LIMITING FACTORS IN MECHANIZED TREE-PLANTING

Ulf Hallonborg
The Forestry Research Institute of Sweden
Uppsala, Sweden

ABSTRACT

Certain properties of continuously advancing planting machines restrict their speed, thereby limiting their capacities. The cycle time of the planting device is predetermined by the design and is therefore difficult to alter. It is easier to influence the cycle time of the seedling feed system, especially by changing the technical properties of the seedlings. In the case of pneumatic feed systems, air flow and hose diameter are also important physical factors. In cases where the seedling is not delivered to the planting device when required, the device will have to wait, and there will be a corresponding fall in productivity.

Consequently, it would be advantageous if we could predict the likelihood of such a delay occurring. To be able to do this, we need to know the statistical distribution of the feed cycle times for different combinations of the physical variables. One hypothesis is that feed cycle times exhibit a chi-square distribution. If this is true, future work should focus on developing transformations between physical properties and statistical parameters.

Keywords: *Mechanized planting, tree planting, seedling feed.*

INTRODUCTION

In planting work, regardless of whether it is manual, or partially or fully mechanized, a planting device has to be positioned in a suitable planting spot, whereupon a seedling is inserted. In manual planting, the planting tube is carried to the next planting spot, where it is pushed into the ground and the tip opened. After the seedling has passed through, the tube is withdrawn and closed. These sub-operations have to be carried out in a certain order, although they may sometimes overlap. Productivity can be raised if the worker is able to close the planting tube and insert the next seedling while walking to the next planting spot. Some work elements, such as walking, can only be speeded up to a limited extent, whereas other work element variables, such as the time it takes for a seedling to drop through the tube, cannot be altered.

In mechanized planting, machine design is the most important factor restricting the sub-operations. Work elements well-suited for manual execution, such as moving the planting tube and transferring a seedling from the tray to the tube, have been shown to be especially critical. The cycle time of the planting device is also largely determined by the technical design, whether the planting device consists of rotating discs that deposit the seedlings in a furrow (as on the Quickwood) where the cycle time for seedling conveyance is governed by the design of the feed mechanism, or of hole-making heads, as on the Silva Nova. In the area of pneumatic seedling conveyance, the technical properties of the seedlings, i.e. their stem stiffness and root armouring, can be of decisive importance.

BACKGROUND

The first known "planting machine," which was a horse-drawn rig, was designed in Nebraska in 1886. The incentive for developing a machine for planting at that time was the same as it is today -- a real or anticipated shortage of labour. The earliest developments were designed for use on fairly easy terrain and on soils free from obstacles. Since the late 1950s, however, development work has focused more on machines for planting on previously forested land, which means that obstacles in the form of stumps and stones have to be taken into account.

Up until 1965, all units seemed to be designed according to the principle of continuous ploughing and were used for planting bare-root seedlings. However, due to the difficult terrain in many regions, intermittent-furrow planting machines were later tested in Sweden and in several other countries, including the former USSR, Austria, Canada, and the USA [2, 10].

In Sweden, trials were also carried out with hole-making or spot-planting machines that advanced continuously, but at the time these were deemed to be technically too complex.

The author is a researcher in Mechanical Engineering.

During the 1980s, several spot-planting machines were developed in North America, but they were mostly combined with intermittent furrow scarification, e.g. the HODAG, MARDEN, and ONE-SHOT planters, or no scarification at all as on the BRAT II.

Thus, historically, there has been a gradual shift from continuous to intermittent plough-type machines, largely owing to problems caused by obstacles in the terrain. Yet, on Sweden's moraine soils, even intermittent plough-type machines were unable to achieve acceptable results.

In the 1970s, several machines were developed that differed in the way they solved the syncronization problem of allowing continuous forward travel of the machine while keeping the planting head stationary at the moment of planting. Examples included the DoRo-Planter and ÖSA/ MoDo Mekan in Sweden and the Serlachius in Finland [1, 6, 8, 9, 10]. Some of these units were in operation for several years in Sweden, during which time they planted many billions of seedlings. Although the Finnish machine was also evaluated in Sweden, at that time the forestry sector had not yet adopted the method of planting in inverted turfs consisting of an inverted humus layer preferably covered with a layer of mineral soil to the extent necessary to make this method feasible. All too often the inverted turfs consisted only of disturbed humus. The basic method of scarification, which involved creating an inverted turf in front of the rear wheels of the machine and then compacting it, is the same as that employed on today's Silva Nova, see Figure 1. Two units of the early version of the Silva Nova with a Wadell cone trencher mounted at the rear were used successfully in Canada (Quebec) in the 1991 season [5, 7].

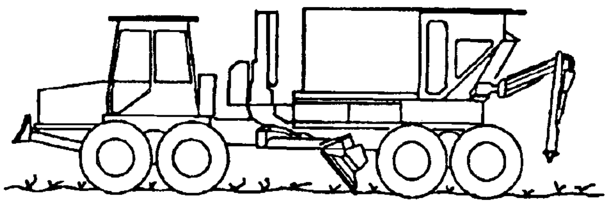

Figure 1. Layout of today's Silva Nova.

In the early 1970s, extensive studies were made of the basic principles of planting machines, and simulations were conducted of machines operating under different terrain conditions [4]. On the basis of the studies and calculated time data, operational costs, expressed in kronor per hectare, were estimated. The principal finding of these analyses, which underlie the joint Silva Nova venture, were as follows [3]:

- In mechanized regeneration, any scarification should be carried out in connection with planting.
- Continuous advance is preferable to intermittent advance.
- Planting heads are clearly superior to both intermittent and continuous furrow-type heads in terrain with a high incidence of obstacles.
- Travel speed and operating width (distance between passes) are the most important factors influencing the productivity of machines with continuous advance.

The significance of the travel speed and operating width of the machine has been confirmed by assessments of the performance of the Silva Nova. The travel speed is sometimes restricted by the cycle time of the planting device or feed mechanism, while at other times it is restricted by terrain conditions. In the last-mentioned case, rectangular spacing can offset the slower travel speed by increasing the theoretical operating width, i.e. the spacing between the machine passes is widened. The cycle times of the planting device and feed mechanism are the principal restraints placed on the productivity of a machine with continuous advance. This is true for all types of machines. The Silva Nova is here merely used as an example that provides practical support for the theories.

OBJECTIVE

The aim of the study was to determine the effects of planting device and feed mechanism cycle times on the forward travel of a continuously advancing planting machine and hence the restrictions that these factors impose on machine productivity.

CYCLE TIME FOR PLANTING DEVICE

Definition

The cycle time, C_p, for the movement of the planting device is defined as the time elapsing between a certain moment in the planting cycle and the corresponding moment in the subsequent planting cycle. In the case of a continuously advancing planting machine with hole-making planting heads, a suitable moment is when the tip of the planting head makes contact with the ground, which is a distinctive, readily identifiable moment.

Planting

To obtain suitable spacing between seedlings in a row, each planting cycle is initiated after the machine has covered a given distance. For a Quickwood-type machine, the planting cycle is linked mechanically to the travel speed and is not dependent on the capacity of any hydraulic system, as on the Silva Nova. The latter case will be dealt with further on when the planting device is not mechanically forced by the machine speed.

Provided the machine's travel speed is low, there will be more than enough time for the planting cycle to be completed before the next is begun. Within this range, the travel speed can be increased without affecting the preset spacing. At a certain speed, the cycle time and travel speed are synchronic with each other, in which case the new planting cycle will begin immediately after the previous one is completed. This is the highest travel speed that can be selected without affecting the spacing. At higher speeds, the planting device will operate continuously without waiting for distance signals, and the spacing will be extended.

Retries

So far, it is assumed that planting takes place each time the tip of the planting head makes contact with the ground. However, if the ground is not suitable a seedling will be wasted. The Silva Nova incorporates a function that records the resistance force on the tip of the head as it contacts the ground and aborts the attempt if the planting spot is deemed unsuitable. This sensing function causes the planting arm to try again. This retry cycle time, C_0, is shorter than C_p. To prevent the retry quotient, k_0, from affecting the number of planted seedlings per ha, the distance between planting attempts is shortened just after a retry until the nominal spacing is achieved. This adjustment can only succeed if the travel speed allows it. When no retry is made, $k_0 = 0$, the maximum travel speed will be:

$$v_0 = \frac{f_p}{C_p} \qquad (1)$$

where f_p is the distance between planting attempts. At a retry quotient of k_0, the average total cycle time, C_T, for the planted seedlings will be:

$$C_T = C_P + k_0 \cdot C_0 \qquad (2)$$

where $k_0 \cdot C_0$ represents the proportion of the retry time that must be added to each attempt. But the retry cycle time can also be expressed in terms of the planting device cycle time, i.e.:

$$C_0 = c \cdot C_P \qquad (3)$$

where c is the ratio of C_0 and C_p, and c is always less than 1. Equation (2) can then be written as $C_T = C_p(1 + k_0c)$. The corresponding travel speed will be:

$$v = \frac{f_p}{C_p(1+k_0c)} = \frac{1}{1+k_0c} \cdot v_0 \qquad (4)$$

With typical values from Silva Nova 1992, $C_p = 2.4$ s and $k_0 = 0.15$ the cycle time will be extended from 2.4 s to 2.4 + 0.15 · 1.2 = 2.58 s when the cycle time for a retry is 1.2 s. The maximum speed at a spacing of 2 m will fall from $v_0 = 2.0/2.4 = 0.83$ m/s to $v = 0.83/(1 + 0.15 \cdot 0.5) = 0.77$ m/s.

Figure 2 shows the highest speed allowed for a given value of c, which is a machine constant, when k_0 is increased to prevent the spacing from being extended. As can be seen, the reduction in speed is fairly modest at a low retry ratio, especially if the retry cycle time is much shorter than the cycle time for a normal (completed) planting attempt. At a high retry ratio, on the other hand, the reduction in speed is considerable. The reason that c can be kept low is closely related to the fact that the planting device does not need to collect a new seedling when making a second attempt at planting (a retry).

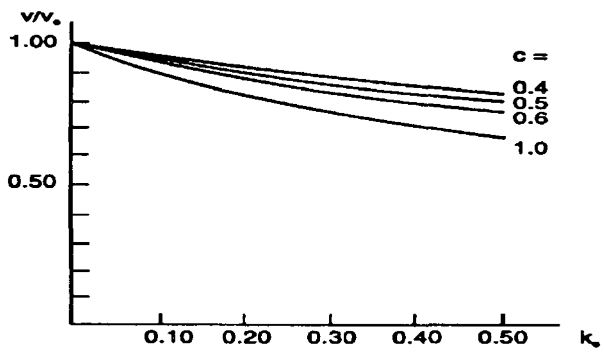

Figure 2. v/v_0 as a function of the retry quotient k_0, at constant c where $c=C_0/C_p$.

Planting Result

Till now, it has been assumed that every planting attempt results in a successful planting. Although some of the attempts are aborted and result in retries, it is not unusual for a completed planting to result in an unsuccessful (unsatisfactory) planting. There is no need here to discuss the criteria for deeming a planting successful or not; it will suffice to consider the number of successful plantings as a proportion, g, of the number of planting attempts. On average, the cycle time for the planting device with regard to successful planting attempts is:

$$C = C_p(1+k_0 c)/g \quad (5)$$

and the reduced speed:

$$v = v_0 \cdot \frac{g}{1+k_0 c} \quad (6)$$

From the reduction factor it is clear that the proportion of successful plantings has a proportional positive effect on the travelling speed, whereas the retry cycle time and retry ratio reduce the negative influence of each other. If k_0 is high, a short retry cycle C_0 is required.

CAPACITY OF THE PLANTING DEVICE

Travel speed is a decisive factor in determining the capacity of a planting machine operating with continuous advance. Substituting equation (1) with equation (6) gives the highest productive speed, v_p, at which a machine with given cycle times can operate on a site with a proportion of k_0 retries and result in a proportion of g successful plantings with distance f_g between them as an average for the site.

$$v_p = \frac{f_g \cdot g}{C_p(1+k_o c)} \quad (7)$$

The product $f_g \cdot g$ of the spacing and the proportion of successfully planted seedlings corresponds to the distance, f_p, between planting attempts. If g = 1, then f_g and f_p will be the same.

To obtain the number of seedlings that one planting device can plant per unit time, the travel speed should be divided by the spacing. An r-row planting machine gives an r folded production.

$$P_0 = \frac{r \cdot g}{C_p(1+k_0 c)} \text{ seedlings per second,}$$

or (8)

$$P_0 = \frac{3600 r \cdot g}{C_p(1+k_0 c)} \text{ seedlings per hour}$$

which is the common way to state the capacity or production in practice. The *capacity* of the machine is thus the number of seedlings planted per *productive planting hour*, i.e. per hour of planting device operation.

Note that the capacity at the optimum travel speed is fully defined by machine properties. On the other hand, to achieve this capacity the speed must be adjusted to the spacing as stated in equation (7).

With the typical values given earlier, the maximum capacity of a two-row machine with 85% of the planted seedlings being accepted will be:

P_0 = (3600·2·0.85)/(2.4·1.075)
=2372 successfully planted seedlings per hour.
The optimum speed with a spacing between accepted seedlings of 1.8 m,
i.e. $f_p = f_g \cdot g = 1.8 \cdot 0.85 = 1.53$ m
between planting attempts, will be:
$v_p = 1.53/2.40 \cdot (1 + 0.15 \cdot 0.5) = 0.59$ m/s.

If the speed should exceed v_p, the spacing will be $f_g = r \cdot v \,/\, p_0$, although the capacity will not be affected. In Figure 3, it corresponds to the area above the p_0 line, which, in the example, gives 2372 accepted seedlings per hour.

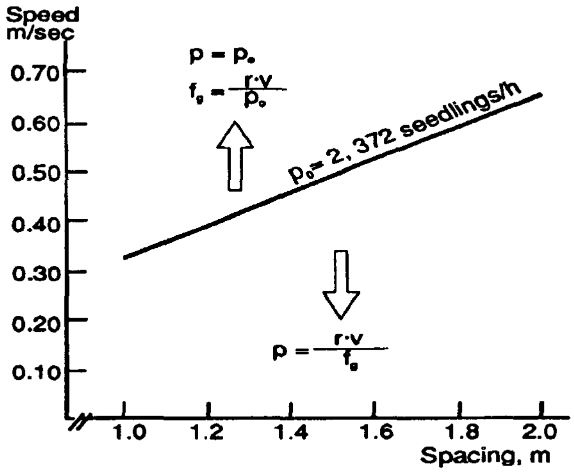

Figure 3. Possible travel speeds for the Silva Nova at different spacing between approved seedlings.

If the speed is below v_p, capacity will fall because the planting device will have to wait for a "go" signal, indicating that the required distance has been covered. As a result, the machine's capacity will not be fully utilized. The machine works at some point below the p_0 line, resulting in a capacity of

$$p = r \cdot v/f_g \text{ or } p = p_0 \cdot v/v_p$$

approved seedlings per time unit. The capacity falls in direct proportion to the speed relative to the highest speed.

In the area below the line, the machine can be used more efficiently by reducing the spacing (moving left in Figure 3) until we are back to the p_0 line. On the other hand, we will then have to increase the spacing between machine passes to maintain the required number of seedlings per ha. At the same time, the distance travelled per ha will be shorter and the number of turns smaller, thus additionally increasing productivity.

Equations (7) and (8) contain the information needed for further analysis of the influence of the planting device cycle time on a machine's capacity.

CYCLE TIME FOR SEEDLING FEED

Definition

The definition of "cycle time" is not very clear in the case of the seedling-feed function. It does not necessarily refer to the time it takes for a seedling to be transferred from the magazine to the tip of the planting head. Here it is defined as the time elapsing between the delivery of one seedling into the planting head and the delivery of the next one. This definition of the cycle time is independent of the type of feed system used and the different functions involved, though its magnitude is affected.

Seedling-Feed Systems

A wide variety of seedling-feed systems has been evaluated, ranging from seedling magazines loaded by hand to sophisticated, fully automated systems that pick the seedlings from the nursery trays. On simple planting machines with intermittent advance, the cycle time does not usually present any problem. On more complex machines that advance continuously, however, the available time during which the next seedling has to be delivered is often so short that it has proved difficult to devise fast and reliable feed systems.

There are two basic approaches to resolving the problem. One is to have a sufficient number of seedlings en route to the planting device so that the last leg is short enough to fit in with the required cycle time. The other approach is to have a fast-operating feed system with a cycle time shorter than that of the planting device.

A principal example of the second approach is the pneumatic seedling conveyor, which blows or sucks the seedling through a hose as far as the tip of the planting tube.

Pneumatic Seedling Conveyor

The basic problem to be overcome here can be described as using a stream of air to transport a seedling a given distance in a given time. The main variables are the type and size of seedling, air-flow rate, and hose size. The quantitative relationships among these variables are not known. The conflicting requirements of a short feed-cycle time, which means high air velocity, and low peat loss from the seedling container result in the need to have the longest feed time allowed by the cycle time of the planting device without having the device to wait too often for a seedling.

As part of a pilot study, seedling feed times were recorded at three air-flow rates, with other factors kept constant. A histogram of the feed times at air-flow rates of 15, 20, and 25 m/s is shown in Figure 4. The tall bar to the right of the diagram at 15 m/s indicates that many seedlings had feed times longer than three seconds. As can be seen, an increase in the air-flow rate reduces not only the feed time but also the spread of the feed time. For a number of reasons, the distribution is more or less skewed, which means that a corresponding proportion of seedlings will arrive so late that the planting device will have to wait, thus reducing the capacity of the machine. This seems to be a general pattern.

If the frequency function, $f(t)$, for the feed time is known, the average feed time, C_s, for the late-arriving seedlings can be calculated:

$$C_s = \frac{1}{1 - F(C_T)} \int_{C_T}^{\infty} t \cdot f(t)\,dt \qquad (9)$$

where $F(t)$ is the distribution function for the seedling feed time and C_T is defined by equation (2). C_s determines the position along the t-axis of the mass centre of the area below the frequency curve in which the values are greater than C_T (see Figure 5).

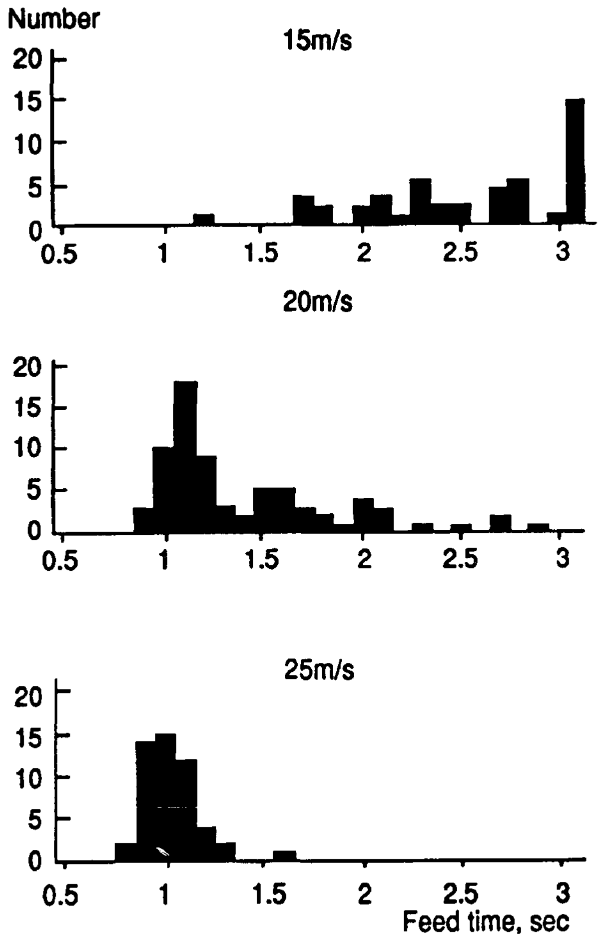

Figure 4. Example of histograms showing feed times at different air-flor rates. All other conditions are equal.

On the basis of Figure 4, it is reasonable to hypothesize that the feed time can be described by the chi-square distribution. The frequency function for three chi-square distributions having 4, 10, and 20 degrees of freedom, respectively, are shown in Figure 6. The characteristics of the chi-square distribution seem to agree with the variation displayed in the histograms. A reduction in the number of degrees of freedom in the chi-square distribution gives rise to a lower mean value and a narrower spread, which corresponds to an increase in the air-flow rate for a given hose diameter.

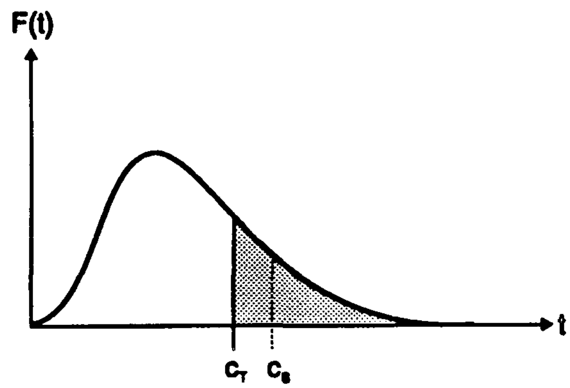

Figure 5. Example of the distribution of seedling feed times for the totalplanting-device cycle time, C_T, and the average cycle time for late-arriving seedlings, C_s.

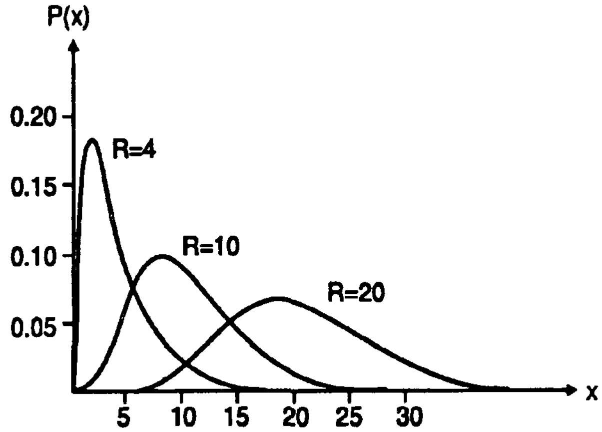

Figure 6. Frequency curves for some chi-square distributions, where R is the number of degrees of freedom.

OVERALL MACHINE OPERATING CYCLE

In practice, the cycle time of the planting device and that of the seedling feed system are taken together as the combined overall cycle time of the machine. Since we are interested in the average cycle time, the extent to which the individual cycles are in phase with each other does not matter. To achieve a systematic spacing between the seedlings it is critical that the planting device moves properly. As far as the planting device is concerned, the individual feed times for seedlings for which the device does not have to wait are of no interest. It can be assumed that all of their feed-cycle times were the same as the corresponding total cycle times for the planting device (C_T). Using C_s from equation (9) gives the average overall cycle time, C_a, for the machine:

$$C_a = F(C_T) \cdot C_T + (1 - F(C_T)) \cdot C_s \qquad (10)$$

The machine's operating cycle is a weighted combination of the planting device's cycle time for those seedlings delivered on time and of the cycle time of the late-arriving seedlings. Using equation (10), we can calculate the cycle time that should really be substituted for $C_p \cdot (1 + k_0 c)$ in equations (7) and (8) so as to obtain the values that take account of how the seedling feed system affects machine performance. Thus the highest possible speed we can use, considering retries and planting results, is

$$v_a = \frac{f_g \cdot g}{C_a} m/s \qquad (11)$$

and the related planting capacity

$$p_a = \frac{3600 r \cdot g}{C_a} \text{ seedlings per hour} \qquad (12)$$

SUMMARY

Equations (11) and (12) allow the innermost part of the performance of a continuously advancing planting machine to be modelled, even if theoretical seedling feed-time distributions have to be applied. Tests of plants in a feeding rig indicate that a skewed feed-time distribution, like the chi-square distribution, could be suitable in the model. However, it remains to determine how the statistical expressions can be linked to the physical properties of seedlings and the feeding system.

REFERENCES

[1] Adelsköld, G. et al. 1983. Mekaniserad plantering -- en ny operation i skogsbruket. Forskningsstiftelsen Skogsarbeten, Resultat nr 19, 1983. (All in Swedish.)

[2] Bäckström, P.-O. 1977. Mechanized planting -- A study of the literature concerning technical developments in artificial regeneration. Forskningsstiftelsen Skogsarbeten, Meddelande nr 12. (Summary in English.)

[3] Bäckström, P.-O. 1978. Mechanized planting -- Basic conditions, techniques, productivity and costs. Forskningsstiftelsen Skogsarbeten Meddelande nr 13. (Summary in English.)

[4] Bäckström, P.-O. and Wahlqvist, Å. 1972. Några system för skogsodling -- en analys. Forskningsstiftelsen Skogsarbeten, Redogörelse nr 10, 1972. (All in Swedish.)

[5] Cormier, D. and Ryans, M. 1992. Short- and long-term evaluation of the Silva Nova planting machine. FERIC Technical note TN-190.

[6] Hallonborg, U. 1991. Den maskinella planteringens utveckling. Plantnytt nr 1, 1991. Information från Skogsbrukets plantgrupp. (All in Swedish.)

[7] Landström, M. 1992. The Silva Nova Tree Planter in Canada. Forskningsstiftelsen Skogsarbeten, Results No 1.

[8] Malmberg, C.E. 1990. Mekanisering av skogsodling. STU. (All in Swedish.)

[9] Myhrman, D. et al. 1983. Fem planteringsmaskiner. Forskningsstiftelsen Skogsarbeten, Resultat nr 18, 1983. (All in Swedish.)

[10] Stjernberg, E.I. 1985. Tree planting machines: A review of the intermittent -- Furrow and spot-planting -- types. FERIC special report no. SR-31.