Feed-Time Distribution in Pneumatic Feeding of Softwood Seedlings

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ABSTRACT

Long seedling-feed times can restrict the performance of a planting machine. In this study feed times were measured in a pneumatic feed-test rig. Test variables were seedling type, air velocity and hose diameter. Feed-time histograms were then tested against chi-square distributions. Each accepted distribution was used for calculating the proportion of seedlings that could reach a planting head in time and the proportion arriving late, with respect to the machine-cycle time. The mean feed times for those two categories were then weighted together to obtain a total feed time. Two models for describing the total feed time, one for "normal" seedlings and one for "butt-ended" seedlings were constructed, with machine-cycle time, air velocity and fullness quotient as input variables.

Keywords: *Mechanized planting, pneumatic feeding, seedling transport, feed distribution.*

INTRODUCTION

Machines for planting softwood seedlings can be equipped with different types of seedling-feed systems. When a pneumatic feeding system is used, that is when the seedlings are blown or sucked through a hose, feed times cannot be fully controlled. Since seedling-feed times can restrict planting capacity, both their mean value and distribution are of interest (1).

The aim of this investigation was to determine whether chi-square distributions (1b) can provide a good model for seedling feed times, and if so, determine a model for the resulting feed time.

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$$f(x) := \frac{\alpha^{\lambda}}{\Gamma(\lambda)} \cdot x^{(\lambda-1)} \cdot e^{-\alpha \cdot x}$$

1(a)

$$f(x) := \frac{1}{2^{\frac{r}{2}} \cdot \Gamma\left(\frac{r}{2}\right)} \cdot x^{\frac{r}{2}-1} \cdot e^{\frac{-x}{2}}$$

1(b)

As chi-square distributions are only defined for integer values (degrees of freedom) on *r* and real values are used. They are in reality gamma distributions 1(a) with values of $\lambda = 0.5 \cdot r$ and $x = 0.5$ that are used. Nevertheless here they will be called chi-square distributions, mainly because they are single parametric. The distributions were used to calculate the proportion of seedlings that reach the planting head in time with respect to the planting head cycle-time and the proportion that arrive too late and cause a decrease in planting capacity.

The only known commercial tree-planting machine equipped with a pneumatic seedling-feed system is the Swedish Silva Nova. Therefore the feed tests were carried out in a rig with a hose configuration and diameters similar to those of the Silva Nova. Seedlings were sampled from production stores in the field. Some samples consisted of pine seedlings only, while others consisted of spruce only, and a third type contained both pine and spruce seedlings.

Although Larsson (3) reported a slight difference in friction coefficient between pine and spruce, no systematic difference between species was found in this study. This factor was therefore disregarded.

Feed-time histograms were obtained experimentally for different types of seedlings. They were fed through hoses with different diameters at controlled air velocities. Histograms obtained were compared with chi-square distributions, and the best-fitting curve was used to calculate the proportion of seedlings that reach the planting head within the machine's cycle time and the proportion of late seedlings.

Mean feed times for the on-time and late seedling groups were then used to calculate a total feed time as a proportion-weighted mean.

A linear model for predicting total feed time was then constructed using the data from each seedling batch as input.

MATERIALS AND METHODS

Seedlings

Seedlings of five types were sampled from production during the 1993 planting season (Table 1). In addition, Plantek seedlings were obtained directly from a new nursery system and thus had smaller green parts owing to their shorter period of growth.

Test rig

The test rig (Figure 1) was quite simple, consisting mainly of an electric fan that sucked air through a hose. Photocells measured the time it took for a seedling to move 4.2 m with a height difference of 1.5 m between two time–measurement points.

Measures and configuration of the hose were chosen to resemble the conditions on a Silva Nova. Likewise, hose type and inside diameters of 38, 50 and 63 mm were chosen. The hoses were made of transparent PVC with an inserted steel spiral that prevents flattening.

The seedlings were inserted vertically into the hose. The bottom of the container passed the first photocell, "starting the clock" once the whole seedling was well inside the hose. After a concave–up bow the seedling passed a point of inflexion and then a concave–down bow before going down to the second photocell, which "stopped the clock". The highest point in the last bow was level with the first photocell and thus 1.5 m above the second photocell. Further downstream there was a box where the seedlings stopped on cushioning material, and the air was led away to the fan. The box could be opened and the seedling taken out for further examination.

Time measurements were taken in hundredths of seconds and could be read from a digital display that was reset between seedlings.

Air velocities of 15, 20 and 25 m/s were chosen to cover the range used in practice. The velocity was measured with a propeller meter (Schiltknecht Miniair 2) and adjusted with a shunt on the above–mentioned box. Measurements were taken in the center of the hose at steady state with no seedling in the hose.

Some seedling–type/hose–diameter combinations were not tested. For very high or low fullness quotients, seedlings could not be properly transported.

Statistical methods

Briefly the idea behind the method is to find chi–square distributions that fit the feed–time histograms well enough to allow calculation of the proportion of seedlings on the right wing that will not reach the planting head in due time according to the cycle time of the machine.

First time readings for each combination of seedling type, hose diameter and air velocity were represented in a number of histograms with different class widths by rounding (Figure 2). For each class i, the histograms were then transformed from the real–time axis t to an x–axis by multiplying by a scale factor s and translating according to equation (2). At this point the scale factor is still an unknown variable

$$x_i = s \cdot (t_i - t_m) \qquad (2)$$

in which t_m is the shortest feed time. The transformed

Table 1. Type and number of tested seedlings, their container volume and largest cross–sectional area. Weight and length are mean values and ranges for the seedling type.

Seedling type	Number	Container volume, cm^3	Container cross-sectional area, cm^2	Total weight, g	Green length, cm
Blockplant 121	632	80	10.9	53	17
Blockplant 100	1132	95	13.0	62	17
Hiko V50	941	50	8.64	34	17
Planta 80	743	48	7.06	36	15
Plantek 121	631	50	10.1	38	12
Plantek 81	317	85	16.8	68	13

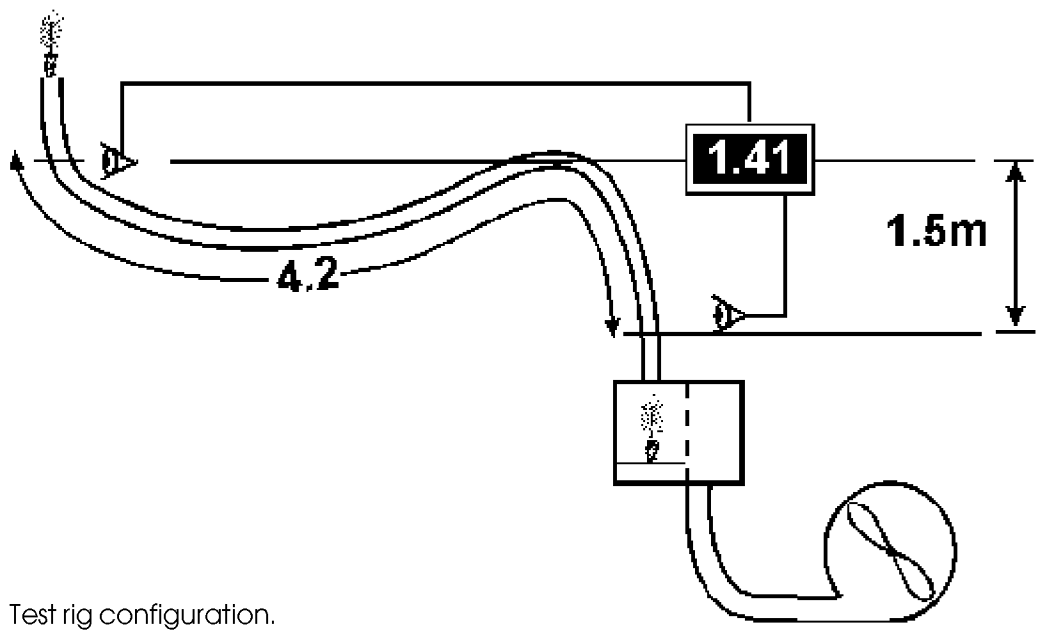

Figure 1. Test rig configuration.

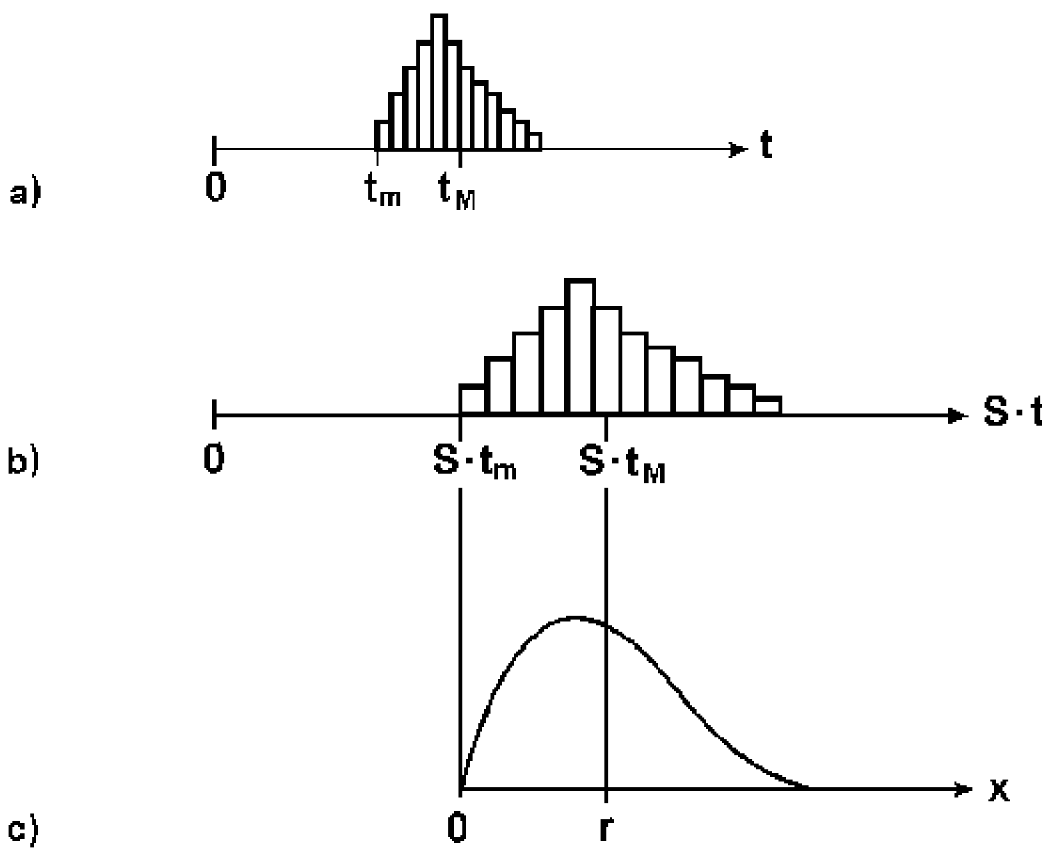

Figure 2. Original feed–time histogram (*a*), translated and multiplied histogram by a scale factor (*b*) and the adapted chi–square distribution (*c*) that starts at zero.

histogram for a specific class width was then compared with chi-square distributions (Figure 3).

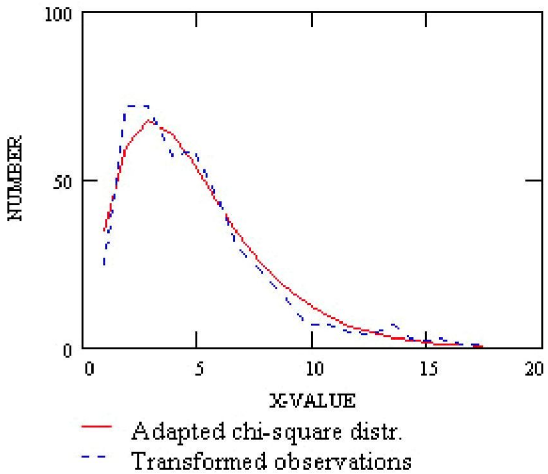

Figure 3. Chi-square distribution with rank 4.97 (solid) fitted to observed values (dashed) with class width 0.18 for Blockplant 100 at 20 m/s in 63 mm hose.

The sum of squared differences for each bar in the histogram was calculated and divided by the number of bars. This LS-mean value, $(obs\text{-}chi)^2/n$, was minimized by stepwise manual interactive adjustment of the rank r of the chi-square distribution and t_m under the condition that the mean value t_M of the histogram equaled the rank of the chi-square distribution, that is

$$r = s \cdot (t_M - t_m) \quad (3)$$

For every minimized LS-mean value a chi-square test was carried out to determine whether there was a significant difference between the histogram and the chi-square distribution function. Bars were augmented so that no more than two bars had theoretical values lower than 5. The number of degrees of freedom in the test was calculated as the resulting number of bars minus one. The significance level was set at 0.05.

The minimum LS-mean values form a regression curve that has its minimum for the class width that gives the best fit. Regression lines for rank, scale factor and lowest value give values for these, corresponding to the best class width (Figure 4). The regression model for LS-mean was a second-order polynomial and for rank, scale factor and lowest value a straight line.

To be able to calculate the seedling proportions, the planting head cycle time t_c must be transformed to the x-axis. This value, x_c, is given by (4)

$$x_c = s \cdot (t_c - t_m) \quad (4)$$

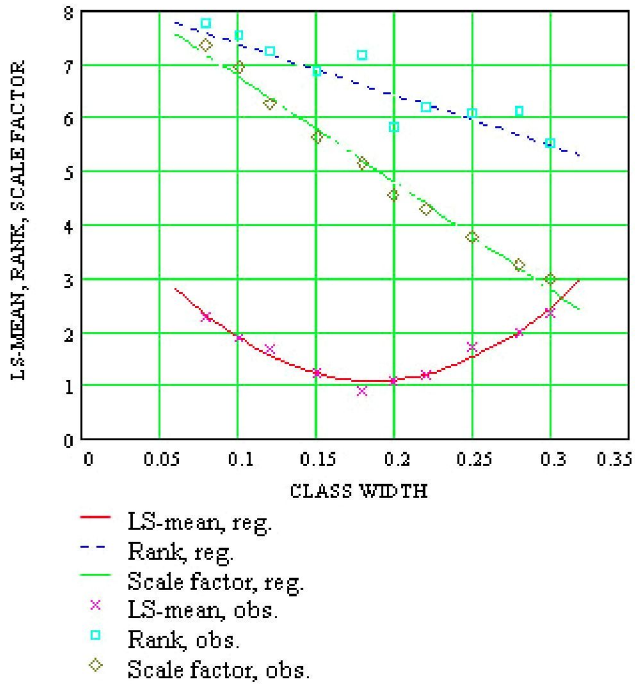

Figure 4. Regression lines over class width for Planta 80 at 15 m/s in a 50-mm hose.

Remaining on the x-axis the proportion of seedlings that reach the planting head at times shorter than or equal to t_c is

$$d = \int_0^{s\cdot(t_c - t_m)} f(x)dx \quad (5)$$

in which $f(x)$ is the frequency function for the fitted chi-square distribution. The late-arriving proportion is $1-d$, and their mean-feed time t_l

$$t_l = \frac{1}{1-d} \cdot \int_{s\cdot(t_c - t_m)}^{\infty} x \cdot f \quad (6)$$

The late feed time can be transformed back to the real-time axis and the resulting total feed time, T, for all plants calculated as the weighted mean of t_c and t_l as

$$T = d \cdot t_c + (1-d) \cdot (t_l / s + t_m) \quad (7)$$

Transformation back to the real time axis by

$$t = x/s + t_m \quad (8)$$

gives the resulting distribution curve in real time (Figure 5).

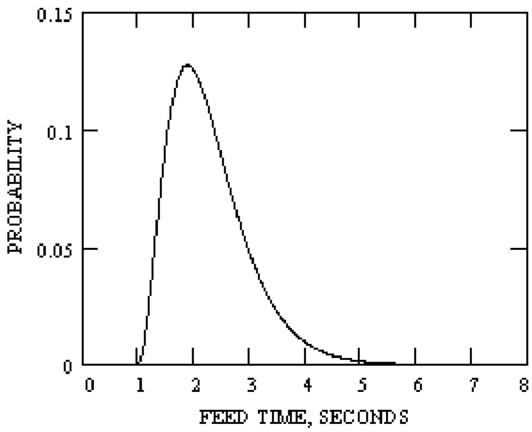

Figure 5. Resulting real–time distribution curve for Planta 80 at 15 m/s in a 50-mm hose.

Calculations according to equation (7) were carried through for each combination of seedling type, hose diameter and air velocity at cycle times of 2.0, 2.4, 2.5 and 3.0 seconds. If the percentage of seedlings arriving in time reached 100 at cycle times shorter than 3.0 seconds, the shorter cycle time was used in constructing the model. The 100-percent limit turned out to be very diffuse due to the smooth asymptotic character of the right wings of the distributions; therefore two values were used: One value where the rounded total feed time equaled t_c and one value where the rounded total feed time was one hundredth of a second longer than t_c. This way each batch that could be used in constructing the model generated at least two sets of input data.

A linear model was then formed with machine–cycle time, air velocity and the quotient of fullness q (container cross–sectional area divided by hose cross–sectional area) as independent variables and the total feed time T as dependent variable. In fact, the test results induced the construction of two separate models by separating the seedling batches into two groups.

More direct methods by Scott and Freedman and Diaconis, reviewed by Hoaglin, Mosteller and Tukey (2), were tried in order to find the best class width. Methods based on the number of observations, n, and standard deviation did not work well. Standard deviation is sensitive to extreme values which are not wanted in this case, especially not on the left wing of the distribution. A more resistant measure is the IQR, the inter–quartile range. Working on the basis of that criterion Freedman and Diaconis arrive at:

$$h = 2 \cdot IQR / \sqrt[3]{n} \quad (9)$$

in which h is the class width. This method was evaluated.

RESULTS

Seedling transport did not work for three out of 33 test batches. All three failures occurred at an air velocity of 15 m/s, which evidently did not provide the drag force on the seedling required to overcome friction and gravity. Test data for the different seedling batches are given in Table 2.

Results of the optimization and goodness–of–fit tests are given in table 3. Rank scale factor and lowest value are the regression values corresponding to the minimum point of the regression line for the LS–mean values. Since the shortest feed time, t_m was only used as a start value in the optimization the resulting lowest value in table 3 is different. Due to the regression procedure the resulting mean feed times can also differ from those in table 2. The regression values do not correspond exactly. These mean feed times are calculated by inserting r for x in eq. (8).

R–square values for the regressions were greater than 0.84 for LS–mean and rank except in one case where it was 0.67 for LS–mean and two cases where it was 0.76 for rank. For the scale factor, R–squared values were at least 0.90 in all cases.

A significant difference between the feed–time distribution and chi–square distributions at the 5% level was only found in six of 30 cases. This indicates that chi–square distributions can be used as an approximation of feed–time distributions.

Four of the six exceptions involve Hiko seedlings. The pine batch run at 20 m/s with 50-mm hose (p=0.002) is adjacent to one for which the transport failed. Moreover, it was the only batch with negative skewness. All three spruce batches had high skewness compared with the rest of the batches. The 15 m/s batch is a limit case (p= 0.047), but the other two show a highly significant disagreement with chi–square distributions with $= 0.5 \cdot r$.

The fifth batch that did not agree with a chi–square distribution was Blockplant 100 at 25 m/s, which also had a high skewness. This batch and the two Hiko batches with high skewness decrease too rapidly to the right of their maximum to agree with distributions with lambda values as high as $0.5 \cdot r$. Lower values on lambda would give a narrower distribution and better agreement.

The sixth batch that disagreed (p=0.011) was Plantek 121 at 15 m/s. No reason for this could be found based on its skewness.

Table 2. Feed test data for the different seedling batches. The quotient of fullness, *q*, is the inside hose cross–sectional area divided by the largest container cross–sectional area. Q_3-Q_1 is the range between the 1st and 3rd quartile.

						Feed time				
Seedling type	Species	n	Hose	Quotient of fullness, q	Air vel. m/s	min, t_m	mean, t_M	Std dev.	Skewness	Q3-Q1
Plantek 121	Pine/	104	38	0.89	15	0.91	1.46	0.49	0.93	0.70
	Spruce	106	38	0.89	20	0.62	0.90	0.26	1.23	0.35
		109	38	0.89	25	0.50	0.75	0.21	1.01	0.29
		107	50	0.51	15	1.16	2.19	0.68	0.55	1.14
		112	50	0.51	20	0.90	1.38	0.36	0.75	0.53
		93	50	0.51	25	0.62	0.85	0.14	1.26	0.13
Planta 80	Spruce	114	38	0.76	15	1.04	1.85	0.56	0.60	0.84
		143	38	0.76	20	0.90	1.45	0.34	0.75	0.47
		107	38	0.76	25	0.85	1.11	0.17	0.55	0.27
		143	50	0.44	15	1.26	2.38	0.59	0.28	0.90
		144	50	0.44	20	0.86	1.50	0.43	0.70	0.61
		92	50	0.44	25	0.78	1.14	0.29	1.21	0.33
HIKO V50	Spruce	154	38	0.62	15	1.06	1.38	0.20	1.92	0.20
		190	38	0.62	20	0.80	0.93	0.13	3.44	0.90
		162	38	0.62	25	0.63	0.85	0.21	2.44	0.13
	Pine	62	38	0.62	15	1.08	1.35	0.13	0.49	0.13
		108	38	0.62	20	0.71	0.86	0.09	0.29	0.14
		52	38	0.62	25	0.61	0.71	0.06	0.54	0.08
		-	50	0.36	15	-	-	-	-	-
		136	50	0.36	20	0.71	1.09	0.17	-0.25	0.25
		77	50	0.36	25	0.79	0.94	0.08	0.28	0.11
Plantek 81	Pine/	93	50	0.86	15	1.02	2.50	0.87	0.01	1.58
	Spruce	107	50	0.86	20	0.87	1.83	0.83	0.93	1.14
		117	50	0.86	25	0.66	1.25	0.45	1.17	0.50
Blockplant 121	Spruce	-	50	0.55	15	-	-	-	-	-
		97	50	0.55	20	1.01	2.90	1.42	0.50	2.41
		139	50	0.55	25	0.81	1.39	0.46	1.64	0.43
		-	63	0.35	15	-	-	-	-	-
		266	63	0.35	20	0.94	1.42	0.42	1.72	0.46
		130	63	0.35	25	0.74	1.00	0.16	1.93	0.12
Blockplant 100	Pine	249	63	0.42	15	1.12	3.12	1.97	0.14	0.58
		437	63	0.42	20	0.79	1.62	0.57	1.35	0.67
		446	63	0.42	25	0.63	0.99	0.27	2.56	0.28

Table 3. Results from optimization and goodness–of–fit test. The three rightmost columns contain class widths obtained by optimization and by using the Freedman and Diaconis formula with exponent 0.333 and 0.268 respectively.

Seedling type	rank r	Scale factor s	G-o-f p	Feed times, second lowest	mean	Class width, seconds optimal	F-D (0.333)	F-D (0.268)
Plantek 121	4.31	6.29	0.01	0.76	1.45	0.12	0.15	0.20
	3.71	10.80	0.07	0.55	0.89	0.08	0.07	0.10
	4.13	12.50	0.14	0.39	0.72	0.08	0.06	0.08
	5.05	3.97	0.26	0.84	2.11	0.24	0.24	0.33
	4.91	7.41	0.70	0.67	1.33	0.13	0.11	0.15
	6.32	24.50	0.22	0.57	0.83	0.04	0.03	0.04
Planta 80	5.07	5.09	0.76	0.79	1.79	0.19	0.17	0.24
	4.72	7.07	0.29	0.71	1.38	0.15	0.09	0.12
	4.37	13.50	0.91	0.74	1.06	0.08	0.06	0.08
	6.55	5.04	0.50	0.99	2.18	0.19	0.17	0.24
	4.88	5.90	0.10	0.63	1.46	0.18	0.12	0.16
	4.53	9.63	0.94	0.65	1.12	0.10	0.07	0.10
HIKO V50	6.18	15.00	0.05	1.02	1.43	0.05	0.04	0.05
	3.85	19.10	0.00	0.73	0.93	0.04	0.02	0.02
	4.08	14.10	0.00	0.56	0.85	0.04	0.02	0.03
	5.68	22.20	0.55	1.08	1.34	0.04	0.03	0.04
	5.64	29.70	0.46	0.65	0.84	0.03	0.03	0.04
	4.90	40.10	0.42	0.58	0.70	0.02	0.02	0.03
	-	-	-	-	-	-	-	-
	5.86	11.30	0.00	0.48	1.00	0.07	0.05	0.07
	4.70	28.40	0.18	0.70	0.89	0.04	0.03	0.03
Plantek 81	5.05	2.33	0.39	0.19	2.36	0.37	0.35	0.47
	3.75	2.84	0.20	0.44	1.76	0.32	0.24	0.33
	5.06	6.54	0.47	0.44	1.21	0.15	0.10	0.14
Blockplant 121	-	-	-	-	-	-	-	-
	3.06	1.36	0.37	0.47	2.72	0.64	0.53	0.71
	3.74	5.49	0.06	0.76	1.44	0.16	0.08	0.11
	-	-	-	-	-	-	-	-
	2.36	4.36	0.30	0.91	1.41	0.20	0.07	0.10
	3.11	14.70	0.08	0.79	1.00	0.07	0.02	0.03
Blockplant 100	6.34	2.50	0.13	0.48	3.01	0.39	0.25	0.36
	5.36	5.80	0.25	0.69	1.61	0.18	0.09	0.13
	5.31	11.00	0.00	0.50	1.00	0.08	0.04	0.05

Treating all batches as one homogenous group was not successful because the characteristics of the individual batches differed too much. By contrast, it was useful to divide the seedling batches into two groups: Group A, containing Plantek 121-, Planta 80- and Hiko seedlings, and Group B, containing Plantek 81- and Blockplant seedlings.

One strong indication that this was a valid partitioning was the difference in mean feed times (Table 2 and 3). In both groups the slopes of the lines were significantly different from zero ($p < 0.003$) and from each other ($p < 0.004$). R–square values were rather low, i.e. 0.6 – 0.7 (Figure 6).

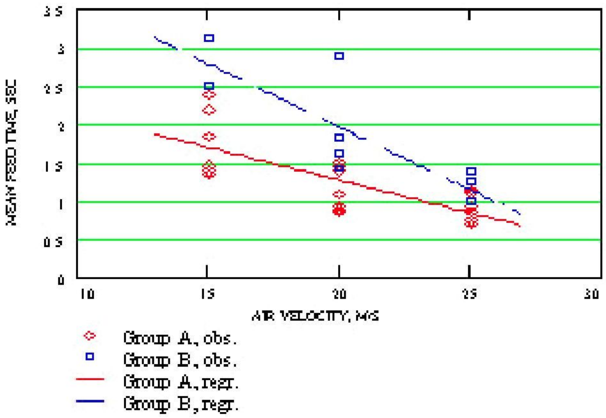

Figure 6. Mean feed times for seedling batches in group A (diamonds) and group B (squares), and their regression lines over air velocity.

For seedling group A the resulting model was:

$$T = 0.977 \cdot t_C - 0.014 \cdot v - 0.179 \cdot q + 0.482 \qquad (10)$$

and for group B:

$$T = 0.793 \cdot t_C - 0.051 \cdot v + 0.418 \cdot q + 1.420 \qquad (11)$$

In both models the coefficients were significantly different from zero ($p < 0.001$ for all except the quotient of fullness for group A, for which $p = 0.005$). The R-squared value is 0.98 for both models and the standard error for T less than 1.5%.

In the Freedman and Diaconis formula, equation (9), $2 \cdot IQR$ corresponds to Q_3-Q_1 in table 2. The third column from the right in table 3 gives the class widths obtained in the optimizing process. Class widths, h, according to (9) are given in the next column. If the exponent in the Freedman and Diaconis formula is altered from 0.333 to 0.268 class widths will be equal to those shown in the rightmost column.

Equations like (10) and (11) can be used to study how a specific planting machine with a given cycle time is influenced by different seedling types or to determine expected feed times at different cycle times for a specific type of seedling. In the first case t_C is held constant and tables like Table 4 are obtained. In the second case q is held constant, and tables like Table 5 are obtained.

Table 4. Total feed times, T, for quotients of fullness, q, between 0.3 and 0.9 for group A seedlings at machine cycle time t_C= 2.5 seconds and air velocities of 15 - 25 m/s.

	Air velocity, m/s										
	15	16	17	18	19	20	21	22	23	24	25
0.30	2.654	2.639	2.625	2.611	2.596	2.582	2.567	2.553	2.539	2.524	2.510
0.35	2.645	2.631	2.616	2.602	2.587	2.573	2.559	2.544	2.530	2.515	2.501
0.40	2.636	2.622	2.607	2.593	2.578	2.564	2.550	2.535	2.521	2.506	2.5
0.45	2.627	2.613	2.598	2.584	2.569	2.555	2.541	2.526	2.512	2.5	2.5
0.50	2.618	2.604	2.589	2.575	2.560	2.546	2.532	2.517	2.503	2.5	2.5
q 0.55	2.609	2.595	2.580	2.566	2.552	2.537	2.523	2.508	2.5	2.5	2.5
0.60	2.600	2.586	2.571	2.557	2.543	2.528	2.514	2.5	2.5	2.5	2.5
0.65	2.591	2.577	2.562	2.548	2.534	2.519	2.505	2.5	2.5	2.5	2.5
0.70	2.582	2.568	2.553	2.539	2.525	2.510	2.5	2.5	2.5	2.5	2.5
0.75	2.573	2.559	2.545	2.530	2.516	2.501	2.5	2.5	2.5	2.5	2.5
0.80	2.564	2.550	2.536	2.521	2.507	2.5	2.5	2.5	2.5	2.5	2.5
0.85	2.555	2.541	2.527	2.512	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.90	2.546	2.532	2.518	2.503	2.5	2.5	2.5	2.5	2.5	2.5	2.5

Table 5. Total feed times, *T*, for machine cycle times, t_C, between 2 and 3 seconds for Planta 80 (q = 0.76) from group A in a 38-mm hose.

	Air velocity, m/s 15	16	17	18	19	20	21	22	23	24	25
2.0	2.083	2.069	2.054	2.040	2.026	2.011	2.0	2.0	2.0	2.0	2.0
2.1	2.181	2.167	2.152	2.138	2.123	2.109	2.1	2.1	2.1	2.1	2.1
2.2	2.279	2.264	2.250	2.235	2.221	2.207	2.2	2.2	2.2	2.2	2.2
2.3	2.376	2.362	2.347	2.333	2.319	2.304	2.3	2.3	2.3	2.3	2.3
2.4	2.474	2.459	2.445	2.431	2.416	2.402	2.4	2.4	2.4	2.4	2.4
t_C, s 2.5	2.572	2.557	2.543	2.528	2.514	2.5	2.5	2.5	2.5	2.5	2.5
2.6	2.669	2.655	2.640	2.626	2.612	2.6	2.6	2.6	2.6	2.6	2.6
2.7	2.767	2.752	2.738	2.724	2.709	2.7	2.7	2.7	2.7	2.7	2.7
2.8	2.864	2.850	2.836	2.821	2.807	2.8	2.8	2.8	2.8	2.8	2.8
2.9	2.962	2.948	2.933	2.919	2.905	2.9	2.9	2.9	2.9	2.9	2.9
3.0	3.060	3.045	3.031	3.017	3.002	3.0	3.0	3.0	3.0	3.0	3.0

In both tables model estimates lower than the machine cycle time are set equal to the machine cycle time.

DISCUSSION

Chi-square distributions can be used as a model to describe the feed-time distribution for many combinations of seedling type, air velocity and hose diameter in the pneumatic feeding of softwood seedlings. Real values for the rank of the chi-square distribution must be used in order to achieve an acceptably high degree of resolution. A full expansion of the model to gamma distributions would probably give significant agreement for all the batches in this study. In that case a computer program would have to be used to handle the stepwise adaption of lambda, rank and lowest value.

The test rig configuration has been fixed throughout this study. The fact that standard deviation as well as Q_3 - Q_1 are proportional to the mean value for both seedling groups confirms that there is no reason to believe that the feed–time pattern would be radically different if the hose length or alignment were slightly altered. Feed times for other hose lengths would then be roughly proportional to the length.

Division of the seedling batches into two groups made it possible to construct good models. There are three main differences between the models:

- Feed times are generally lower for model A.
- Model A is less dependent on air velocity.
- Model A has a negative coefficient for dependence on quotient of fullness, whereas model B has a positive one.

The first two mentioned differences are not unusual. The third however, a positive coefficient for dependence on quotient of fullness is not logical. A reason for this outcome could be differences in the aerodynamics around the container bottom (4). All seedling types in group B have a rather large butt–end area perpendicular to the container axis. Furthermore Blockplant seedlings have an equally thick container. As a result, eddies form at the container end. Under certain conditions the eddies are continuously shed alternately from different sides of the container, causing the seedling to wobble. The container would be flung from one side of the hose to the other, resulting in a prolongation of the feed time.

Wobbling was observed visually during the study, and wobbling seedlings were counted. Wobbling was rare at 15 m/s. At 20 or 25 m/s the percentage of wobbling seedlings was clearly higher for group B seedlings (10-75%) compared with group A seedlings (at most 15%). For several batches the wobbline percentage was highest at 20 m/s, which suggests that there is a maximum at some intermediate air velocity. In any case, wobbling could not be included in either of the two linear models. Still wobbling may be an important factor responsible for differences in seedling behavior between A and B.

Finding the best class width for adaptation of the chi-square distribution through optimization requires a lot of calculations. The Freedman and Diaconis formula provides a good start irrespective of whether the traditional exponent is changed slightly. It is standard practice to use class widths of the form 1, 2 or 5 times a power of 10. Direct use of the formula gave 12 hits out of 30 batches. For all except one of the other batches, class widths were one step narrower. When 0.268 was used as the exponent instead of 0.333 the number of hits reached a maximum of 21. Three out of four misses in seedling group A involved batches without a matching chi-square distribution. The fourth was due to double rounding.

Some practical problems were encountered during the feed tests. For instance, some seedlings did not stop the time measurement, especially at low quotients of fullness, resulting in a reduced number of observations.

At low quotients of fullness and low air speeds some seedlings have feed times that are three or four times the machine-cycle time. What should the longest allowable feed time be?

Some types of seedling containers tend to release peat which moves ahead of the seedling and shuts off the time measurement too early. Therefore it is important to scrutinize raw data, especially the left wing of the obtained distribution.

SUMMARY

Feed-time distributions in pneumatic seedling-feed equipment can be satisfactorily described by chi-square distributions. For very fast seedling types (Hiko) values smaller than $= 0.5 \cdot r$ should be used. Though butt-ended seedling types show an illogical behavior, probably due to wobbling, their feed-time distributions can also be obtained with the described method. The proportion of late seedlings calculated from the chi-square distributions agree rather well with those observed within the range of interest. Differences in behavior between seedling types led to the development of two models for describing the total feed time. These two models can be used to simulate the productivity of planting machines with pneumatic seedling-feed systems or to analyze such systems in other ways.

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