweden

Cradle type multi-stem delimber

BO DAHLIN
Department of Operational Efficiency

Studia Forestalia Suecica
No. 185 · 1991

ISSN 0039-3150
ISBN 91-576-4493-4

Abstract

Dahlin. B. 1991. Cradle type multi-stem delimber. *Studia Forestalia Suecica 185*. 31pp. ISSN 0039-3150. ISBN 91-576-4493-4.

Multi-stem delimbing devices may rationalise processing of small-sized trees. Different types of delimbing device are reviewed. Some basic features of cradle delimbing were studied experimentally. for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) separately. As standard for delimbing quality. the proportion of branches cut shorter than a specified value is proposed. Acceptable delimbing quality was defined in the study as 75 per cent of the branches cut shorter than 25 mm. Efficiency was measured as the time required to achieve the defined delimbing quality. Loss of stemwood was measured simultaneously with delimbing efficiency. The delimbing process followed an 'S'-shaped function. When a bunch of trees first enters the cradle. little delimbing takes place. A period of fairly rapid delimbing follows. succeeded by a period of decreasing efficiency in the final stages. Active delimbing devices. with a momentum of their own. are more efficient than passive devices. The delimbing devices must have sharp edges for efficient delimbing of Norway spruce. Rotors were the most efficient of several delimbing devices tested. The design of the cradle itself. especially the inclination of the long-sides. was shown to be important in improving delimbing efficiency. The optimum speed of the conveyor rotating the bunch within the cradle was found to be ca 1.5 $m \cdot s^{-1}$.

Key words: Delimbing. multi-stem. processing. machine. *Pinus sylvestris, Picea abies.*

Bo Dahlin. Department of Operational Efficiency. Swedish University of Agricultural Sciences. S-770 73 Garpenberg. Sweden.

Contents

MS. received 15 August 1991
MS. accepted 6 November 1991

016.27 Tofters tryckeri ab, Östervåla 1991

Introduction

Background

Delimbing—the removal of branches to improve the handling characteristics of the wood and to allow fuller loading of transporting devices—is one of the major operations in logging in most forest regions of the world. Most forest industries are not capable of utilising the main byproducts of delimbing (branches, needles and leaves) in the industrial process. If utilised, the material is mainly used as fuel.

Sawmills generally demand that branches be removed much closer to the stem than do pulp mills, and usually rely on single-stem debarking, which makes use of rotating chisels or knives. Most pulp mills in Sweden employ drum debarkers, which tumble the stems against each other as a meansof removing bark. This process can better deal with residual branch stubs and associated bark. Recent models of drum debarkers are, in general, more capable of coping with branches and branch stubs. Delimbing is therefore primarily a requirement from the industry, the accceptable quality being determined by the type of industry and by the way in which it handles the wood. Most pulp industries in Sweden are currently capable of utilising, without major difficulties, wood delimbed to lower standards than those set many years ago.

A decline in the dimensions of harvested trees and in the piece-size is expected, especially in developed countries around the world. In Sweden this is because a higher proportion of thinnings is used as industrial furnish (Anon., 1983). Elsewhere, the transition from natural and old-growth stands to managed second-growth forests is the cause. An additional cause is increased utilisation of the stem, as the minimum top-diameter has declined. Whatever the reason, these changes will lead to products of lower unit value at the same or a higher cost. To maintain operating economy and competitiveness, future harvesting systems must allow higher productivity, and exhibit less sensitivity to tree dimensions, than those in use today. This is especially true of delimbing, commonly the most labour-intensive and costly operation in forest harvesting. Multi-stem technology offers a means of improving both delimbing and wood-handling efficiency, while minimising the influence of tree size on productivity.

The rapid increase in the cost of energy during the 1970s brought about an interest in utilising forest residues, especially those from delimbing operations, for fuel. Several research projects have illuminated the prospects and problems of utilising forest fuels (Anon., 1977*a*; Andersson & Björheden, 1986; Hakkila, 1989). Most have been concerned with the utilisation of stems for pulping, sawtimber or other conventional forest products, and of branches, needles, leaves and bark for energy.

Whole-tree harvesting, that is, harvesting of all aboveground parts of the tree, has been developed. In Sweden, particular attention has been given to tree-section systems. Multi-stem delimbing, with capture of the residues in a form suitable for fuel, is a vital part of such harvesting methods. The forest industry was first in utilising woody residues as fuel on a large scale, but recently district heating plants and other markets have emerged for forest fuels. This has increased interest in full-tree and tree-section harvesting, hence also in multi-stem delimbing. In 1986 there were 18 multi-stem delimbing facilities operating in Sweden (Jonsson, 1986*a*).

The productivity of conventional delimbing is very sensitive to tree diameter (Ager, 1967). A trend in modern industrial practice is to handle small pieces as a group or batch, to minimise the influence of individual piece-size. By delimbing several trees simultaneously, the efficiency of the operation may be improved and the influence of tree dimensions reduced. Some single-stem delimbers can occasionally handle two or more trees at once, depending both upon the characteristics of the tree species being processed, and on the quality of delimbing required. This can be illustrated by the results of three studies, which came to contradictory conclusions. Bredberg, Liedholm & Moberg (1975) found the results to be poor, while the others found them satisfactory (Lilleberg, 1987; Kuitto & Mäkelä, 1988). However, the occasional handling of several stems by a single-stem delimber does not eliminate the problems associated with the great influence of tree diameter on productivity.

Multi-stem delimbing methods

Numerous multi-stem delimbers have been constructed during the past 20 years. Delimbers can be classified into four broad categories:

1. Rake type
2. Flail type
3. Drum type
4. Cradle type

Multi-stem delimbers have been developed in Scandinavia, the Soviet Union, North America, Australia and New Zealand. Differences in the types of delimber that have been developed, reflect differences in forestry. Tree properties, such as branchiness, branch angle and brittleness, differ widely between tree species, and result in different development approaches. Therefore, results obtained under different conditions can not easily be compared.

Rake delimbers

Rake delimbers use a scraping action to break off the limbs. They normally perform "rough" delimbing, i.e. some branches or branch stubs remain. There are two main types of rake delimber: the first consists of a blade, usually mounted on a skidder, to scrape off the limbs. The most simple example is the ordinary skidder blade, which operates by running the blade along the length of the tree. Improved versions equip the blade with grooves, or to design it like a rake, to allow it to conform better to the shape of stems (Fig. 1*a*; Séguin, 1979).

The second rake delimber requires two devices: a skidder or winch and the delimber. The trees are pulled, pushed or winched through the delimber. The most simple example is a framework of iron bars, commonly known as a gate-delimber (Fig. 1*b*; Gordon, 1978). The trees are pushed by a skidder through the gate and then pulled back. As is the case with the first type of rake delimber, delimbing quality can be improved by making the delimber better conform to tree shape (Taraldrud, 1972; Folkema, 1979).

Many tropical and subtropical tree species have branches that tend to break close to the stem. This could favour survival in regions occasionally subject to very strong winds, but would not be appropriate in snowy regions. The gate-delimber was developed to deal with such tree species, e.g. pines in the south-eastern USA. It should not follow the stem form, and works best if the bars of the gate meet the branches at some distance from the stem. High productivity and satisfactory delimbing quality can be achieved with a gate delimber under appropriate conditions.

Flail delimbers

A flail delimber commonly consists of a rotating drum with attachments, which is either moved along the trees or the trees are moved beneath the drum. As the trees pass the drum, branches are beaten or bro-

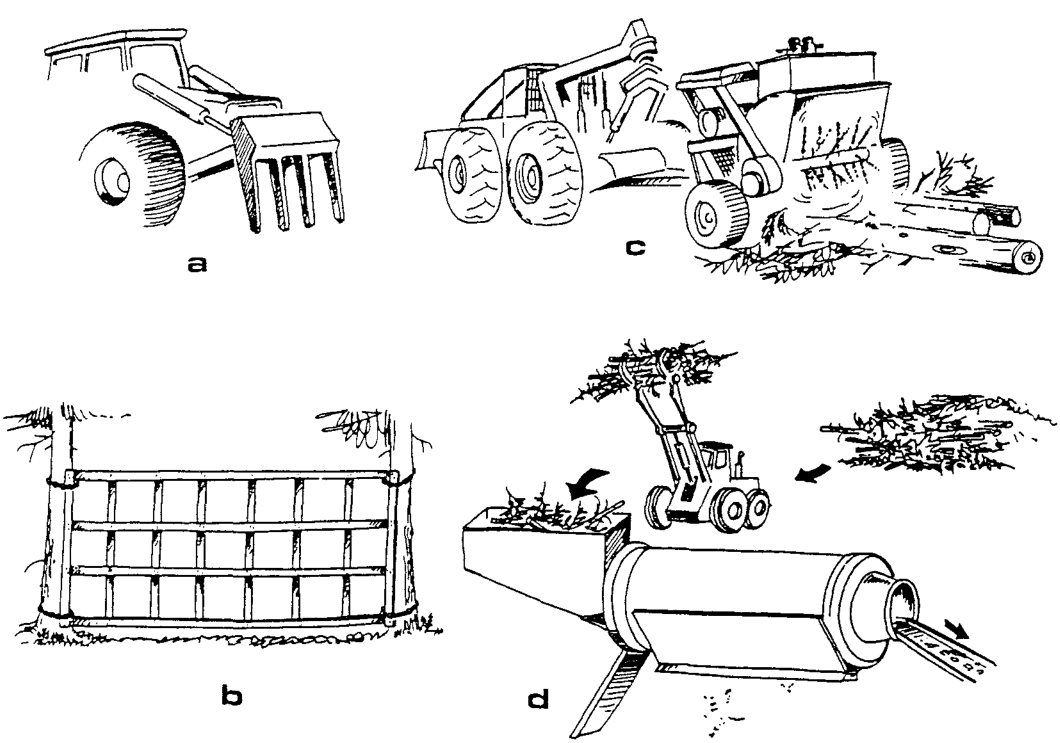

Fig. 1. Examples of different multi-stem delimbers.
(a) Rake type, skidder blade attachment; (b) Rake type, gate-delimber; (c) Flail type, towed chain flail; (d) Drum type, central processing installation.

ken off by the attachments. The method is commonly referred to as chain flail delimbing, because chain has proved to be one of the most robust and versatile attachments.

This device has been considerably developed during the past twenty years. There are examples of small flail delimbers mounted on a tractor, (Fig. 1*c*; Taylor, 1977; Anon., 1978) towed (Anon., 1977*b*) and even mounted on a boom (Andersson, 1979; Heiersdorf, 1980). These devices either drive along a bunch of trees lying on the ground or move a boom along the portion of the bunch needing delimbing. There are also larger machines (Jonsson, 1986*b*; Jonsson & Nordén, 1987) that feed trees through the delimber and utilise two drums, one above and one below the stems, to improve delimbing quality.

Quality of delimbing varies with flail machines. Stubs are commonly left, which might require trimming after processing or, if the material is left in the flail long enough to remove even these stubs, considerable loss of fibre occurs. For certain tree species, as is mentioned in connexion with the gate-delimber, it might give an acceptable result.

Drum delimbers

Drum delimbing is essentially an extension of the drum debarking process, commonly used in forest industries. The logs are placed inside a rotating drum and delimbing depends upon the rotation of the drum. Friction from pieces tumbling against each other and against the interior of the drum, causes delimbing.

There is extensive experience of using drums from the drum debarkers. A study has been made of delimbing in a debarking drum, with quite good results (Brattberg, 1977). Modifications and improvements have been incorporated in other machines. Commonly, these involve adding fixed or powered delimbing knives or devices to the drum's interior. A number of drum delimbers has been constructed since, most of them large, stationary units (Fig. 1*d*; Ronström, 1984; Johansson, 1984; Jonsson & Nordén, 1986), but a mobile unit also exists (Wrobelski, 1984; Nordén, 1987).

Cradle delimbers

The main difference between drum and cradle delimbers is that in the cradle delimber, the outer shell remains stationary and material is rotated within it by chains, screws or other feed devices. The fact that the outer shell of the cradle is open-topped and stationary, both allows the construction of smaller units and permits the mounting of various delimbing devices in the belly of the cradle.

One of the first cradle delimbers was "Skruven" ("the Screw"), built by Kockums (Fig. 2*a*; Rydin & Österblom, 1969; Bredberg et al., 1975). It was made in two versions, the one built on an offroad vehicle to operate in the stand, the other built on a trailer to operate on the landing. The few machines built were used well into the 1980s with rather good results (Svensson, 1984). The delimbing devices were rollers, or rather augers, with knives welded at right-angles to the edge of the flys placed in the belly of the machine. Tumbling was achieved by another kind of auger, placed at right-angles to the logs, forcing the stems to tumble.

In the USSR a delimber, MSG-1 ("the Bear"), was constructed in the 1960s (Fig. 2*b*; Almqvist & Österblom, 1971; Bredberg et al., 1975). Tumbling was accomplished by conveyors in one long-side and the delimbing devices were fixed knives. Apparently, development has continued, since studies of a similar machine, but with delimbing devices like the ones of "Skruven", have been reported (Krasilnikov & Petruchin, 1986). A machine similar to "the Bear" was constructed in Finland, mounted on a trailer (Bredberg et al., 1975). The machine, called the "Delimbing trailer", was intended to delimb stems while transporting them to the landing.

In Sweden, a prototype similar to "the Bear" was constructed. The machine, "the Trough" (Fig. 2*c*; Bredberg et al., 1975), had fixed knives for cutting off branches. From the experiences of "the Trough" a commercial delimber was built by Hydrovåg and later by AC Invest, which combined the design of "the Trough" with rollers as delimbing devices (Fig. 2*d*; Scherman & Nordén, 1983; Sandström, 1984).

ÖSA AB, the Swedish manufacturer of forest machines, built a prototype in which delimbing takes place in a small cradle, above the load of a forwarder (Fig. 2*e*; Forslund, 1985). As with the Finnish "Delimbing trailer", delimbing is carried out during transport, thus taking little or no extra time. In contrast to the Delimbing trailer, the functions delimbing and transport are separated. When logs have been delimbed they are released onto the trailer. On the first prototype, the logs were tumbled by arms, which threw the logs toward the delimbing devices, open rollers with teeth.

As illustrated above, cradle delimbers may be used for delimbing in the forest, during transport, at the landing, at terminals or at the mill. The flat and stationary inner surfaces may be used for mounting other active delimbing devices, which can improve the delimbing quality achieved by tumbling. Conse-

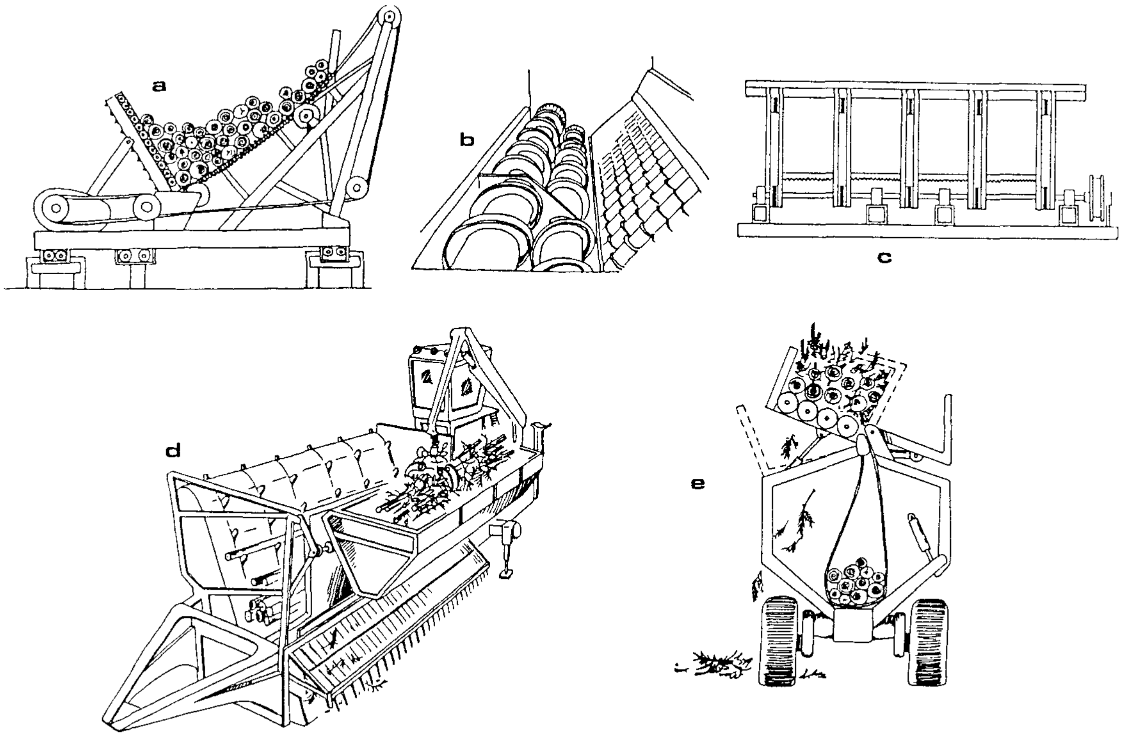

Fig. 2. Examples of cradle type delimbers.
(a) The Bear. Soviet delimber; (b) Skruven; (c) The Trough, prototype; (d) AC Invest bunch delimber; (e) ÖSA forwarder-delimber, prototype.

quently, the delimbing time may be reduced. Thus, cradle delimbers may be used where mobile and compact bunch delimbing systems are required. All the cradle delimbers mentioned are batch machines. A bunch of logs is put into the machine, processed and taken out, before more logs can be added. Continuous-feed machines could be constructed, with the advantage that by increasing the machine's length and feed-rate, higher productivity could be achieved. However, these machines sacrifice mobility and increase size and capital cost.

Since machines of the same type differ greatly, it is difficult to be specific about productivity or cost for different delimbers. For correct evaluation of delimbing, the entire system has to be considered. The Norwegian rake delimber "Rispekvisteren" (Taraldrud, 1972) may serve as an example. The delimber alone could probably be built at a fairly low cost. But to perform the delimbing, a skidder with chokers has to be used and additional trimming by chain saw may be needed. Poor quality delimbing may cause extra costs for transport as well as for handling and debarking at the industry; the size of which costs will depend on the conditions. Likewise, production depends on dimensions and delimbing quality. By building a larger—or longer—delimber, it is often possible to increase productivity, but the investment cost will increase as well and so will the requirement of machines and space in conjunction with delimbing. For most multi-stem delimbers, productivity is dependent on the required quality of delimbing. The better the quality, the longer is the processing time, hence productivity decreases (Bredberg et al., 1975; Andersson, 1979). The tree species, the topography of the forest, the tradition of forest harvesting, and the characteristics of the market are other items that influence the adoption of a system and determine its capacity.

The influence of tree dimension on productivity differs for different types of delimber. Dahlin (1989) indicates that the relation between production capacity and tree dimensions may be as follows:

1. Production capacity is proportional to the square of tree diameter
2. Production capacity is proportional to tree diameter
3. Production capacity is not influenced by tree diameter

Rake delimbers are of little interest under Swedish conditions, since few industries can accept logs with the poor delimbing quality resulting from most rake delimbers. It is noteworthy that the more the knives are adapted to the shape of stems, the more the relation between production capacity and stem diameter approaches relation 1 above (Dahlin, 1989). However, one use of rake delimbers in Nordic conditions might be for 'rough' delimbing, to remove the small branches and needles in the forest. This would minimise the nutrient removal associated with whole tree harvesting, and could perhaps simplify final delimbing, which could be done at the landing or the terminal.

Flail delimbers suffer from some of the problems of rake delimbers, i.e. poor delimbing quality, and they may also excessively damage stems. Considerable work is going on with flail delimbers, and these problems may be solved. Flail delimbers, being more readily adaptable to Nordic conditions, are of greater interest than are rake delimbers.

Most rake and flail delimbers from North America and Australia and New Zealand are intended for systems and handling quite different from those in Scandinavia, in that delimbing residue is usually not utilised. These systems are normally "hot", i.e. felling, extraction delimbing and transport to industry, are very interdependent. Harvesting operations are not generally carried out in this way in Scandinavia, and the implementation of such integrated systems would probably be difficult. The Bruks flail delimber (Jonsson, 1986*b*) can be considered as an adaptation of the technology to Nordic conditions.

Relation 3 above is mainly applicable to drum and cradle delimbers. Thus, these are less affected by the size of the tree and are suitable for processing small-diameter logs. Drums have the advantage that they can be made very large, hence achieve high productivity. However, the shape of the drum makes compact construction difficult. The mobile delimbing drum by Cabro (Wrobelski, 1984; Nordén, 1987) is interesting, since it combines the drum with active delimbing devices.

The flat inner surfaces of the cradle delimber facilitate the use of active delimbing devices. It is most interesting for mobile, semi-mobile and smaller stationary applications. A continuous-feed construction could also be suitable for larger industrial applications. As may be seen above there are various solutions for the design and placement of delimbing devices, how the stems are set in motion, the design of the cradle, etc. The cradle type allows great freedom to consider different aspects and conditions.

Of the drum and cradle delimbers, drums have the greater volume. Cradle delimbers can be constructed more freely and flexibly to suit different conditions and constraints, such as working site, mobility, size. Most of the studies of cradle delimbers, e.g. studies of "Skruven" (Rydin & Österblom, 1969; Bredberg et al., 1975), "the Trough" (Bredberg et al., 1975) and the AC-Invest bunch delimber (Scherman & Nordén, 1983), have dealt with the performance of specific existing designs or prototypes. Very little information on cradle shape, on the delimbing devices that could be used, and on conveyor speed and machine performance, was available when this study began.

Objectives

Acceptance of multiple stem harvesting systems has increased, both because of the decrease in tree size mentioned earlier, and the mechanical capability of harvesting equipment. Conditions in the Nordic countries, with the interest of the forest industry in cut-to-length systems, makes the cradle delimber a particularly appropriate multi-stem processing unit.

The primary aims of this report are to describe, analyse and evaluate multi-stem delimbing of small-sized trees with a cradle-type multi-stem delimber, with respect to delimbing quality, loss of stemwood and efficiency.to aid the development of more efficient cradle delimbers. The following secondary aims may be defined:

- to analyse the delimbing process,
- to study differences between tree species,
- to compare different types of delimbing devices,
- to study the influence of the design of the cradle,
- to study the influence of the speed of the conveyor.

Materials and Methods

Experimental rig

Previous work indicated that the trough was one of the more efficient cradle delimbers. This fact, coupled with the availability of staff experienced in the construction and evaluation of "the Trough" (Bredberg et al., 1975), implies the adoption of this basic design for the test rig (Fig. 3). The design used was

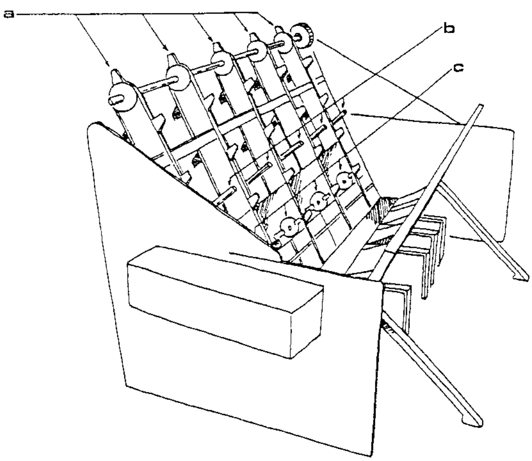

Fig. 3. Design of the experimental rig and its various parts. (a) conveyor, chain with lugs; (b) returning arms; (c) delimbing devices

more flexible than that of the earlier machine. It is longer and is provided with points for attaching active delimbing devices. In addition, the external structure of the device was open, to make it possible to study variables of interest. The rig was made to allow the angle of inclination of both of the long-sides to be changed, and a variable speed drive for the conveyor was included.

Originally, the rig was built with one of the short-sides open, to allow a good view of delimbing. However, during test runs logs stuck fast, broke and were thrown out of the cradle. The inner surfaces were therefore covered with steel plates. It was concluded that the inner surfaces of a cradle should be as even as possible, although some openings must be left, to permit the cut-off branches to leave it.

To keep the logs properly aligned, they should be as long as possible. Conversely, the extraction and handling of long logs with branches, is difficult. The length of the cradle is 4.9 m, chosen as a compromise between these factors. The bottom of the cradle is 0.65 m wide and has an inclination of 15° from the horizontal plane. The height of the short sides is 1.73 m above the bottom. The five returning arms, which are 0.48 m long, are placed 1.45 m above the bottom in the conveyor long-side, and have an angle relative to the conveyor long-side of 131°. The conveyor consists of five chains. On each chain lugs 0.15 m long are mounted. The distance between two lugs on one chain is 0.60 m.

As a source of power, a diesel engine of 105 kW (DIN) was used. The engine was run at 1 600 r/min, and drove two hydraulic pumps. One of the pumps, with variable displacement, drove a hydraulic motor (displacement 929 cm^3/r) connected to the conveyor. The speed of the conveyor was determined by the displacement of the pump, which was varied between 17 and 67 cm^3/r in the study. The other pump, with a displacement of 105 cm^3/r, drove the hydraulic motors connected to the delimbing devices. Each active device had a separate hydraulic motor with a displacement of 39 cm^3/r and a torque of 108 Nm.

Delimbing devices

Four different delimbing devices were studied: fixed knives, open rollers, closed rollers and rotors. The open rollers and rotors were modified, so two versions of each were studied.

The delimbing devices in the study represent different principles regarding design and function. The fixed knives depend on the movement and force of the logs to cut and break off the branches, while rollers and rotors are actively driven. Fixed knives and rollers have previously been used in constructions of cradle delimbers, while rotors are a new concept in this context. Existing constructions have served as the basis for the fixed knives and the two roller types. The fundamental difference between rollers and rotors is the rotation. The rotation of a roller is axial, while that of a rotor is radial.

The speed of rotation of the delimbing devices was in all cases approximately 700 r/min or 12 r/s. This was as fast as the construction safely permitted.

The delimbing devices were mounted into frames fitting into spaces provided between the conveyor chains on the active long-side of the trough. The experimental rig demonstrated that performance of the active devices was best if they were placed as near the bottom of the trough as possible. The edges of all delimbing devices were allowed to extend 5 mm above the conveyor, to give an aggressive delimbing action while keeping stem damage within acceptable bounds. Damage is minimised when the devices are level with or below the level of the conveyor chains. However, delimbing quality decreases. Extending the delimbing devices more than 5 mm beyond chains, results in very aggressive delimbing, but also caused the devices to remove part of the surface of the bole. The devices also tend to push logs off the lugs, resulting in less efficient delimbing.

Resources permitted construction of only two devices of each type, with the exception of the large diameter rotor, which was made in four replicates. The two test devices were mounted in the two centre openings in the cradle, where they would be most efficient; since positions were symmetrical to the centre of the bole, stem orientation would not bias the results (see p. 15).

Fixed knives

The fixed knives are designed similarly to the knives used in the earlier prototype "the Trough" (Bredberg et al., 1975). The knives were made of 10 mm thick steel plate with sharpened teeth, spaced 62 mm apart and with depth 50 mm. The effective cutting width of each knife was 0.88 m (Fig. 4).

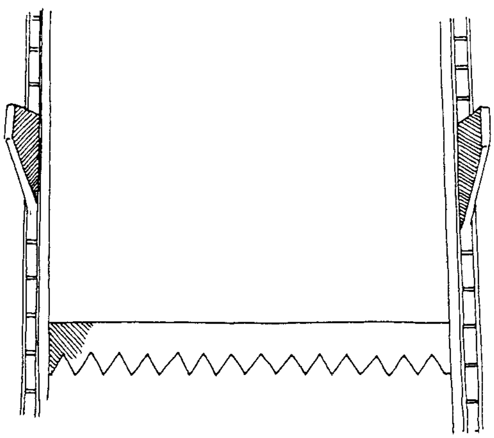

Fig. 4. Fixed knife, delimbing device.

Open rollers—teeth

The open rollers (Fig. 5) are similar to those used on the ÖSA forwarder-delimber prototype (Forslund, 1985). The device is called the open roller because less than one quarter of the circumference of the cylinder behind each knife is closed. This construction results in a very lightweight tool, which was important when the rollers were mounted high on a forwarder. The diameter of each roller is 302 mm, with two diametrically opposed knives provided with teeth 60 mm apart and cut to a depth of 39 mm. The teeth were not sharpened, since the operating motion was expected to wedge the branches between the teeth, then tear them off the stem.

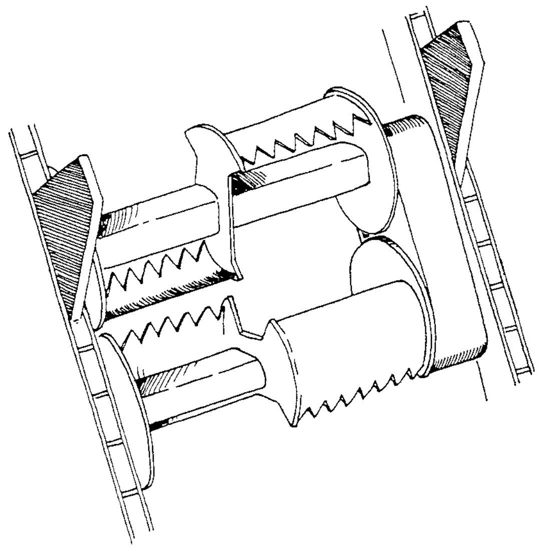

Fig. 5. Open rollers—teeth, delimbing device.

Two of the open rollers were paired within a single frame. The lower roller was driven by a hydraulic motor and connected to the upper roller by a chain drive. The construction permitted both rollers to be operated or, by simply removing the chain, one active and one passive roller could be utilised for a test. The delimbing width for each roller was 570 mm, but because they were not exactly in line, the effective working width for a pair of rollers was 590 mm.

Open rollers—sharp edges

During the study of the open rollers, there was interest in comparing them with similar rollers, but with sharp edges. The teeth of the open rollers were therefore cut off, and sharp edges were made (Fig. 6). No other changes were made, so the same specifications are valid (see p. 15).

Closed rollers

The closed rollers are copies of the devices used in the AC-Invest bunch delimber (Scherman & Nordén, 1983). Two knives were mounted diametrically opposite each other, on a steel roller, 283 mm in diameter. The knives were 12 mm thick and had an edge angle of 55°. The edge extended outward from the surface of the roller for a distance of 19 mm. Ridges or bars, 18 mm high, were attached to the surface of the roller at 90 degrees from the cutting edges of knives and 290 mm apart, to minimise damage to the stem as it passed by the delimbing device. The rollers could not be made to full length, i.e. the width of the frame, as

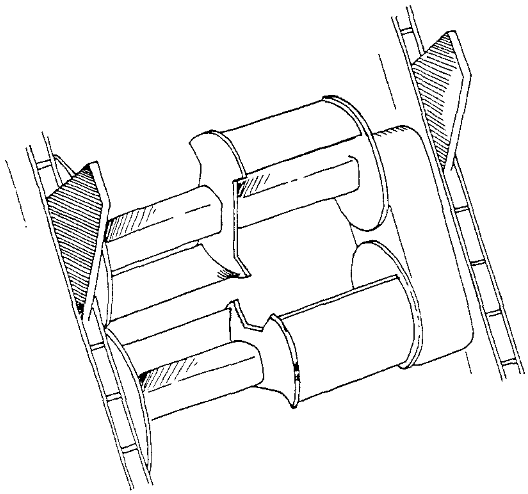

Fig. 6. Open rollers—sharp edges, delimbing device.

space had to be provided for the hydraulic motor. The effective cutting width of each of the closed rollers was 640 mm (Fig. 7).

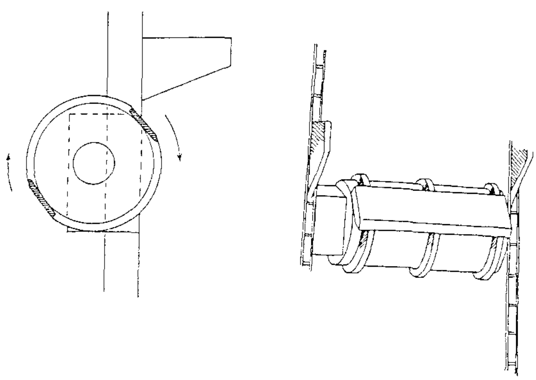

Fig. 7. Closed roller, delimbing device.

The AC-Invest bunch delimber also features another model of roller with rectangular steel profiles instead of knives. According to the manufacturer, those are primarily for debarking and are considered to be less effective for delimbing. For the present study, those rollers are of less interest than those with knives.

Rotors

The function of the rotors used for delimbing is similar to that of a lawn-mower. Two knives are attached to a disk. As the knives can rotate on the pivot, they can retract when exposed to abnormal forces, to prevent damage to the stems or to the knives themselves.

The edges of the knives were ground to angle of 60°. This is greater than the maximum favourable cutting angle for shearing wood (Nurek, 1984), but was a reasonable compromise between shearing capability and safety. There would be an obvious hazard if a part of the edge was broken off and flung away at almost 30 $m \cdot s^{-1}$.

The length of the knives was determined by the working diameter of the disk (the distance between the two pivot points). The distance from the centre point of the pivot to the end of the knife must be slightly less than one half the working diameter of the disk, or the knives will strike each other if they are thrown back towards the disk centre.

Two rotors were made, viz. a small rotor, with essentially the same effective cutting width as the open and closed rollers discussed earlier, and a large rotor to take full advantage of the spacing between the conveyor chains. The small rotor had a total working diameter of 572 mm (distance between the tips of the knives in a radial direction). The disk used to mount the knives had a diameter of 355 mm and a weight of 11.3 kg. The knives were attached 155 mm from the centre of the disk and each knife was 165 mm. The distance between the pivot point and the end top of the knife was 131 mm, allowing 110 mm of the knife to extend beyond the disk when in the radial position. This part of the knife actually cuts the branches. The weight of one knife is 1.3 kg.

The large rotors had a total diameter of 764 mm, with the knives radially extended (Fig. 9). The diameter of the disk in this case was 460 mm and the weight 24.1 kg. The distance between the centre of the disk and the centre of the pivot point for a knife was 195 mm and the knives were pivoted 187 mm from the working tip. Therefore, 152 mm extended beyond the disk radially. Each knife was 221 mm long and weighed 1.8 kg. For both rotors the disks acted as flywheels, the speed of rotation not being appreciably affected by the delimbing forces exerted on the knives.

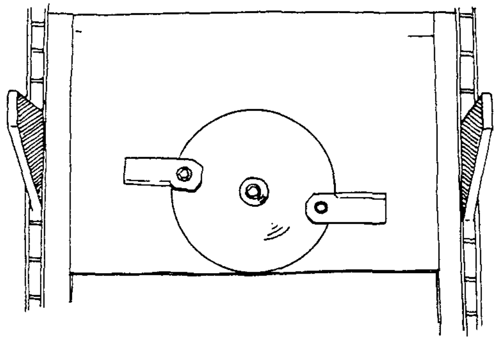

Fig. 8. Rotor—small diameter, delimbing device.

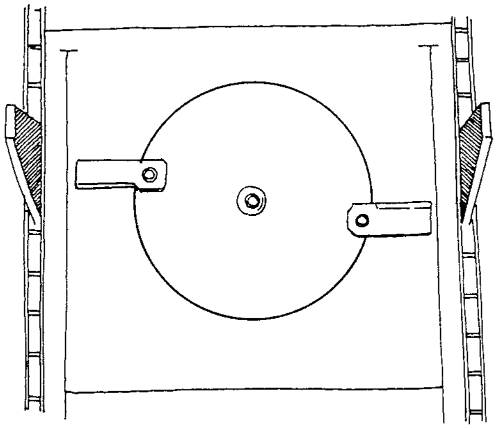

Fig. 9. Rotor—large diameter. delimbing device.

Wood data

Multi-stem delimbers are primarily intended for trees and logs of small dimensions. Therefore, the trees for this work were taken from first thinnings.

Two tree species are represented in the study, Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst). These are the dominant species in the forests of the Nordic countries, and the ones of greatest economic importance.

The delimber was tested at Garpenberg, central Sweden (lat. 60°N, long. 16°E), trees for the test being selected from neighbouring stands. An attempt was made to maintain the properties of the trees and of the stands as constant as possible between trials. The Scots pines were taken from a 34-year-old stand, with an average yield class of about 6 m^3 per ha per year. The spruces were taken from a 32-year-old stand, with an average yield class of 8 m^3 per ha per year. The stands were representative of the average type selected for first thinnings in that region of Sweden (Svensson & Braide, 1987). Some characteristic data of trees and logs are shown in Table 1.

Evaluation criteria

A number of criteria may be used to evaluate delimbing. These could include ergonomic factors, such as noise level, working conditions, monotony and other such influences. Ergonomic factors were little considered in this case, as the machine constructed was a test rig. However, this aspect must be carefully considered by a manufacturer. A manufacturer might also be interested in adapting the delimbing device to a variety of base machines, and to durability and power requirements. This study, however, addressed more fundamental questions. The evaluation criteria chosen for this work are three: delimbing quality, loss of stemwood, and efficiency. These three criteria are related, as discussed below (p. 25). Efficiency can be considered to be the main criterion of evaluation, as it determines the potential for the commercial development of a technique.

Data collection

The routine for preparing, measuring and delimbing the trees in this work is shown schematically in Fig. 10. In the forest the trees were felled, bucked and marked manually. The trees were bucked into approximately 4.5 m long logs, with the exception of

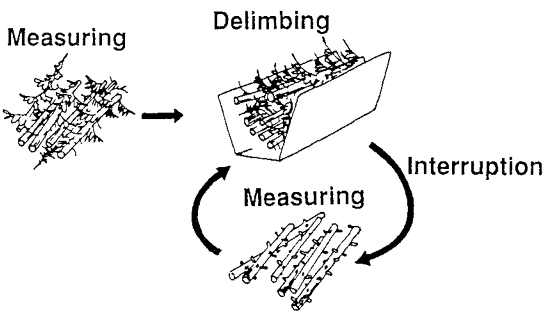

Fig. 10. Scheme of measuring and delimbing.

Table 1. *Data for trees and logs per bunch, mean values and standard deviation*

	Scots pine		Norway spruce	
	Mean	Std. dev.	Mean	Std. dev.
No. of trees per bunch	22	5	12	2
DBH, mm	93	14	103	7
No. of logs per bunch	35	4	25	2
Length of logs, m	4.3	0.1	4.1	0.2
Volume stem-wood per bunch, m^3	0.77	0.18	0.63	0.14
Stem-wood <5 cm, %	8.2	4.2	5.2	2.1

the top, which in most cases was shorter. If the top was less than 2.0 m it was rejected. Log length was set at 4.5 m, because test runs had shown that shorter logs would more often become disaligned and cause trouble. Logs 4.5 m long were judged to be the longest that could be handled in the 4.9 m cradle. Since logs in a bunch do not always stack with the ends in a line, problems in loading the cradle could still arise. These problems had to be solved manually.

The logs were marked to be able to identify all logs from the same tree, and to separate the logs from each other during interruptions in delimbing. All logs from several trees were united in the same bunch. In this way, it is possible to correlate the results with tree-data. Bucked trees were carried by a forwarder to the delimber. To prevent storage and drying from influencing the results, the time between felling and delimbing was kept as short as possible. In most cases it was less than one week. The number of trees in each bunch was chosen so that the bunch filled the cradle. The logs were measured before and during delimbing. For the first bunches, delimbing was interrupted at one-minute intervals. The logs were removed from the cradle, measured and replaced. After several bunches, the number of interruptions could be somewhat reduced, e.g. if from experience, the total processing time could be expected to be about five minutes, the first pause could be made after three minutes instead of after the first minute. Delimbing was halted when more than 75 per cent of the branches cut were shorter than 25 mm. The definition of acceptable delimbing quality is discussed below (p. 13).

Measurements—all logs

Before delimbing, the length of log and diameter at both ends were recorded for all logs. To reduce the effect of butt swell, diameter was measured 0.2 m from the end. For every butt log, DBH (diameter at breast-height), crown height and green-crown height were recorded. During interruptions in delimbing, the loss of stemwood was estimated for all logs. The volume of each log was calculated from the two measured diameters, assuming the shape to be similar to the frustum of a cone.

Measurements—sample logs

Two trees in each bunch were chosen as sample trees. However, sampling was limited to trees giving exactly two logs. Among these trees a randomised sample was taken. Sampling was limited to two-log-trees mainly to obtain a more homogeneous material. Sample trees consequently had a larger DBH than the average tree (cf. Tables 1 and 2).

The logs from the sampled trees, here called sample logs, were measured and recorded more thoroughly than the others. On each sample log four measurement sections were marked, or as many as possible if the log was not of full length. Each section was 0.50 metre long and the distance between two sections was also 0.50 m. The first section started 0.70 m from the end with the largest diameter. The sections were designed in this way to ensure that each section, as far as possible, would be processed by a single delimbing device during delimbing. Test runs had shown that logs tended to align themselves with the thicker end against the short side. This served as the basis of the design. For a log of the full 4.5 m length, each section was almost exclusively delimbed by a single delimbing device. However, if the log were shorter, it might move sideways in the cradle. The design of the sections is illustrated by Fig. 11.

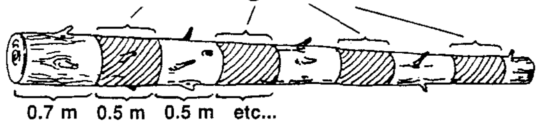

Fig. 11. For sampled logs, sections were marked in which measurements were made.

In each measurement section, every third branch was marked and measured. By measuring only every third branch, the work required for measuring could be restricted. Length, diameter and whether green or

Table 2. *Data for sample logs, mean values and standard deviation*

	Scots pine		Norway spruce	
	Mean	Std. dev.	Mean	Std. dev.
DBH, mm	101	13	110	15
Length of logs, m	4.4	0.1	4.3	0.3
No. of branches per log	40	6	63	12
Branch diam., mm	15	2	11	1
Green branches, %	58	7	68	16
Green branch diam., mm	15	2	11	1

dry were recorded. Diameter was measured 50 mm from the stem. At each interruption of delimbing, the lengths of the sampled branches were remeasured. Because of the marking, it was possible to identify every branch. Table 2 presents the main characteristics of the sample trees and logs.

Sampling can be characterised as a combination of a stratified random sampling (sampling of trees) and a two-phase systematic sampling (sampling of sections and branches).

Computations

Experimental unit

The choice of experimental unit is of vital importance to the analyses. For the analysis of loss of stemwood, the only reasonable choice of experimental unit is the bunch of logs in one batch, since all logs are measured and only a few logs will actually be damaged in each bunch. For the analysis of efficiency, the choice is not as self-evident. However, the bunch, represented by the two sample trees, was also used in this case.

The use of another experimental unit, when analysing efficiency, would have caused problems related to correlations within bunches and, additionally, the handling loss of experimental units due to damage. For instance, each log of the sample trees can be used as an experimental unit, but would result in increasingly complex statistical analyses necessitating the use of a mixed model.

Dependent variables—delimbing result

When comparisons and evaluations are made for delimbing, three factors are of primary importance: efficiency (or productivity), delimbing quality and damage. For most multi-stem delimbers, these three factors are intimately interrelated. Productivity, as well as delimbing quality and damage, depends on processing time. The processing time is the time it takes to delimb a bunch of logs. But it is difficult to decide when to consider the bunch adequately delimbed. Productivity, defined as production per time unit, depends on the definition of an acceptable delimbing quality.

There is no obvious way of defining delimbing quality. A common way of specifying quality in studies similar to this, is to weigh the logs before delimbing, after delimbing and finally after additional trimming if necessary. In this way it is possible to specify delimbing quality as the proportion of branches removed (Helgesson, 1977; Scherman & Nordén, 1983; Jonsson, 1986b). However, this way of defining quality demands thorough sorting of rejects into branches, bark and stemwood, to obtain the correct figures for quality and damage. Other ways of expressing delimbing quality may be the average or median length of remaining branches, or the relative frequency of branches longer or shorter than a specified value (Bredberg et al., 1975). The most natural way would be to relate the definition to the standards set for pulpwood, as this is what a multi-stem delimber will be processing most of the time. However, since the standards for pulpwood in Sweden are defined for a single log (Anon., 1979) and since the result of multi-stem delimbing is bound to differ between logs, this is not very appropriate. It is also stated in the pulpwood definition that logs with a branch stub longer than 80 mm shall be rejected. To adopt this definition would cause substantial problems in evaluating delimbing quality. For instance, if one branch stub remains which is difficult to remove, e.g. a branch with an acute angle, when should the bunch be considered to have an acceptable delimbing quality? Should one wait for this sole branch stub to be removed? This would not be very realistic. A better solution could be to decide on an acceptable distribution, such as that a certain percentage of the branches should be shorter than a specified length. The values chosen for the percentage and for branch length could be adjusted for different conditions.

In this work, the main standard for acceptable delimbing quality is defined as that 75 per cent of the branches should be shorter than 25 mm. Delimbing quality is estimated from measurements of the sampled branches. The subjective impression was that this measure of quality is compatible with what can generally be considered an acceptable delimbing quality. The processing time required to achieve this quality, is the main result variable in the work, and has been obtained by linear interpolation from two successive interruptions. Note that this is an estimate, not of productivity, but of efficiency. Productivity can be obtained by dividing the volume of a bunch by the processing time. There are three main reasons for using efficiency rather than productivity: (1) Delimbing time is an easier unit to understand than is volume per unit time. (2) Productivity readily gives the impression that all parts of the process are included, which in this case is not true. The delimbing process itself is included, not the loading or unloading of the delimber. (3) Productivity may be unfairly influenced by one or a few trees with large volumes in a bunch, although efficiency is not affected. Thus, efficiency is likely to be a better variable than productivity in a study such as this.

A few bunches were especially studied with regard to the length distribution of branches at the time when the defined delimbing quality is attained. The figures are from the interruption closest to the calculated delimbing time. This should give the correct average, but will make the longer lengths slightly preponderant. Fig. 12 illustrates the result, and shows a fairly regular distribution, except for the small excess at +20 cm. On closer examination, this appears to originate partly from bunches delimbed with fixed knives. Difficulties occurred with fixed knives when coarse branches with an acute angle were involved, but some of the excess is derived from bunches with the shortest delimbing time. This is discussed below (p. 24).

In this study, damage has the restricted meaning 'loss of stemwood'. It is derived from the measurements in the pauses of delimbing. As all logs are measured, it is possible to estimate the loss from all logs, not from the sample logs only. If a log is damaged or broken, the amount of missing stemwood or the present length of the log is recorded. The present volume of all logs can be calculated and the loss estimated. It is necessary to relate the loss of stemwood to a delimbing time, as the loss increases with longer processing time. However, to obtain a fair comparison, the delimbing time of interest is taken to be that at which the required delimbing quality is attained. Thus, loss of stemwood is estimated at the time when 75 per cent of the branches have been cut shorter than 25 mm. This value has also been obtained by interpolation.

Statistical methods

For evaluating the results, appropriate statistical methods must be selected. Primarily, standard analysis of variance (ANOVA), in most cases two-by-two factorial analysis, and where appropriate, regression analysis have been used. In conjunction with the analyses, normal tests of inference have been made, such as the F-test and Student's *t*-test. In the analysis of the delimbing process other analytical methods have been used, but are presented in connection with the results. The SYSTAT statistical package (version 4.0 for MS-DOS) was used for the computations. The significance levels used are the following: * more than 95 per cent, ** more than 99 per cent and *** more than 99.9 per cent.

Experimental design

A major problem in designing studies such as this, is to obtain results that shed light on the specific questions asked. To achieve this, given a material over which full control is impossible (trees), various means may be considered, alone or in combination. The material may be kept as constant as possible, the material may be randomised, experimental control may used (the disturbance factors are included as treatments) and finally statistical control may be used.

To use randomisation alone to control the variation of the material, would require a very large material to obtain small standard errors of the estimates. Since the sampling method is quite demanding, in respect both of time and work, the resources available did not permit sampling of a very large material. Difficulty in identifying and categorising factors that determine the delimbing difficulty of a tree, makes the method of experimental control very hard to use. However, tree species, which is easy to identify and categorise, is included as a treatment. The intention has been to have rather few observations, while using a material as homogeneous as possible and, if necessary, to control differences in the material by statistical methods.

The experimental design may be considered to consist of two principally different parts:

1. Comparison of different delimbing devices
2. Study of the influence of cradle design

The experiments were conducted as follows: first, a number of delimbing devices was compared in a series of experiments with a fixed cradle design. Secondly, a number of different machine design variables was studied, using the delimbing device with the best performance according to the first series of experiments. Material from both series is used to study the delimbing process and the influence of tree properties. What follows is a presentation of the variables of classification and the categories or levels chosen in this work.

Delimbing process

For a sample of the bunches the delimbing process was more explicitly examined (Table 3). The data had to be somewhat reorganised to make possible a closer examination of the material, since the records from each interruption are used as observations.

Beside the ordinary measurements, a box with an opening area of 0.2 m^2 was placed beneath one of the centre sections to provide an estimate of the amount of debris produced per unit time. The debris was sorted by size and weighed after every minute's delimbing. This was done for two bunches only of each tree species. The delimbing devices were open rollers with edges and the conveyor speed was 1.0 $m \cdot s^{-1}$.

Table 3. *Experimental design for the study of the delimbing process, number of bunches*

Delimbing device	Tree species: Scots pine	Norway spruce
Open rollers, edges		
speed of conveyor, m·s^{-1}		
1.0	3	3
1.5	2	2
1.9	2	2
Rotors, small diameter		
speed of conveyor, m·s^{-1}		
1.0	4	4
large diameter		
speed of conveyor, m·s^{-1}		
1.0	4	4
1.5	4	2
1.9	4	2

For some of the bunches, a camera equipped with a motor was used to record delimbing, at intervals of one second. Originally, the intention was to achieve an exact description of the movement of the logs. But as stated above (p. 8), the open design of the cradle had to be abandoned and the openings covered. Consequently, the delimbing could not be photographed from the short side, which would have given the best view. Instead, photographs were taken from a position above and beside the delimber, down in the cradle.

Tree properties

Many tree properties affect the delimbing process. It is most likely that several factors interact. However, this work is mainly concentrated on technical factors, the aim being to keep tree properties as constant as possible. The only conscious variation is that two tree species, Scots pine and Norway spruce, were tested. Both tree species are represented for all other variables of classification. Thus, it should be possible, not only to discover differences between species, but also to discover whether or not there are interactions between species and other variables.

Delimbing devices

As mentioned above (p. 9), only the two delimbing devices in the centre were shifted. The outer ones were always rotors with the large diameter. To reveal the effects of the two centre devices, only the two measuring sections in the centre of a log are included when comparing different delimbing devices. Although the logs may move somewhat sideways in the cradle, the probability is high that most of the delimbing of the centre sections is carried out by the two devices in the centre. The probable effect of this is that differences in results between different devices will be smaller and more difficult to detect, than if all four devices had been shifted.

The studies of the delimbing devices can be characterised as a series of consecutive comparisons, to be able to identify one or a few devices as superior. The number of bunches delimbed by each device is presented in Table 4. For each delimbing device both tree species are represented. First, there is a comparison between passive delimbing devices—the fixed knives—and active delimbing devices—the remainder. The question then arises, as to what would be the most appropriate device with which to compare the fixed knives. The active device most resembling the fixed knife is the open roller with teeth, although the teeth of the roller were not sharpened. The fixed knives were compared both with the toothed open rollers and with all active devices.

Table 4. *Experimental design for the studies of delimbing devices, number of bunches*

Delimbing device	Tree species: Scots pine	Norway spruce
Fixed knives	3	3
Open rollers, teeth		
single	2	2
double	2	2
Open rollers, edges	3	3
Closed rollers	3	3
Rotors		
small diameter	4	4
large diameter	4	4

To estimate the effect of having several successive devices in the conveyor long-side, a comparison was made in which one or both of the two open rollers in a frame was active. As mentioned above (p. 9), the blunt teeth with which the open rollers originally were provided, were cut off and replaced with sharp edges. These two types of edge were compared. The two rollers, open and closed, available for this study were quite different in design. The two were compared. The open rollers with sharp edges were chosen for the comparison with the outcome of the previous experiment.

The result of this experiment led to the choice of using the open rollers with sharp edges to study how rollers and rotors differ in performance. The small rotors were used in the experiment, to give a fair comparison in respect of the active width of the devices. Rotors were made in two versions, with different diameter. A comparison was made of the effect of diameter.

Cradle design

Several variables of the cradle design may be expected to influence delimbing. The following may be mentioned as examples:

- Inclination of conveyor long-side
- Inclination of long-side opposite to conveyor
- Length of the cradle
- Height of the cradle
- Width of the bottom
- Inclination of the bottom
- Speed of conveyor
- Design of conveyor

Some of these factors are very difficult to alter once the cradle has been constructed, e.g. the length and height of the cradle and the design of the conveyor; therefore a choice had to be made in the initial stages of construction, based on experience from earlier construction. The variables judged to be most important were studied, viz.

- Inclination of conveyor long-side
- Inclination of the long-side opposite to conveyor
- Speed of the conveyor

The inclination of the conveyor long-side may be expected to influence delimbing in two ways. (1) The movement of the logs will differ when the geometry changes and the pressure of logs towards the conveyor and delimbing devices will change. (2) The inclination of the long-side opposite to the conveyor should influence the movement of the log in the cradle as well. Both of these variables also determine the inner volume of the cradle and limit the maximum size of one bunch of logs. As default values, both long-sides have an inclination of 28°. This angle was chosen with experience from the earlier prototype "the Trough" in mind. In the present study, the conveyor long-side was studied at gradients of 23° and 38°, beside the 28° inclination. These values were chosen because they still seemed to be realistic, and yet different enough from the default value to result in detectable differences. The design of the experiment is presented in Table 5.

The intention was to study the long-side opposite to the conveyor at a gradient of 38°, in addition to 28°. A greater angle is interesting, as this provides a larger volume inside the cradle. However, during delimbing of the first bunch at 38°, the process had to be stopped on several occasions, because logs jammed. On every occasion the logs had to be removed from the cradle to release the jam. A second bunch was run, but as the same problems occurred again, this experiment was discontinued.

The speed of the conveyor will probably influence the required delimbing time, as also the amount of damage and loss of stemwood. The default value for conveyor speed is 1.0 $m \cdot s^{-1}$. As complements to the default value, 0.6, 1.5, 1.9 and 2.3 $m \cdot s^{-1}$ were chosen. A speed of 2.3 $m \cdot s^{-1}$ is as fast as the equipment safely permits for pine. The results indicated that it was not necessary to study 0.6 and 2.3 $m \cdot s^{-1}$ further, and in the following studies, only the conveyor speeds 1.0, 1.5 and 1.9 $m \cdot s^{-1}$ were studied. As a further complement, the speed of the conveyor was altered for the open rollers. The design of the experiment is presented in Table 6.

Table 5. *Experimental design for the study of the influence of the inclination of the conveyor long-side, number of bunches*

	Inclination, °		
Tree species	23	28	38
Scots pine	2	4	2
Norway spruce	2	4	2

Table 6. *Experimental design for the study of the influence of the speed of the conveyor, number of bunches*

	Speed of conveyor, $m \cdot s^{-1}$				
Delimbing device	0.6	1.0	1.5	1.9	2.3
Open rollers, edges					
Scots pine	–	3	2	2	–
Norway spruce	–	3	2	2	–
Rotors, large diam.					
Scots pine	4	4	4	4	4
Norway spruce	–	4	2	2	–

Results

Delimbing process

Multi-stem delimbing is much more of a stochastic process than single-stem delimbing. The distribution of diameters and lengths of the logs, their positions, movements and interactions during delimbing are examples of factors that to a large extent, when considering a specific bunch, can be considered stochastic. Therefore, in the process of delimbing there is a stochastic factor that can be controlled only by statistical means.

From the photographs of delimbing, it is not possible to follow the movements of single logs. However, the bunch as a whole can be observed. From the series of photographs and from direct observations, the following subjective description of the delimbing process in general was constructed. Initially, the logs are interlocked by their branches, and the bunch behaves as a bundle. As delimbing progresses, logs become detached from the bundle, and finally, all logs act as 'individuals'. The duration of the bundle phase is much longer for Norway spruce than for Scots pine, probably because of the greater branchiness of spruce, which makes for stronger interlocking.

When the proportion of branches shorter than 25 mm is plotted against delimbing time, the development can be detected to have an 'S' shape (cf. Fig. 14). The pattern is the same if 50 mm is chosen instead of 25 mm, only the level of the curve being different.

The curve may be divided into three phases. In the initial phase of the process, branches are cut or broken at half their length and only a small proportion of them is cut shorter than the specified length. This phase is not very well illustrated by the figure, as the large rotors are comparatively efficient, and this phase is very short. For less efficient configurations of machine variables, this phase can be clearly detected. In phase two, branches are more exposed and an increasing proportion is cut or broken close to the stem. In the third phase, the amount of branches delimbed per unit time begins to decrease, and the line levels out.

The impression from this might be that delimbing is not as efficient at the beginning of the process. But the source of inefficiency is that branches are not cut close to the stem. If Fig. 14 is compared with Fig. 13, which shows the amount of debris, a contrast may be seen at about the initial stage. The amount of debris is at its highest at the beginning, declining with time. Furthermore, the debris contains a large proportion of large pieces at the beginning, the proportion of small and very small pieces gradually increasing. The conclusion must be that most of the branch is removed at the beginning of the delimbing process, and that delimbing tends to become more an adjustment of the length of branch stumps at the end of the process.

To model the delimbing process, several 'S'-shaped functions are available and might be considered. In this study, an exponential type of function was found best to describe the delimbing process. The function reads as follows:

$$Y = 1/(1+e^{(\alpha+\beta\cdot ln(t))})$$

where Y = proportion of branches cut shorter than 25 mm at time t;
t = delimbing time, min.;
α, β = coefficients;

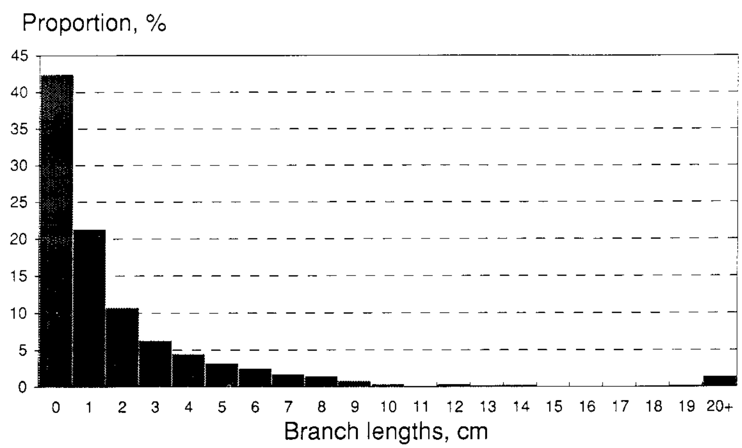

Fig. 12. Distribution of length of branches at the time when 75 per cent of the branches are shorter than 25 mm. For Scots pine and Norway spruce and various delimbing devices. 16 bunches.

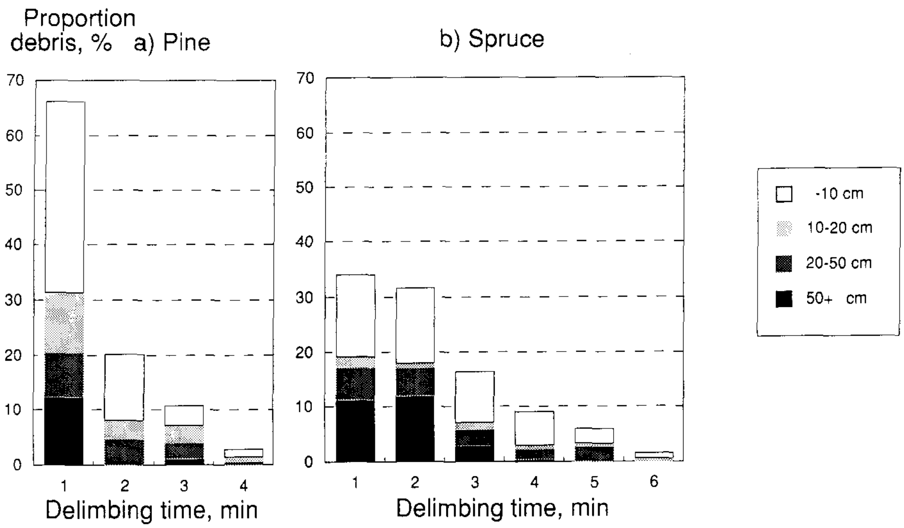

Fig. 13. Proportion of debris produced during each minute of delimbing. The bars are also divided by the size of the debris. (a) Scots pine (b) Norway spruce.

The logarithm of time was used because this transformation causes the function to pass through origo. Although no values for time equals 0 are included, it is evident that the values for that time should be zero for all cases. As the function is applied to the results, the values listed in Table 7 are obtained.

As the function is non-linear, it was not possible to use standard regression analysis. The function was solved by a standard non-linear procedure. Fig. 14 illustrates the function for two different configurations. The estimated curves fitted the original values quite well. The r^2-values were almost consistently lower for pine than for spruce, compared at the same configuration. This could be due to the fact that the logs of pine are not as attached to each other, and the first phase of delimbing is much shorter. Thus, at the beginning of delimbing, the delimbing quality will differ much between the logs in the same bunch. The variation between logs diminishes as delimbing proceeds. When the defined delimbing quality is reached, no difference between the two species, as regards variance, could be detected (cf. Table 9).

It was more difficult to fit any function to the development of the loss of stemwood. The results seemed more stochastic, as is revealed by the large variance. However, here also there was a tendency

Table 7. *Results of applying the function $Y = 1/(1+e^{(\alpha-\beta \ln(t))})$ to the delimbing results for various configurations. Y = proportion branches cut shorter than 25 mm at the time t; t = delimbing time, min; α, β = coefficients; SoC = speed of conveyor, $m \cdot s^{-1}$*

Configuration		α	β	r^2 (adjusted)
Open rollers, edges				
SoC 1.0	S. pine	1.714	−2.311	0.972
	N. spruce	4.486	−3.639	0.947
SoC 1.5	S. pine	0.084	−1.355	0.583
	N. spruce	1.961	−2.873	0.891
SoC 1.9	S. pine	0.723	−1.597	0.630
	N. spruce	1.898	−2.629	0.994
Rotors, small				
SoC 1.0	S. pine	3.250	−3.386	0.497
	N. spruce	2.672	−2.402	0.888
Rotors, large				
SoC 1.0	S. pine	0.641	−2.218	0.783
	N. spruce	1.786	−2.288	0.926
SoC 1.5	S. pine	−1.023	−2.288	0.795
	N. spruce	3.800	−6.329	0.976
SoC 1.9	S. pine	−0.477	−1.777	0.592
	N. spruce	0.886	−2.177	0.593

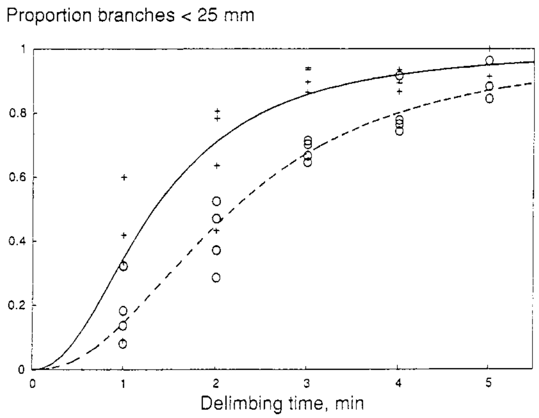

Fig. 14. Fitted exponential functions for Scots pine and Norway spruce, for large rotors and speed of conveyor = 1.0 $m \cdot s^{-1}$. The original values are indicated. + = pine, o = spruce.

towards an 'S'-shaped process. Little was lost at the start, but as the covering branches were removed, an acceleration in the rate of loss could be detected. Finally, this rate seemed to decline. This could be due to the fact that most top logs, the pieces that most easily break, have already broken and left the cradle as breakage. However, for some configurations of the independent variables, this stage was never reached, since the defined delimbing quality was attained at an earlier stage. Consequently, the loss of stemwood in those cases was small.

There was a strong correlation between loss of stemwood and the required delimbing time. In a regression analysis of the loss of stemwood, required delimbing time proved to be a highly significant variable (see p. 21). The result is presented in Table 8. The loss of stemwood could be placed in perspective by comparing it to the percentage of stemwood with a diameter less than 5 cm. Since 5 cm is normally the minimum top diameter in Sweden, this volume is an addition to what should have been utilised with conventional methods. For the most efficient configurations (e.g. see Fig. 17), the level of loss of stemwood was below or close to the percentage of stemwood with a diameter less than 5 cm (cf. Table 1). Thus, the volume of stemwood was in those cases at least equal to what should have been obtained by conventional delimbing methods. Furthermore, the breakage and the debris can in many cases be utilised, some for pulp and the rest for fuel.

Tree properties

Tree species

The two species in this study, Scots pine and Norway spruce, differ in many ways. The number of branches differs and so does their shape, angle, placement, etc. Wood properties in the branches also differ, pine branches appearing to be more brittle than spruce branches. The differences also showed in the results, especially for the different delimbing devices. As a rule, spruce required a longer delimbing time than pine, to reach the same delimbing quality (Fig. 15). If

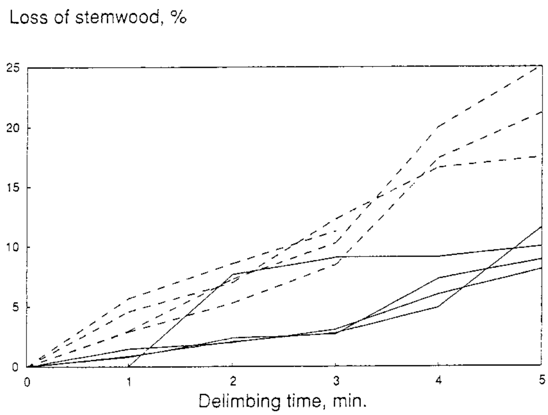

Fig. 15. Loss of stemwood, as percentage of the initial volume of stemwood in a bunch, over delimbing time. For Scots pine and Norway spruce, large rotors, speed of conveyor = 1.0 $m \cdot s^{-1}$. - - - = pine, ---- = spruce.

productivity is compared, the difference between the species increases, as the bunches of spruce contained a smaller volume of stemwood (cf. Table 1).

Table 8. *Result of regression analysis for the influence of different variables on the loss of stemwood.* $n = 42$. *Model:* $LoS = constant + a_1\ type + a_2\ speed^2 + a_3\ time$, $r^2 = 0.45$. LoS = *Loss of stem-wood, %; type = dummy for delimbing device: small rotor = 1, large rotor and roller = 0; speed² = square of the conveyor speed,* $m \cdot s^{-1}$*; time = delimbing time when 75% of branches <25 mm, min.;* a_i = *coefficients*

Variable	Coeffic.	Std. err.	*t*-value	Prob.	Sign.
Constant	−3.85	2.88	−1.34	0.190	–
Type	−5.06	1.81	−2.78	0.008	**
Speed²	3.02	0.72	4.16	<0.001	***
Time	2.70	0.64	4.18	<0.001	***

To delimb pine primarily, great force is needed to break off the branches. Study of the different edges of the open rollers showed that a sharp edge did not contribute significantly to the efficiency of delimbing pine. However, a sharp edge will first make a cut into the branch before the branch breaks off, or cut it all the way through, whereas with a dull edge, it will break all the way. Branch stubs are therefore more ragged when a dull edge is used. For the fixed knives, which have no force of their own, the difference in required delimbing time between pine and spruce was clearly less than for the other devices, which illustrates the importance of the force needed to delimb pine.

For spruce, the conclusion must be that, in addition to a force, a sharp edge is essential to achieve efficient delimbing. Comparisons of the two species showed that the volume of branches was larger for spruce. When the cradle is filled, it contains 21 per cent more stemwood for pine, the difference being mainly ascribable to the difference in branchiness. There was 32 per cent by weight more spruce than pine debris.

Other tree properties

It was not possible to detect significant effect of tree properties other than species or the results for the bunches. The average values for the bunches were too similar. But when logs and branches within the same bunch were compared, differences could be seen. As might be expected, dry branches could be removed faster than green, and coarse branches required a longer time than fine. Top logs required a longer delimbing time than butt logs, probably because of the larger proportion of green branches on the top log, but also because of the lower weight of the top logs, which led to a relatively lower pressure of the logs against the delimbing devices. Branch angle appeared to be another factor of importance, as it proved to be difficult to obtain a short branch stump when branch angle was extremely acute.

Delimbing devices

The main results of delimbing with the different delimbing devices are presented in Table 9. The results of the statistical analyses are presented below.

Passive versus active devices

The fixed knives differed from the other devices in the sense that they are passive and non-movable, while the others are active, having a momentum of their own. Passive devices have the advantage of being more simple to construct and maintain, and of not requiring a power supply.

The results of the ANOVA (Table 9) show that the active device open rollers with teeth, were significantly (*) more efficient than the passive, fixed knives. The figures for active devices are derived from the open rollers with teeth. When the average for all the active devices was compared to that for the fixed knives, the difference was greater (***) and the interaction of type and species was also significant (*). The latter finding depends on the result that fixed knives were comparatively less efficient in delimbing pine than spruce. Except for the large rotors, all active devices had a length of about 0.6 m, while the fixed knives were 0.88 m long; the total delimbing length varying from 2.7 m to 3.3 m, being therefore ca 22 per cent longer for the passive devices. Since this favours the passive devices, the difference in efficiency is bound to be underestimated.

Table 9. *Results from delimbing with various delimbing devices. Only the two centre measuring sections are included. n = number of bunches, mean = estimated mean value, s.e. = standard error of estimate*

	Delimbing time, min.						Loss of stem-wood, %			
	Pine			Spruce			Pine		Spruce	
Delimbing device	*n*	mean	s.e.	*n*	mean	s.e.	mean	s.e.	mean	s.e.
Fixed knives	3	5.49	0.48	3	8.59	0.73	17.9	3.7	12.1	3.5
Open rollers, teeth										
single	2	3.86	0.03	2	6.88	0.52	7.2	4.0	9.2	2.0
double	2	3.55	0.30	2	7.38	0.52	11.9	5.5	19.8	5.2
Open rollers, edges	3	4.30	0.06	3	5.89	0.08	13.5	1.4	13.9	3.7
Closed rollers	3	3.93	0.54	3	7.46	0.22	15.0	3.8	16.8	3.6
Rotors,										
small	4	3.55	0.08	4	5.51	0.13	4.8	1.1	4.4	1.0
large	4	2.25	0.31	4	4.17	0.17	7.9	0.5	7.8	0.5

There was no difference in loss of stemwood between the fixed knives and the open rollers with teeth. When fixed knives were compared with all active devices, the loss of stemwood was higher (**). This was not expected, as the greater aggressiveness of the active delimbing devices could be expected to cause more damage to stems. This result may be explained by the longer processing time required for fixed knives. The relation between the required delimbing time and loss of stemwood is discussed above (p. 19).

Single versus double devices

A question of interest is whether, as compared with one device, several successive delimbing devices placed in the conveyor long-side will improve the results? The open rollers were constructed in such a way that this hypothesis could be tested.

An analysis of the results (Table 9) shows no significant difference between single and double rollers in delimbing time or loss of stemwood. As the double rollers were not quite in line, the effective delimbing length was 40 mm (1.5 per cent) longer, which should make no difference. No difference in the loss of stemwood was observed.

The conclusion of the experiment must be that little or nothing would be gained by placing several delimbing devices in series in the conveyor long-side.

Open rollers, teeth versus open rollers, edges

The open rollers were originally made with teeth and without sharp edges. These rollers were compared with the rollers in which the teeth had been cut off and replaced by a straight, sharp edge.

There was a large (Table 9) and significant (***) difference in the required delimbing time between the two types of edge for spruce, the sharp edges being the more efficient, while the difference was smaller for pine, and in favour of the teeth. There was no significant difference in loss of stemwood.

The purpose of the teeth is that branches will become fixed between the teeth and be pulled off. However, there was no sign of branches' having been pulled off.

Open rollers, edges versus closed rollers

The results (Table 9) indicate that there was a significant (*) difference in delimbing time between open and closed rollers for spruce, while the difference for pine was smaller. It is noteworthy that although the large difference for spruce was to the advantage of open rollers, the closed rollers had the shorter delimbing time for pine. There was no significant difference in loss of stemwood between the two types of roller.

Rollers versus rotors

For the comparison of rollers and rotors, the rotors with the smaller diameter and the open rollers with sharp edges were used. This was done to make the delimbing width of the devices as equal as possible.

The required delimbing time was significantly (***) shorter for the rotors compared to the open rollers with edges, but the difference was not great for spruce. The rotors had a considerably smaller stemwood loss (***).

Rotors, small diameter versus large diameter

The difference in delimbing time for the two rotors (Table 9) was greater (***) than expected, at least if only the difference in active delimbing width is considered. The loss of stemwood was significantly (**) less for the small rotors.

Cradle design

Inclination of the conveyor long-side

The conveyor long-side was studied in three different positions. The results show that a very upright position of the long-side increased delimbing time (Fig. 16). This is probably due to the decreased force of the logs on the delimbing devices. A log weighing X kg transported by the conveyor exerts a vertical force of X kg·g, where g is the acceleration of gravity ($\approx$9.8 m·s^{-2}). A log with a mass of 50 kg exerts a vertical force of 490 N. The vertical force may be divided into two other forces, one parallel to the long-side and the other perpendicular to it. The latter may be expresse-

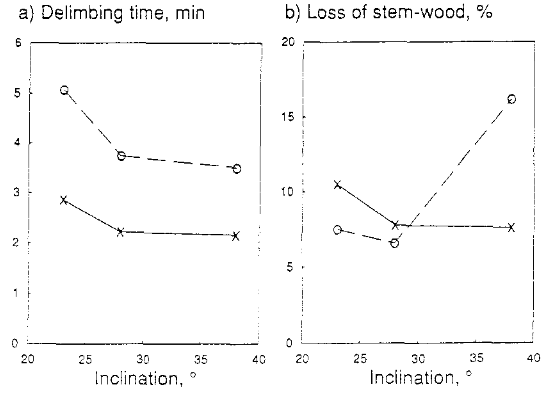

Fig. 16. Required delimbing time (a) and loss of stemwood (b) for various inclinations of conveyor long-side. x — x = pine, o - - o = spruce.

das the mass of the log multiplied by the sine of the angle of inclination of the conveyor long-side. This force is important for two reasons: first, it determines the pressure of the log on the delimbing devices and secondly, it determines the force required to push a log off the conveyor. If the second of these is too small, a log often will be pushed off the conveyor before it reaches the delimbing devices. The most probable conclusion from the results is that the optimum is somewhere between 28° and 38°. According to the regression analysis, the optimum for delimbing time is a little over 30° (Table 10).

Beside the forces described here, which may be characterised as single-stem and static forces, there are dynamic forces and forces originating from the other logs in the bunch. Those forces are more difficult to estimate. The dynamic forces would mostly work in the opposite direction, i.e. pushing the log off the conveyor, while each log in the bunch tends to push the other logs from itself, thus increasing the force towards the conveyor long-side.

The movements of the logs in the cradle during delimbing are very important to the results. At the greater inclination of the conveyor long-side, tumbling was clearly disrupted. Logs at the top of the conveyor, returning to the bottom of the cradle, fell on logs on their way up, often pushing them off the conveyor. This was more apparent for spruce, where logs are more attached to each other. An indication of this disorderly movement of logs was that the loss of stemwood was greater at the 38° inclination for spruce. The inclination also affects the transverse distance in the cradle (the distance between the long-sides). An increased transverse distance makes it easier for the logs to lose their correct alignment and to break.

Speed of conveyor

Five different speeds of the conveyor were studied: 0.6, 1.0, 1.5, 1.9 and 2.3 $m \cdot s^{-1}$. The speed of the conveyor played a significant part, both for delimbing time and loss of stemwood, as can be seen in Fig. 17 and Table 11.

The optimum conveyor speed, with regard to efficiency, seems to be quite close to 1.5 $m \cdot s^{-1}$, probably a little more rather than less (according to the fitted model in Table 11, it was 1.7 $m \cdot s^{-1}$). It was approximately the same for pine and spruce. For minimising the loss of stemwood, the optimum speed of the conveyor can be estimated for pine to be close to the optimum speed with regard to efficiency, while for spruce, the picture was not as distinct. For rollers and spruce, the same pattern as for pine could be detected, while for rotors and spruce the loss of stemwood was least at the lowest speed, although the difference was not very great.

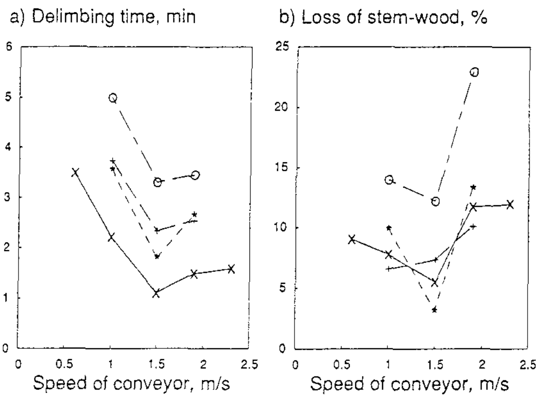

Fig. 17. Required delimbing time (a) and loss of stemwood (b) for various speeds of conveyor, mean values. x---x = rotors, pine, +-- --+ = rotors, spruce; * - - * = rollers, pine; o -- - -- o = rollers, spruce.

Table 10. *Result of regression analysis for the influence of the inclination of conveyor long-side. n = 16.*
a) Required delimbing time, Model: Dt = a_1 *constant+*a_2 *incl+*a_3 *incl*^{2}*+*a_4 *species,* $r^2 = 0.88$
b) Loss of stem-wood. Model: LoS = b_1 *constant+*b_2 *species+*b_3 *species incl,* $r^2 = 0.25$.
Dt = required delimbing time, min.; LoS = Loss of stem-wood, %; incl = inclination,; species = dummy for species, pine = 0, spruce = 1; a_i, b_i *= coefficients*

Variable	Coeffic.	Std. err.	*t*-value	Prob.	Sign.
a					
Constant	15.55	3.40	4.58	0.001	***
Incl.	−0.82	0.22	−3.64	0.003	**
Incl^2.	0.01	0.00	3.37	0.006	**
Species	1.65	0.18	9.39	<0.001	***
b					
Constant	8.30	1.38	5.99	<0.001	***
Species	−18.41	7.69	−2.39	0.032	*
Incl. species	0.66	0.25	2.60	0.022	*

Table 11. *Result of regression analysis for the influence of the speed of the conveyor. n = 42.*
a) Required delimbing time,
Model: Dt = a_1 *constant+*a_2 *speed+*a_3 *speed*^{2}*+*a_4 *species+*a_5 *type,* $r^2 = 0.82$*,*
b) Loss of stem-wood.
Model: LoS = b_1 *constant+*b_2 *speed+*b_3 *speed*^{2}*+*b_4 *type+*b_5 *speed species,* $r^2 = 0.37$*.*
Dt = required delimbing time, min.; LoS = Loss of stem-wood, %; speed of conveyor, $m \cdot s^{-1}$*; species = dummy for species: pine = 0, spruce = 1; type = dummy for delimbing device: rollers = 0, rotors = 1;* a_i*,* b_i *= coefficients*

Variable	Coeffic.	Std. err.	*t*-value	Prob.	Sign.
a					
Constant	8.20	0.76	10.72	<0.001	***
Speed	−6.79	1.10	−6.14	<0.001	***
Speed^2	1.93	0.38	5.10	<0.001	***
Species	1.35	0.19	7.30	<0.001	***
Type	−1.13	0.19	−6.03	<0.001	***
b					
Constant	23.6	6.4	3.71	<0.001	***
Speed	−22.0	9.2	−2.40	<0.022	*
Speed^2	8.6	3.1	2.74	<0.010	**
Type	−4.4	1.6	−2.86	<0.007	**
Species	2.4	1.1	2.30	<0.027	*

Discussion

Methods

Measuring methods

The measuring methods used were rather time-consuming, and could be simplified without greatly reducing the quality of data. The number of measured branches in each measuring section and of each sample log could be decreased, while the number of sample logs per bunch could be increased. This would reduce the influence of broken sample logs. If the aim is to determine the delimbing time required to achieve a certain delimbing quality, the number of interruptions for measurement during delimbing could be reduced if they were adapted to the process. However, this will give a poorer material for estimation of the delimbing process over time.

Experimental design

At the initial stage of this study, there was some hesitation as to whether to design the experiment as a large matrix, with all factors included, or whether to make a number of experiments, with a few factors in each. A completely balanced experiment, containing all factors at all levels was out of the question, as this would have increased the number of bunches that had to be run, to more than resources would permit. Even an unbalanced design would have meant a large number of bunches. The aim of the design used was first, to compare different delimbing device, then to study the other machine variables. By making a series of experiments, it is possible to add extra experiments during the work, while if a single large experiment was chosen, the design would have to be followed in detail.

Dependent variables

A major problem with a study of this nature, is to obtain a relevant result. There is no unequivocal way of expressing delimbing quality and, most importantly, the meaning of 'acceptable delimbing quality' differs between industries and even within the same industry, depending e.g. on the time of year. Any attempt at establishing a 'true' standard is bound to fail.

Bredberg et al. (1975) had a quite different approach. They fitted an exponential function to the results and by applying regression analysis, determined the coefficients for different variables. The t-values were used to determine the significance of the variables. The method has two disadvantages, however. First, the result, i.e. the values of the coefficients of different variables, is rather abstract and it is difficult to visualise their meaning. Secondly, there are statistical difficulties associated with having a number of intercorrelated observations from the same bunch. This calls for some correction of the degrees of freedom. Furthermore, there is an under-lying assumption that the delimbing process will have the same appearance, irrespective of conditions, and that only the level of the curve will change for different variables. If this does not hold, the comparison is not meaningful.

The method chosen for expressing acceptable delimbing quality has its weak points, too. It does not reflect in any way the distribution of the length of remaining branches beyond what is determined by the definition of the result. But as Fig. 12 illustrates, the distribution of the lengths of branches is quite well balanced, with the exception of the small excess at +20 cm. It is interesting that some of these branches originate from some of the most effective machine configurations. The shorter delimbing time, which implies a smaller number of passes by the delimbing devices, may increase the risk that some branches are not in the correct position for delimbing (see p. 14).

Another disadvantage of the definition of delimbing quality used, which is closely connected with the inability to reflect the distribution of the length of branch stubs, is that if one experimental category, e.g. a particular delimbing device, is not capable of cutting the branches close to the stem, the choice of the critical length of the branch stumps is decisive for the result. If a delimbing device, as a rule, leaves 30 mm branch stumps as a minimum, to use 25 mm as the discriminating level would be unfair, and a comparison would be misleading. However, in this study no such tendencies have been observed. Regardless of the model of delimbing device, great efforts were made to ensure that the edges of the delimbing devices were always at the same level. If one compares 25 mm and 50 mm as discriminating levels, the result is very similar. Seventy-five per cent of the branches not exceeding 25 mm in length corresponds approximately to 90 per cent of the branches shorter than 50 mm. To use 75 per cent and 50 mm corresponds approximately to 50 per cent and 25 mm. These two latter definitions have been compared to the original one. The delimbing time will evidently be shorter in those cases. The variation of the result is larger at the beginning of the delimbing process, probably owing to a greater stochastic influence, but the variance tends to stabilise after a time. Accordingly, these alternative definitions are not as robust as the one used. To summarise, the used definition of an acceptable delimbing quality, viz. 75 per cent of the branches less than 25 mm long, is not perfect in all respects, but it does have good features.

Reliability of results and sources of error

The most obvious possible source of error is that the sample is not representative. However, the subjective opinion obtained while watching, and especially while measuring the logs, was that an estimate could be made of the whole bunch, which would correspond well with what was measured on the sample logs. However, the correspondence was poorer at the beginning of the process. Logs are not delimbed uniformly over a period of time, but this lack of uniformity decreases the longer is the delimbing time.

The limiting of possible sample trees to trees with two logs confers uniformity. Differences between sample trees are relatively small, for which reason tree-specific variables, as well as species, play a very small part in the result. The variance of the biological factors is so small that there was no need to control the variance statistically.

The figures for both delimbing time and loss of stemwood were obtained by linear interpolation. As both these processes are not linear, there is an error in the estimates. However, as there is never more than half a minute to the closest interruption, this difference should not matter to any great extent. Although the processes, on the average, follow a certain pattern, this does not apply to the individual bunch during a very short interval of delimbing. Both delimbing and loss of stemwood are discrete events; a branch is cut off and a log is broken at a certain time. The results in fact evolve in a discontinuous fashion. Linear interpolation therefore seems to be the best possible method.

Another possible source of error is that sample logs sometimes break off, which can influence the result. But here, too, time seems to have a stabilising effect, and the loss of stemwood also tends to stabilise. However, where the loss of stemwood is higher than the average, there is a great risk of underestimating the delimbing time. It is the top logs that break first, and those logs have the most branches which are all green. Accordingly, if a top log breaks and disappears from the cradle, the result will be influenced positively, i.e. the proportion of branches shorter than 25 mm will increase abruptly. However, the cases with high stemwood loss in the study were not significantly related to short delimbing time, in fact the reverse was true: the loss of stemwood was positively correlated with delimbing time. There is, however, reason to be cautious when comparing results, if the loss of stemwood differs greatly.

The volume of each log was calculated from the two recorded end diameters and the length, assuming a shape resembling the frustum of a cone. However, the shape of a tree is not quite linear and a small error will result from this. The butt swell, the most important deviation from linear form, is not large on trees as small as those used in this study. Measuring diameter 0.2 m from the ends, should reduce this error to a negligible size. The usual way of measuring the volume of pulpwood logs is to take the diameter at the centre of the log, calculating the volume by the formula for a cylinder. The method used in the present study should give more accurate results than are obtained by that method.

The variance of biological factors for the sampled trees was small and did not appreciably influence the results. The same conclusion can be drawn as regards the variance of the whole bunches, the number of logs and the volume of stemwood. Besides those factors, other biological factors may also be important. Although the intention was always to use as fresh wood as possible, there was some variation of the storage period between felling and delimbing, ranging from one day to about a week. During storage for one week, the moisture content of the wood may decrease if the weather is fine, and the properties of the wood change. A slight tendency could be found in the material that even a few days' storage could positively influence efficiency, but this could not be statistically verified.

Besides providing different drying conditions, temperature may influence the properties of the wood. In cold weather, wood will be harder and more brittle. The studies were conducted during the autumn months: from the end of August, through September and October to the beginning of November. The temperature ranged from about +5°C to +15°C. In this interval there is a small change in wood properties. No influence of temperature was revealed in the analysis.

In addition to the problems of controlling the variation of biological origin, the measuring methods themselves may be sources of error. The interruption required for making an objective measurement, naturally influences the results. Branches and logs were broken during handling, and logs cannot be replaced in the same position as before. However, when runs with the same configuration, but with a different number of interruptions were compared, no evidence of a difference could be found.

Inaccuracy in the time statement may cause a serious risk of error in measurement. However, if the process is interrupted after 3:57 or 4:05 minutes instead of at 4 minutes exactly, the result will not change dramatically. While there are further factors that may reduce the reliability of the results, no errors should be so great that the conclusions must be reconsidered.

Delimbing process

The delimbing process is most efficient at the beginning, efficiency gradually declining as fewer branches remain. This applies as regards the separation of branches from the stem, expressed as volume per unit time. If, instead, the proportion of branches satisfactorily cut or broken off is considered, another relationship may be recognised. The number of branches cut off per unit time with an acceptably short branch stump, is initially small, increases, then declines again. One advantage of the function used to depict the delimbing process (p. 17), is that both level and form may be varied.

Bredberg et al. (1975) used another type of exponential function to describe the process of delimbing. The function reads $Y=e^{((a+bB+cC)/t)}$, where Y is the proportion of branches cut shorter than a specified length at the delimbing time t, B and C are independent variables and a, b and c are coefficients. Dehlén et al. (1982) used the same type of function to describe the debarking process in a cradle-type machine. These functions may be transformed to a linear form. While this was formerly an essential property, there is now a number of programs which can deal with non-linear models. Following transformation, standard regression analysis could be used to fit the model to the observed values. The function used by Bredberg et al.(1975) is rather rigid and only the level, not the form, of the curve can be influenced by the coefficients. The function proposed in the present study is more flexible and fits the measured values better.

Kurelek (1981) has pointed out that there is a relationship between quality, cost and damage for flail delimbers. Better quality increases both cost and damage. The same relation is valid for the cradle-delimber. A demand for better quality not only affects delimbing time and productivity,but also the amount of damage (see p. 11).

No function was fitted to the observations concerning the loss of stemwood over time. The process appears to be 'S'-shaped, however, but for the most efficient configurations, the stagnation phase (upper asymptote) is never reached. The delimbing time is of great importance to the loss of stemwood. In general, the longer the delimbing time, the greater the loss of stemwood. Hence, the aim of attaining as efficient delimbing as possible, also reduces the loss of stemwood.

Tree properties

Tree species is in reality a category which includes a range of characteristics. If the physical properties of trees could be exactly described, species would lose most of its meaning in a study such as this. However, these properties cannot be exactly measured and described; species is therefore a convenient means of categorising the material. Norway spruce requires a longer delimbing time than Scots pine. This is the result found in most other studies (e.g. Bredberg et al., 1975; Helgesson, 1977). The greater number of branches and the larger volume of branches and needles in spruce, are evident causes. The proportion of stemwood in relation to the total amount of biomass of a tree is generally less for Norway spruce than for Scots pine (Hakkila, 1972; Marklund, 1988). But, as the results indicate, the relation between delimbing time for pine and spruce differs for the various delimbing devices. Devices with sharp edges are required for efficient delimbing of Norway spruce. To delimb Scots pine efficiently, greater force is needed to break off the branches. Branches of spruce seem to be more flexible than those of pine, which are more brittle. To delimb both species successfully, both force and cutting ability must be present.

Unfortunately, very few studies have been made on branch properties. Kempe (1967) studied the forces required to shear stems and Nilsson (1976) reported experiments on the shear forces required to cut off branches, but nothing was reported concerning bending strength or shock resistance, which are of interest here. These properties have been extensively studied as regards stemwood, especially in the dry state (Bodig & Jayne, 1982), but branch properties are quite different, since branches are not totally lignified. Freezing temperatures and reduced moisture content change wood properties similarly: wood loses some flexibility and becomes more brittle (Bodig & Jayne, 1982). Consequently, the required delimbing time is influenced by such changes. Bredberg et al. (1975) and Jonsson (1986*b*) report the positive effect of low temperature and low moisture content on productivity. Storage of trees for some weeks before delimbing, while the branches dry, positively affects productivity; and so do temperatures below freezing.

Delimbing devices

The first question to ask, is whether changing the two centre devices only, affects the results in such a way that they are not fully reliable? The arrangement was not satisfactory, but had to be accepted. If the two centre devices are less effective than the two outer devices, the retention of a greater proportion of branches in the centre will increase pressure against the two centre devices, and increase their delimbing capacity. Accordingly, more effective devices in the centre will increase the logs' pressure against the outer ones. When results obtained from the two centre sections were compared with those from all four sections, only small differences were found. The values were almost equal and the limitation to two sections increased the variance only slightly. Therefore, the only real influence this should have on the results is that the differences found would be underestimated. As regards the tests of significance, there is a risk that if variance decreases, significance may be found where there is none. But since a smaller difference between the values works in the opposite direction, this should not be a serious risk. The risk is instead the reverse, i.e. that a null hypothesis cannot be rejected, although there is a real difference.

The superiority of active devices to passive, as regards delimbing time, is not surprising, but it illustrates the importance of efficient delimbing devices. Bredberg et al. (1975) also found large differences between "the Trough", with passive devices, and "Skruven", with active ones. In that study the loss of stemwood was higher for "Skruven", but in the present study, no significant difference in loss of stemwood between active and passive devices was observed. The greatest difference is probably in the placement of the delimbing devices. In the V-shaped "Skruven" (cf. Fig. 2), the delimbing devices are placed in the more horizontal long-side, which could be described as a combination of the bottom and the long-side opposite the conveyor of the delimber studied in this work. This placement of the delimbing devices increases the risk of logs being damaged by them. The passive devices (the fixed knives) in this study, have a longer effective cutting width than the active ones, which is an indication that the difference may be underestimated.

The effect of having several delimbing devices placed one after another in the conveyor long-side compared to having one only, is very small. As a log is picked up by the lugs, it will probably remain in the same position until it is pushed off the conveyor. Hence, the same side of the log will be exposed to all delimbing devices. If the devices are effective enough, nothing will be gained by passing a second device. It would be a different matter were additional delimbing devices placed in the bottom or on the other long-side. In such a case, there would be space and time enough for the logs to change position between passages of the devices. The different placements would probably complement one another much better than when the devices were placed one after another. Unfortunately, the design of the rig did not permit this to be studied.

Delimbing devices with no sharp edges have one large advantage: such devices require virtually no maintenance, as there are no edges to be sharpened at regular intervals. But to delimb spruce effectively, the device must have sharp edges. It seems to be more efficient to cut, rather than to beat off, the more flexible branches of spruce. No signs of branches wedged between the teeth and torn off were observed, which was the original intention with the open rollers.

The closed rollers proved to be less effective than the open rollers with sharp edges for delimbing spruce, although the closed rollers had very sharp edges. Most probably, flexible branches are bent by the cylinder, and the knives never achieve a clear perpendicular cut on the branches, since this is prevented by the small gap between the edge of the knives and the surface of the cylinders on which the knives are mounted. There is plenty of space between and beneath the knives of the open rollers, while there is only 19 mm between the edge and the surface of the cylinder of the closed roller. Since pine branches are quite brittle, it does not matter if the knife cannot strike the branch at right-angles: the branch will break off on impact. For spruce, however, a cut not made at right-angles will fail to sever the branch. Several cuts are therefore necessary before the branch has been totally removed, hence a longer delimbing time is required. Furthermore, the relatively denser crown of spruce (cf. the number of branches in Table 2) acts as a shock absorber, reducing the striking effect of the delimbing devices. The difference between open and closed rollers as regards pine is more difficult to understand and explain, but it might be due to the greater mass, and therefore greater momentum, of the closed rollers.

The rotor, a new concept for delimbing devices, has proved to be somewhat more efficient than the best rollers, i.e. the open rollers with sharp edges. The effective delimbing width is about the same for the two devices. If one assumes the roller to be effective 25 mm below the conveyor,the area of active delimbing is 0.12 m^2 for one roller, and twice this in the case of two in series. The corresponding area for one rotor with small diameter is 0.16 m^2, the upper half of this area being probably ineffective and comparable with the upper roller, hence smaller for the rotor. The difference in diameter is more probably a main cause of the difference in efficiency. On average, the speed of the knives of the roller was 11.4 $m \cdot s^{-1}$, while the velocity of a knife of the rotor was 17.5 $m \cdot s^{-1}$. This is, of course, of importance to the momentum of the knives and the force with which a branch is struck. The rotors also have the practical advantage over rollers in that they are fairly easy to maintain. The knives are very easy to change, and it would be possible to have several sets of knives that were changed regularly.

The clearest difference between the two rotors is the active delimbing width, which is 34 per cent greater for the larger rotor. However, beside the active delimbing width, the diameter of the rotor affects several other factors. A larger diameter means that the knives will reach a higher speed.The higher speed and the greater weight of the knives imply a greater momentum, therefore a greater force. The momentum was 147 per cent greater for the larger rotor at the top of the knives. Furthermore, as both types of rotor are mounted in the same place in the rig, the lower half-circle of the knives, most important for cutting off branches, will reach deeper into the cradle on the rotor with the larger diameter. Delimbing seems to be more effective farther down in the cradle, because logs create a pressure on the logs below them. Consequently, the pressure towards the inner surfaces of the cradle and delimbing devices is higher further down in the cradle. Thus, the ability to reach as close to the bottom of the cradle as possible is an advantage. The longer knives also mean that the area of active delimbing for a rotor is significantly increased, from 0.16 m^2 to 0.29 m^2 or by 81 per cent.

Cradle design

Inclination of long-sides

It is of vital importance when designing the cradle, to ensure that tumbling and the movements of the logs are as smooth and as free from disturbance as possible. This influences both the delimbing time and the loss of stemwood. The inner surfaces should be as even as possible, especially the long-side opposite to the conveyor and the bottom. When logs are pushed off the conveyor, one end of the log often hits the long-side or the bottom before the other. If there are holes, openings or other unevenness, the end of the log may stick fast and the log be broken.

Another critical factor is the relation between the length of logs and the distance between the long-sides. The wider is the cradle, the greater is the risk that the direction of logs will deviate, vertically, horizontally or both, from the direction of the cradle. This is illustrated by what happens when the inclination of one of the long-sides is increased, and by the fact that logs shorter than average, either by origin or by being broken, have a higher risk of being broken.

The result does not seem to be as sensitive to the inclination of the conveyor long-side as to that of the other long-side. It may be assumed that the fact that logs are pushed from the top of the conveyor toward the opposite long-side, makes greater demands on the design of the latter. If there are holes and unevenness in the long-side (as on the machine studied), there is a great risk that logs will stick, causing disturbances to tumbling. This happened in the experiment involving a 38° inclination of the long-side opposite to the conveyor, which could not be completed. Besides influencing tumbling and the movement of the logs, the inclination of the conveyor long-side determines the pressure of the log perpendicular to the conveyor and delimbing devices. With the most vertical position studied (23°), a longer delimbing time is required. However, the results indicate that the delimbing time is similar for a rather wide range of inclinations of the conveyor long-side. There is a region in which the features of tumbling and pressure outweigh each other; the required delimbing time is rather independent of changes within this region. The loss of stemwood tends to increase somewhat with a more horizontal position.

Although the cradle is filled totally at the start of delimbing, it does not take long before it appears as if a few isolated logs are tumbling in the bottom of the cradle. The space set free by the disappearance of the branches has two disadvantages. Delimbing would be more efficient if the logs did not pass sections of the cradle where no delimbing takes place. The extra space allows logs to move more freely, with an increased risk that logs will deviate from the alignment of the cradle, and break. The ideal solution would be to have a cradle that changed its inner volume in accordance with the volume of the logs within it. This could be achieved in either of two ways: by moving the returning arms downwards as the height of the bunch decreases, or by moving the long-side opposite the conveyor towards the conveyor long-side. Were one or both of these measures implemented, the efficiency of the later phases of the delimbing process would probably increase. Furthermore, the long-side opposite the conveyor need not be flat, as in this case. A rounded long-side, like a section of a drum, could form something resembling a roof over the bunch, the shape of which would probably favourably affect the tumbling and alignment of the logs.

Speed of conveyor

A higher conveyor speed means that each log will pass the delimbing devices more times per unit time. If delimbing quality was determined only by the number of passes, the relation between required delimbing time and the speed of conveyor would be of the kind: $Y = A/X$, where Y is delimbing time, X is speed of conveyor and A is a constant. Analysis of the results confirms that there is good agreement with this relationship, up to 1.5 $m \cdot s^{-1}$. A break-point in the interval 1.5–1.9 $m \cdot s^{-1}$ can be detected. This break-point seems to be identical for the two delimbing devices and the two tree species tested. The increase in required delimbing time at a speed greater than 1.5 $m \cdot s^{-1}$ is probably associated with logs' not attaining the right position for the conveyor. Thus the break-point is likely to be influenced by other factors, such as the distance between the lugs, the design of the lugs and with what force the logs are pushed towards the conveyor. The last of these is very much determined by the design and inclination of the bottom and long-side of the cradle.

The dynamic forces are proportional to the square of the speed. Hence, logs could be expected to be broken more frequently with increasing speed. However, the loss of stemwood generally follows the same pattern as delimbing time. There is a decline up to 1.5 $m \cdot s^{-1}$, after which losses begin to increase. At conveyor speeds above 1.5 $m \cdot s^{-1}$, a clear trend towards increasing loss of stemwood is recognisable. The longer processing time, together with the increased dynamic forces, are probably the main causes.

Bredberg et al. (1975) refer to a study of the speed of the conveyor with the Soviet "Bear" delimber. Two levels, 0.3 and 0.8 $m \cdot s^{-1}$, were studied, the higher speed proving superior in that study.

Practical implementation

The results of this work give some information as to how a multi-stem delimber of cradle type should be constructed to be efficient. The cradle concept may be used, as indicated above, for various kinds of delimber.

Delimbers made for working in the stand must have good off-road mobility. They must fit the strip-roads, and should not be larger than other logging machines. Mobile delimbers working on landings or terminals have other restrictions. Length, width and total weight are restricted by the laws concerning public roads, which differ between countries. However, these restrictions are less strict than those for off-road vehicles, and a larger and more efficient construction may be considered. Stationary units may be constructed still more freely. For stationary constructions, it is also possible to make cradles with continuous feed, similar to delimbing drums.

Batch processing, i.e. the feeding of a number of logs into the delimber, processing and removing the delimbed logs, tends to be a "hot" system, i.e. sensitive to connecting operations. To obtain high productivity, loading and unloading of a delimber has to be efficient, as well as delimbing itself. With continuous feeding, it is easier to establish buffers in the system. In this study, the delimber was loaded by a rear loader, but this could be done in a variety of ways. Unloading was accomplished by removing the returning arms and using the conveyor to push the logs over the edge of the conveyor long-side. This can be done more effectively by opening one of the long-sides to remove the logs. One basic aim should be to handle the logs in bunches in as many operations of the harvesting system as possible. By this method, the advantages of multi-stem handling can reach their full potential.

Beside weight, the higher peripheral speed of the rotors calls for some caution. If a knife loosens from its attachment or if a piece of the edge is broken off, the situation is highly dangerous. Some thought must be given to safety aspects when designing delimbing devices. A construction having the knives more integrated with the disk would be preferable from this point of view.

In constructing a delimber, consideration must be given to various restrictions, and an optimal solution may contain components that are not the most efficient when considered alone. For example, rotors are more efficient than rollers, but for safety reasons, rollers might be preferable.

One concept previously discussed (Bredberg, 1984) is to combine a cradle delimber with a single-stem delimber with transverse feeding called "Gasslare" (Arvidsson et al., 1980). The aim is that most of the branches will be removed in the cradle. Final trimming will be carried out in the succeeding "Gasslare". However, the present study has shown that the time from which the logs are detached from the bunch and are able to act as single stems, to that at which an acceptable result is achieved, is so short, that moving the logs into a single-stem delimber will probably only extend delimbing time. The concept might be of interest if the required delimbing quality was extremely high.

Conclusions

The cradle-type multi-stem delimber has a number of features that make it advantageous as compared to other types of delimber. The cradle concept permits a flexible design and can be adapted to particular needs. The size may range from small forwarder-mounted delimbers, to huge industrial constructions. It is also simple to include active delimbing devices in the construction, to increase the efficiency and productivity of delimbing.

The delimbing process may mathematically be described by an 'S'-shaped exponential function. The loss of stemwood is positively correlated with the processing time required to achieve the defined delimbing quality. It is therefore of interest that delimbing should be as efficient as possible, both to maximise productivity and to minimise the loss of stemwood. Active delimbing devices, i.e. devices with a momentum of their own, are more efficient than passive devices. The two tree species Scots pine and Norway spruce made quite different demands on the design and function of the delimbing devices. To obtain a delimbing device that is efficient for both species, it must combine striking force with shearing capacity. Active devices are more efficient than passive devices. The rotor delimbing device was the most efficient delimbing device in the study.

The tested machine variables, delimbing devices, inclinations of long-sides and speed of conveyor, all had a great influence on delimbing efficiency and on the loss of stemwood. Much can be gained by choosing a good configuration of these variables when constructing a delimber.

The cradle multi-stem delimber can be made very efficient, with a low level of loss of stemwood and good delimbing quality. It has a great potential for development and may be the model of delimber needed in the 1990s and beyond the turn of the century.

Some basic knowledge is still lacking. Most important is the influence of cradle dimensions and bunch volume on productivity. To study this, a machine with adjustable length, width and height is required. A larger cradle has another relationship between the surface area of the logs and the inner surface area of the cradle, as compared to a smaller one with the same length. This means that there will be more branches per area of active delimbing, assuming the area of active delimbing is proportional to the area of the inner surfaces of the cradle. This implies less efficient delimbing. However, the dimensions of the cradle may be changed in different ways. For two cradles with the same inner volume, but with different lengths, the longer one should be the more efficient, owing to its larger inner surface area and to the opportunity of having a larger area of active delimbing.

The experimental rig in this work was constructed in such a way that delimbing devices could be mounted only in one of the long-sides. It would be of interest to discover the effect of having additional delimbing devices in the bottom and the long-side opposite the conveyor.

One area that is very poorly known, concerns the properties of branches. Knowledge about the shearing, bending and shock resistance properties of branches of different tree species, and how these properties are influenced by water content and temperature, would much facilitate analyses and evaluations of delimbing. This should be regarded as a high-priority task for wood technology research.

References

Ager, B. H. 1967. *Tidformler för huggning—baserade på fältstudier* 1959-67. Forest Operations Institute. Redogörelse nr 12, 1967.

Almquist, A. & Österblom, U. 1971. *Drivningsteknik i Sovjetunionen.* Forest Operations Institute. Redogörelse nr 2, 1971.

Andersson, B. 1979. A new approach to chain flail delimbing. *Pulp & Paper Canada 80,* no. 12, 76–80.

Andersson, S. & Björheden, R. 1986. *Skogsbränsleuttag—ny teknik.* Statens energiverk, Stockholm.

Anon. 1977a. *PHU—Final Summary Report* 1977. The Swedish Forestry Association.

Anon. 1977b. *Mechanised delimbing.* N.Z. Logging Industry Research Association. Machinery Evaluation, Vol. 2, no. 1.

Anon. 1978. *Further mechanised delimbing developments.* N.Z. Logging Industry Research Association. Machinery Evaluation, Vol. 3, no. 2.

Anon. 1979. *Mätningsinstruktioner rekommenderade av Virkesmätningsrådet, nr 1–79.* Virkesmätningsrådet. Stockholm.

Anon. 1983. *Skogsdata 83.* Swedish University of Agricultural Sciences. Department of Forest Survey.

Arvidsson, A., Gasslander, J.-E., Johansson, J. & Moberg, L. 1980. *Terminalkvistare—orienterande försök.* Swedish University of Agricultural Sciences. Department of Operational Efficiency. Stencil nr 116/1980.

Bodig, J. & Jayne, B. A. 1982. *Mechanics of Wood and Wood Composites.* New York, N.Y.: Van Nostrand Reinhold Company.

Brattberg, T. 1977. *Rensning av klena träd i barktrumma.* Projekt Helträdsutnyttjande. PHU rapport nr 33. Stockholm.

Bredberg, C.-J., 1984. Tillgänglig och tänkbar teknik—kvistningsprinciper. In: *Kvistning av klenvirke* (ed. B. Dahlin). Swedish University of Agricultural Sciences. Department of Operational Efficiency. Stencil nr 265/1984 17–20.

Bredberg, C.-J., Liedholm, H. & Moberg, L. 1975. *Buntkvistning av klenvirke (Delimbing of small-wood bundles).* Swedish University of Agricultural Sciences, Department of Operational Efficiency, Rapporter och Uppsatser nr 92.

Dahlin, B. 1989. The influence of tree dimension on the production capacity for different delimbing principles. *Scand. J. For. Res. 4,* 267–272.

Dehlén, R., Herlitz, A., Johansson, I., Långström, B. & Regnander, J. 1982. *Trågbarkning av massaved (Trough-debarking of pulp wood).* Swedish University of Agricultural Sciences. Department of Operational Efficiency. Report no. 143.

Folkema, M.P. 1979. Delimbing—problems and prospects. *Pulp & Paper Canada 80,* no. 9, 63–69.

Forslund, T. 1985. *Maskin för kvistning av i buntar anordnade träd, i synnerhet klenträd.* Swedish Patent Office, Patentansökan nr 8500542-9.

Gordon, R.D. 1978. *Delimbing studies.* N.Z. Logging Industry Research Association, Project Report 4.

Hakkila, P. 1972. *Coniferous branches as rawmaterial source.* Metsäntutkimuslaitoksen Julkaisuja, 75:1.

Hakkila, P. 1989. *Utilization of Residual Forest Biomass.* Berlin & Heidelberg: Springer-Verlag.

Heiersdorf, E. 1980. *Development and evalution of GLFP/NESCO boom-mounted flail delimber.* FERIC Technical Report No. TR-36.

Helgesson, T. 1977. *Gisselkvistning, en buntkvistningsmetod för gallring- och röjningsvirke (Flail delimbing—a bundle delimbing method for wood removed in thinning and cleaning).* Swedish Forest Product Laboratory, STFI-meddelande serie A, nr 472 (TT A:86).

Johansson, H. 1984. Lyckseleterminalen—funktionsbeskrivning och erfarenheter. In: *Kvistning av klenvirke* (ed. B. Dahlin). Swedish University of Agricultural Sciences, Department of Operational Efficiency, Stencil nr 265/1984, 9–13.

Jonsson, T. 1986*a*. Bearbetningsanläggningar för träddelar finns över hela landet. In: *Rationaliseringskonferens -86.* Forest Operations Institute, Redogörelse nr 2, 1986, 36–40.

Jonsson, T. 1986*b*. *Buntkvistning av träddelar med Bruks kedjekvistare—studie vid Anderssons Sågverks AB, Borgstena, 1986.* Forest Operations Institute, Stencil 1986-10-30.

Jonsson, T. & Nordén, B. 1986. *KMWs kvistningstrumma.* Forest Operations Institute, Resultat nr 19, 1986.

Jonsson, T. & Nordén, B. 1987. *Multiple tree delimbing/debarking by the Manitowoc flail.* Forest Operations Institute. Stencil 1987-09-07.

Kempe, C. 1967. *Forces and damage involved in the hydraulic shearing of wood.* Studia For. Suec. 55.

Krasilńikov, B. N. & Petruchin, G. G. 1986. Bunkernye sučkoreznye ustanovki. *Lesnaja Promyšlennost' 5,* 1986, 25.

Kuitto, P.-J. & Mäkelä, M. 1988. *Kuormainharvesteri ensimmäisessä ja toisessa harvennuksessa.* (Boom-mounted harvester in first and second thinnings). Metsäteho, Metsätehon katsaus 7/1988.

Kurelek, J. 1981. Delimbing and bucking at roadside—into

the 80's. *Pulp & Paper Canada 82: 5.* 55–59.
Lilleberg, R. 1987. *Pika 45—prosessori harvennus- ja päätehakkuissa. (Pika 45 processor for thinning cutting and final cutting).* Mätseteho. Mätsetehon katsaus 14/1987.
Marklund. L. G. 1988. *Biomassa funktioner för tall, gran och björk i Sverige (Biomass functions for pine spruce and birch in Sweden).* Swedish University of Agricultural Sciences. Department of Forest Survey. Report no. 45.
Nilsson. B. 1976. *Maskinell kvistning (Mechanized delimbing).* Forest Operations Institute. Meddelande nr 11, 1976.
Nordén. B. 1987. *Produktionsstudie—Cabro buntkvistare.* Forest Operations Institute. Stencil 1987-10-27.
Nurek, T. 1984. Badanie wpływu geometrii noża i siły docisku na jakość okrzesywania (Studies on the influence of the knife geometry and the pressure force on the quality of limbing). *Sylwan 128*:9. 47-54.
Ronström. J.-Å. 1984. Billeruds helträdsmetod. In: *Kvistning av klenvirke* (ed. B. Dahlin). Swedish University of Agricultural Sciences. Department of Operational Efficiency. Stencil nr 265/1984, 14-16.
Rydin. J. & Österblom. U. 1969. *Kvistningsmaskinen Skruven.* Forest Operations Institute. Teknik nr 5. 1969.
Sandström. G. 1984. Kvistning med Buntkvistaren. In: *Kvistning av klenvirke* (ed. B. Dahlin). Swedish University of Agricultural Sciences. Department of Operational Efficiency. Stencil nr 265/1984. 4–6.
Séguin. A. 1979. Le Débrouillard. *Pulp & Paper Canada 80:* 12. 80–81.
Sherman. S. & Nordén. B. 1983. *Kvistning av träddelar med AC Invests (Hydrovågs) buntkvistare.* Forest Operations Institute. Resultat nr 27. 1983.
Svensson. P. 1984. Kvistning med Skruven. In: *Kvistning av klenvirke* (ed. B. Dahlin). Swedish University of Agricultural Sciences. Department of Operational Efficiency. Stencil nr 265/1984. 7–8.
Svensson. S. A. & Braide. A. 1987. *Tekniska skogsdata.* Swedish University of Agricultural Sciences. Department of Forest Survey. Arbetsrapport 1 1987.
Taraldrud. H. 1972. *Maskinell kvistning ved tynningsdrifter.* Norsk Institutt for Skogsforskning. Driftsteknisk rapport nr 11-1972.
Taylor. R.W. 1977. *The chain-flail—A practical answer to delimbing problems?* National Timber Research Institute. C.S.I.R.. Pretoria. South Africa. H-3-77.
Wrobelski. F. 1984. *Buntkvistare.* Swedish Patent Office. Patentansökan nr 8405744-7.

Acknowledgments

This work was funded by the Nordic Council of Forest Work Studies and the Programme for Technical Research in Forestry. The equipment was granted by the National Board of Energy.

Domänverket. through Göran Johansson. provided the trees for the study. AC-Invest allowed us to use the blueprints of their rollers. FMG ÖSA AB. represented by Jan-Erik Hedin and Torsten Forslund. provided us with their rollers and modified them to our specifications. Sincere thanks to all.