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TECHNOLOGICAL RESEARCH OF PNEUMOSEPARATOR FOR FOREST SEED EXTRACTION

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ABSTRACT

A technological study on the operation of a pneumatic separator on a BCC Cleaner&Seed Sizer (mini) machine for extraction of Scots pine (*Pinus sylvestris* L.) seeds has been carried out. It is part of the new technological equipment for greenhouse production of container seedlings in the Lokorsko forest nursery. Compared to the traditional production of saplings in Bulgaria for afforestation, the new production requires the extracted seeds to have higher quality indicators. In order to establish the optimal operating modes of the pneumoseparator for high quality seed production, with minimal seed losses in the waste in the aspiration system, a multifactor active experiment and optimization in the treatment of Scots pine seeds was conducted. The obtained results were used to establishment of a regression models to predict the technological parameters and the quality of the obtained seeds depending on the operating modes of the machine. The optimal parameters for setting the pneumatic separator have been established and functional modes for Scots pine seeds extraction have been determined.

Key words: pneumoseparator, scots pine seeds, quality, models, optimization.

INTRODUCTION

The production of forest seeds with good genetic and quality indicators plays an important role in the sustainable regeneration of forest ecosystems at the regional and global level. According to data from the Executive Forest Agency in Bulgaria, during the period 2005 to 2015 year, there is a significant decline in forest seeds yield. After 2017 there is a certain increase in the yield of seeds of coniferous species, and this trend is more noticeable after 2019. This can be explained by the increase in afforestation and the commissioning of a modern line for the production of container seedlings in the forest nursery in the Lokorsko village. In 2018, a new technological system of modern machines for seed extracting and production of containerized saplings were implemented in the Lokorsko forest nursery with an annual capacity of 1.4 million saplings. Compared to the traditional technology for production of saplings with open root system, the new technology has a number of advantages, such as shorter growing period, extension of the afforestation period, better survival rate of the planted seedlings and less technological waste; introduction of full mechanization and automation of the production process, better working conditions, etc. (Marinov 2012). The machines and technological equipment were supplied by the Swedish company BCC "Plant the Planet", a leader in technology and machinery for forest seed production and production of container saplings for afforestation purposes.

The main part of the produced seeds is used in the nursery for exact sowing in the production of containerized saplings. This implies that the seeds have high germination and purity. When germination is lower it is necessary to sow 2 or 3 pcs. of seeds in a container nest. The use of seeds with lower sowing qualities leads to less efficient use of the expensive greenhouse area, increasing the cost and price of seedlings (Zhigunov 2000, Marinov 2012).

For producing seeds with high sowing qualities, a precise adjustment of the working bodies of the machines is required (Glushkov et al. 2009, Zemlyanukhin and Skrynnikov 1990, Sviridov 1986, Sviridov and Skrynnikov 1987). The machine for cleaning and sorting seeds BCC Cleaner & Seed Sizer / mini / consists of a pneumatic separator and two flat cascade sieves (Fig. 1). For the removal of empty and underdeveloped seeds from Scots pine, the working speed of the air flow in the pneumatic separator must be not less than 7 m/s (Marinov 1998, Skrynnikov 1985).

The operating modes of the pneumatic separator of BCC Cleaner & Seed Sizer are controlled by an adjustable valve (aperture), located in the working channel of the aspirator and a belt conveyor (feeder), feeding the processed seed material from the feed hopper into the aspirator channel. Currently, the forest enterprise does not have an instruction or manual for setting up the pneumatic separator for Scots pine seeds production, harvested from local seed plantations in Bulgaria, which significantly complicates its operation.

Figure 1: BCC Cleaner & Seed Sizer pneumoseparator image (photo K. Marinov)

The aim of the present study is to determine the way of influence of the working components of pneumatic separator BCC Cleaner & Seed Sizer on the technological parameters of the process and to establish the optimal technological regimes and functional settings of the machine for cleaning and sizing of Scots pine seeds from indigenous plants.

MATERIALS AND METHODS

To achieve the goal of the study, an active experiment is planned with a BCC Cleaner & Seed Sizer pneumoseparator for the production of Scots pine seeds from local sources. The obtained results will be used to compile mathematical models expressing the relationship between the main technological indicators of the studied process. With their help it will be possible to find optimal solutions and functional regimes for extraction of Scots pine seeds with certain quality indicators. The working sizes of the sieves are selected in accordance with the normal biometric parameters of Scots pine seeds obtained from our local sources (Vassilev 1964, Marinov 1996).

Preliminary experimental observations show that for the production of Scots pine seeds, the first sieve must have holes with a diameter of ø2.25 mm and for the second sieve – ø3.25 mm, which produces three fractions: – normally developed seeds, small impurities with underdeveloped seeds and large impurities.

Research parameters

Input parameters. To conduct the experiment, the control elements of the pneumatic separator were selected as input control factors: – feeder speed regulator (supply belt) and aperture level position for regulating the air flow rate in the working channel of the aspirator. These bodies meet the requirements of manageability, compatibility and mutual independence. The two controllable factors in the design of the experiment have the following designations:

X_1 – feeder speed, adjustable on a ten-point scale;

X_2 – hood of the aspirator, adjustable on a fifteen degree scale.

Output parameters. The initial parameters are selected in accordance with the purpose of the study and are directly related to the technological indicators of the studied process. The following indicators were selected as initial parameters of the study:

Y_1 – percentage of harvested whole grain seeds, %

Y_2 – purity of the obtained seeds, %;

Y_3 – percentage of whole grain seeds in the waste of the pneumatic separator, %

Y_4 – operating capacity of the pneumatic separator and the machine, kg/h.

The indicator Y_1, percentage of whole grain seeds in the yield, is the main criterion in determining the germination of seeds used for sowing. It expresses in percentage terms the number of complete viable seeds obtained in relation to their total number. The purity of the harvested seeds Y_2 is the main indicator characterizing the efficiency of the seed cleaning machine. It expresses as a percentage the quantity of pure seeds obtained in relation to the total quantity of seeds obtained. The percentage of whole grain seeds in the waste – Y_3 characterizes the loss of seeds in the cyclone of the pneumatic separator. The operational productivity Y_4 is a key indicator of the technological capabilities of the machine and the time consumption for the production of 1 kg of seeds.

Materials, methods and working conditions

For the study, wingless Scots pine seeds were used, treated with a wet aqueous and then dried to humidity W = 8 ÷ 10%. The sowing materials were obtained in 2021 from autochthonous seed plantations in the Western Rhodopes Mountains, from the area of Mihalkovo State Forestry, subdivision 69 "e", at an average altitude of 1500 m. They have a certificate for identification of reproductive material № BG P13100121/ 10.12.2021 and registration № according to the register of WBG: CO2 – PSY – 08-6-221-1–2. The seed control samples are made at the entrance and exit of the machine and were tested in the laboratory of the Forest Seed Control Station – Sofia according to the approved methods of the Bulgarian State Standard (BDS 1953:99) and the International Seed Testing Rules (IRST). The sowing qualities are determined in accordance with the requirements of the standard “Seeds of forest trees and shrubs. Sowing qualities" (BDS 208:99).

The initial parameter Y1, whole grain seeds in yield, is determined by the formula,

$$\boldsymbol{Y_1} = \frac{\boldsymbol{N}_{\text{п}}}{\boldsymbol{N}_{\text{o}}}.100,\ \% \qquad \textbf{(1)}$$

where $N_{п}$ is the number of whole grain (non-empty) seeds,

N_o is the total number of tested seeds;

The initial parameter Y_2, purity of the obtained seeds, is determined by the formula:

$$\boldsymbol{Y_2} = \frac{\boldsymbol{m_o}}{\boldsymbol{M}}.\mathbf{100},\%, \qquad \textbf{(2)}$$

where m_o is the mass of pure seeds after treatment, g;

M is the total mass of seeds before treatment, g.

The initial parameter Y_3, whole grain seeds in the waste, is determined in the same way as the parameter Y_1, with the difference that the test samples are from the waste fraction.

Operational productivity Y_4 is determined by timing according to the following formula:

$$\boldsymbol{Y_4} = \mathbf{3.6}\frac{\boldsymbol{M}}{\boldsymbol{t}},\ \text{kg/h}, \qquad \textbf{(3)}$$

where t is the duration of the experiment, s.

Methodology of experimental research

Design of experiment

From the experimental studies conducted so far on the pneumoseparator it was found that the change of the output parameters Y_j has a nonlinear character, compared to the change of the input factors X_i (Marinov and Ivanov 2021). Given this fact and the possibility of active control of the two input factors, as well as the search for optimal solutions for setting up the machine, for conducting the experimental study was chosen D-optimal composition plan of the second order – type B_m (Vuchkov and Stoyanov 1986). The selected plan of type B_2 has two input control factors X_1 and X_2, with three levels of variation (Table 1).

This design is suitable for conducting both single-purpose and multi-purpose optimization to establish the optimal values of the factors. Nine experimental points are planned for the study, with three repetitions at each experimental point, at different levels of variation of the factors.

Table 1: Design of two-factor active experiment for forest seeds cleaning in the pneumatic separator of BCC Cleaner & Seed Sizer machine

№ Exp.	Input parameters		Output parameters			
	Coded form		Non-empty produced seeds	Purity of produced seeds	Seed losses	Operational productivity
	X_1	X_2	Y_1 [%]	Y_2 [%]	Y_3 [%]	Y_4 [kg/h]
1	1	1	$Y_{1,1}$	$Y_{2,1}$	$Y_{3,1}$	$Y_{4,1}$
2	1	-1	$Y_{1,2}$	$Y_{2,2}$	$Y_{3,2}$	$Y_{4,2}$
3	-1	1	$Y_{1,3}$	$Y_{2,3}$	$Y_{3,3}$	$Y_{4,3}$
4	-1	-1	$Y_{1,4}$	$Y_{2,4}$	$Y_{3,4}$	$Y_{4,4}$
5	1	0	$Y_{1,5}$	$Y_{2,5}$	$Y_{3,5}$	$Y_{4,5}$
6	-1	0	$Y_{1,6}$	$Y_{2,6}$	$Y_{3,6}$	$Y_{4,6}$
7	0	1	$Y_{1,7}$	$Y_{2,7}$	$Y_{3,7}$	$Y_{4,7}$
8	0	-1	$Y_{1,8}$	$Y_{2,8}$	$Y_{3,8}$	$Y_{4,8}$
9	0	0	$Y_{1,9}$	$Y_{2,9}$	$Y_{3,9}$	$Y_{4,9}$

The required mathematical model, which can express the expected result as a function of the response, is described by a second-order polynomial and has the following form:

$$\hat{y} = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i<j} b_{ij} x_i x_j + \sum_{i=1}^{m} b_{ii} x_i^2 \qquad \textbf{(4)}$$

where $-1 \leq x_i \leq 1$ are the coded values of the factors $i = 1, 2, \ldots, m$;

$m = 2$ are the number of input control factors;

b_o is the regression coefficient of the free member;

b_i are the regression coefficients of the linear members;

b_{ij} are the regression coefficients of interaction between the linear members;

b_{ii} are the regression coefficients of the square terms.

Optimization of the technological process

The optimal parameters of the studied process are determined by applying technological and technical-economic criteria (Marinov 2008).

Technological criteria:

Maximum germination (non-empty) of the obtained seeds:

$Y_1 \rightarrow$ max;

Maximum purity of the obtained seeds:

$Y_2 \rightarrow$ max;

Minimum loss of whole grain seeds:

$Y_3 \rightarrow$ min;

Techno-economic criteria:

Maximum operational productivity:

$Y_4 \rightarrow$ max;

The optimization study is performed on the basis of the objective functions of formula (4). It can be performed by single-purpose or multi-purpose optimization. The method of the gradient algorithm is used for the search for optimal solutions in the one-goal optimization, and in the two-goal optimization – the genetic algorithm. When applying the single-purpose optimization, it was found that with fewer computational procedures, results are obtained that do not differ significantly from those of the dual-purpose optimization. Therefore, to simplify the procedure, single-purpose single-function optimization is applied in the present work.

The presence of empty seeds in the yield has a very strong influence on the final quality of the obtained seeds. This determines the great importance of the first studied parameter Y_1 when choosing a target function. The second indicator Y_2 also strongly influences the quality of the obtained seeds and is an important target function. For both functions it is necessary to find their maximum. The third parameter Y_3 affects the yield and losses of whole seeds, but not the quality of yield. The fourth parameter Y_4 affects only the technical and economic indicators of the process.

The production of container saplings requires precise exact sowing with seeds with the highest level of germination and whole grain. This implies that the seeds used for sowing should be of maximum high grain size and purity, which determines the choice of the following two target optimization functions:

$$Y_1 \rightarrow \text{max};\ Y_2 \rightarrow \text{max} \qquad \textbf{(5)}$$

To find the maximum of the objective functions and define the optimal solutions, the method of the gradient algorithm is applied, with up to 500 iterations (Vuchkov and Stoyanov 1986).

RESULTS

The seed control samples were tested in the laboratory of the Forest Seed Control Station – Sofia in the spring of 2022. The input factors were controlled by changing the speed of the feeder and the aperture of the aspirator, according to the experimental plan (Table 1). To establish the optimal parameters of the studied process, an active experiment was carried out with Scots pine seeds, with three levels of variation of factors. The values of the variation of the factors in explicit and coded form are:

Levels of the "Feeder" factor: – natural form X_1 = 3; 5; 7; – coded form X_1 = -1; 0; 1.

Levels of the "Aperture" factor – natural form X_2 = 5; 8.5; 12; – coded form X_1 = -1; 0; 1.

The results of the preliminary experimental observations showed that these levels of factors are compatible and favorable for the optimization of the studied technological process. The results of the experiment are presented in Table 2. Based on them, graphical dependences are constructed, expressing the change of the studied parameters Y_1, Y_2 and Y_3 depending on the input factors X_1 and X_2 (Fig. 2, Fig. 3 and Fig. 4).

Table 2: Experimental results on the quality of Scots pine seeds produced and seed losses

№ Exp.	Input parameters				Output parameters		
	Coded form		Natural form		Non-empty produced seeds	Purity of produced seeds	Seed losses
	X_1	X_2	X_1 Feeder speed [level]	X_2, Aperture of aspirator [level]	Y_1 [%]	Y_2 [%]	Y_3 [%]
1	1	1	7	12	81	97.8	0
2	1	-1	7	5	93	99.3	3
3	-1	1	3	12	88	99.1	3
4	-1	-1	3	5	99	99.9	8
5	1	0	7	8.5	89	99	2
6	-1	0	3	8.5	95	99.7	6
7	0	1	5	12	85.5	98.6	1.5
8	0	-1	5	5	97.5	99.7	5.5
9	0	0	5	8.5	93	99.4	4

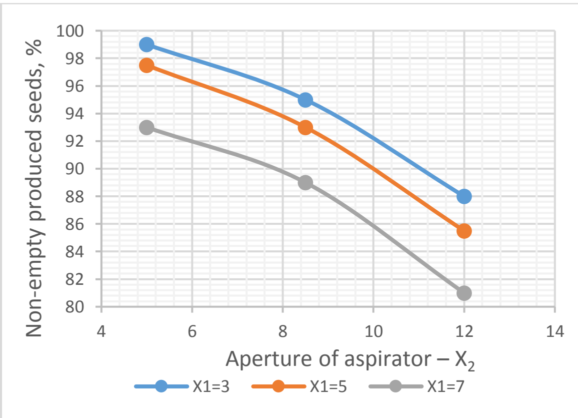

Figure 2: Variation of the non-empty produced seeds -Y_1, depending on X_1 and X_2

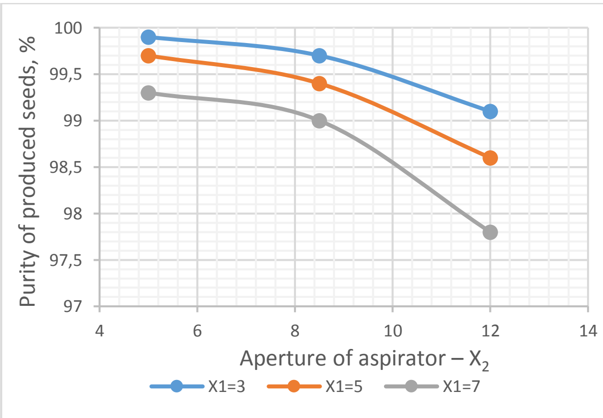

Figure 3: Variation of the purity of the produced seeds – Y_2, depending on X_1 and X_2

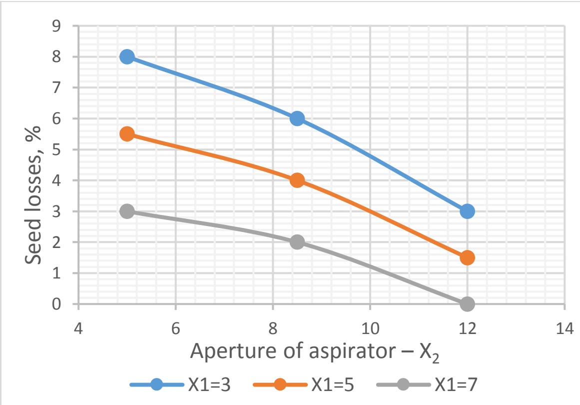

Figure 4: Variation of the losses of seeds – Y_3, depending on X_1 and X_2

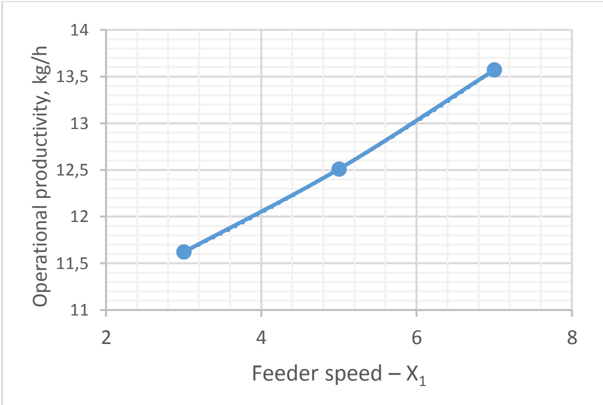

Figure 5: Variation of the productivity – Y_4, depending on the feeder speed – X_1

Operational performance, as the fourth parameter Y_4 studied, depends only on the feeder speed. The obtained results for the operational productivity are given in Table 3. Based on them, a graphical dependence is constructed, expressing the change of the operational productivity of the machine when cleaning Scots pine seeds, depending on the level of the feeder regulator (Fig. 5).

Table 3: Experimental results for the machine productivity in Scots pine seeds cleaning

Feeder speed (level)	3	5	7
Operational productivity – Y_4, kg/h	11,62	12,51	13,57

The obtained results were subjected to statistical processing with a computational program for regression analysis – QstatLab 6. As a result, adequate regression models were obtained, which describe the researched process through 2nd order equations. After excluding the insignificant coefficients in them, for the three initial parameters describing the qualitative indicators of the studied process, the following equations are obtained:

For the first parameter Y_1 – obtained non-empty seeds:

$$Y_1 = 93.111-3.167X_1-5.833X_2-1.167X_1X_1-1.667X_2X_2,\ \% \quad \textbf{(6)}$$

For the second parameter Y_2 – purity of the obtained seeds:

$$Y_2 = 99.367-0.433X_1-0.567X_2-0.3X_2X_2-0.175X_1X_2,\ \% \quad \textbf{(7)}$$

For the third parameter Y3 – loss of whole grain seeds in the waste fraction:

$$Y_3 = 4-2X_1-2X_2-0.5X_2X_2+0.5X_1X_2,\ \% \quad \textbf{(8)}$$

The significance of the regression coefficients bi, bij and bii was determined at level $\alpha = 0.05$. A stepwise regression analysis was applied to eliminate the insignificant regressors. In models with worse properties, they are excluded from the regression equations. To assess the adequacy of the obtained models and their properties for predicting the initial parameters, in accordance with the adopted methodology, the coefficient for multiple correlation R and F-criteria was used. The results of the statistical analysis of the regression models Yi are presented in Table 4.

Table 4: ANOVA analyses of the regression models

ANOVA					
Source	**Sqr. Sum**	**DOF**	**Variance**	**F**	**P**
Y_1 – Produced non-empty seeds					
Модел/Model	272.6111	4	68.15278	613.37500	0.00001
Остатък/Residual	0.44444	4	0.11111		
Общо/Total	273.05556	8			
T(0.025,4)= 2.77645; F_{table} (0.050,4,4)= 6.38823; Residual St. Dev = 0.33333; R-sq = 0.99837; Radj-sq = 0.99674; PRESS = 2.25000; R-sq(pred) = 0.99176					
Y_2 –Purity of the produced seeds					
Model	3.35583	4	0.83896	75.98113	0.00050
Residual	0.04417	4	0.01104		
Total	3.40000	8			
T(0.025,4)= 2.77645; F_{table} (0.050,4,4)= 6.38823; Residual St. Dev = 0.10508; R-sq=0.98701; Radj-sq=0.97402; PRESS = 0.31944; R-sq(pred)=0.90605					
Y_3 – Seed losses					
Model	49.50000	4	12.37500	1452.03372	1.4791E-31
Residual	7.8886E-31	4	1.9722E-31	4.5036E15	
Total	49.50000	8			
T(0.025,4)= 2.77645; F_{table} (0.050,4,4)= 6.38823; Residual St. Dev = 4.4409E-16; R-sq=1; Radj-sq=1; PRESS = 0.00000; R-sq(pred)= 1.00000					

The results of the statistical analysis of the multiple correlation coefficients of the obtained models show high values of Fisher's F-test. Estimates of R-sq (pred) predictors also have high values, tending to one, which means that the obtained models have high predictive properties and can be used to determine the technological indicators and the quality of cleaning of scots pine seeds with the studied pneumoseparator.

From the obtained regression models it is established that the two factors X_1 and X_2 have a significant influence on the indicators of completeness Y_1 and purity Y_2 of the extracted seeds, as a certain advantage is observed in the second factor X_2 – level of the aperture of the aspirator. Regarding the third studied parameter – Y_3, it was found that both factors X_1 and X2 have an equally strong influence on the loss of seeds in the waste. On the fourth studied parameter Y4, only the speed of the feeder X1 has an effect. After interpolation of the obtained experimental results with the calculation program Excel, for the productivity of the separator the following equation of the 2nd order is obtained, which with high accuracy (R = 1) describes the researched process:

$$Y_4 = 10.604 + 0{,}275X_1 + 0{,}0213X_1^2, \text{ kg/h} \quad \textbf{(9)}$$

The regression models obtained from the experimental study are used to determine the optimal parameters of the studied process. Empty and immature seeds in yield have the strongest effect on seed germination and quality. This determines the importance of the two studied parameters Y_1 and Y_2 in the selection of target optimization functions. The regression models in equations (6), (7) and (8) were used to determine the optimal parameters. After optimization and processing of the obtained results with the program QstatLab 6 by the method of the gradient algorithm, the following solutions were found:

1. Optimal solution for maximum non-empty yield of produced seeds $Y_1 \rightarrow max$:

Solution	X_1	X_2	Y_1
No 78	-1.00 / level 3	-1.00 / level “5“	99.28%

2. Optimal solution for maximum purity of produced seeds $Y_2 \rightarrow max$:

Solution	X1	X2	Y2
No 73	-1.00 / level 3	-0.65 / level „7.3“	99.93%

The graphical representations of the lines with the same values and the surface of response for the objective functions Y_1 and Y_2 and their optimal points, in case of pneumoseparation of Scots pine seeds, are given in Figure 6 and Figure 7.

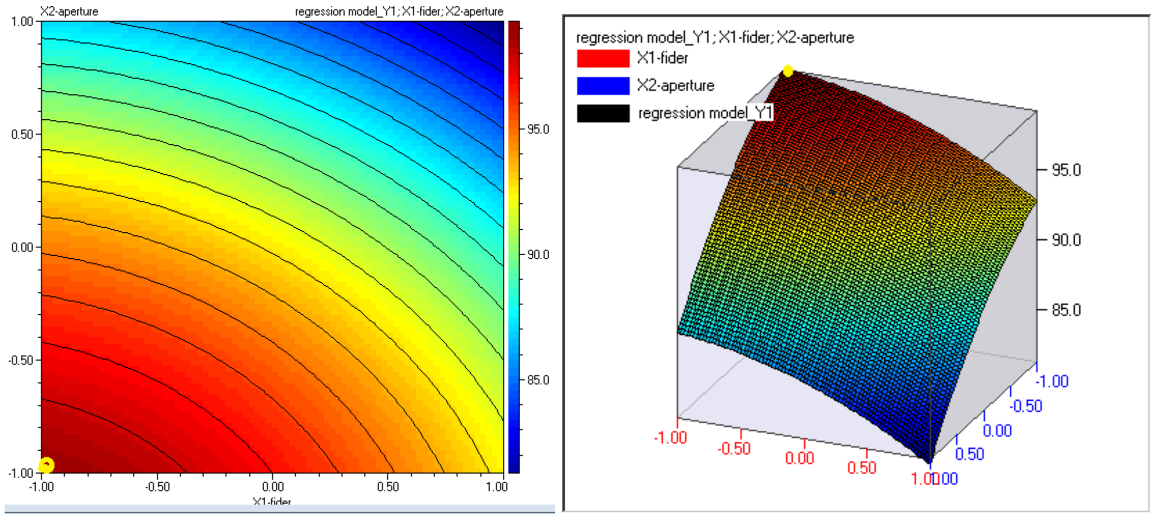

Figure 6: Diagram of the isolines with equal values and surface of response for the objective function Y_1 – produced non-empty Scotch pine seeds – Y_1 = max = 99.28 % at X_1 = -1 и X_2 = -1

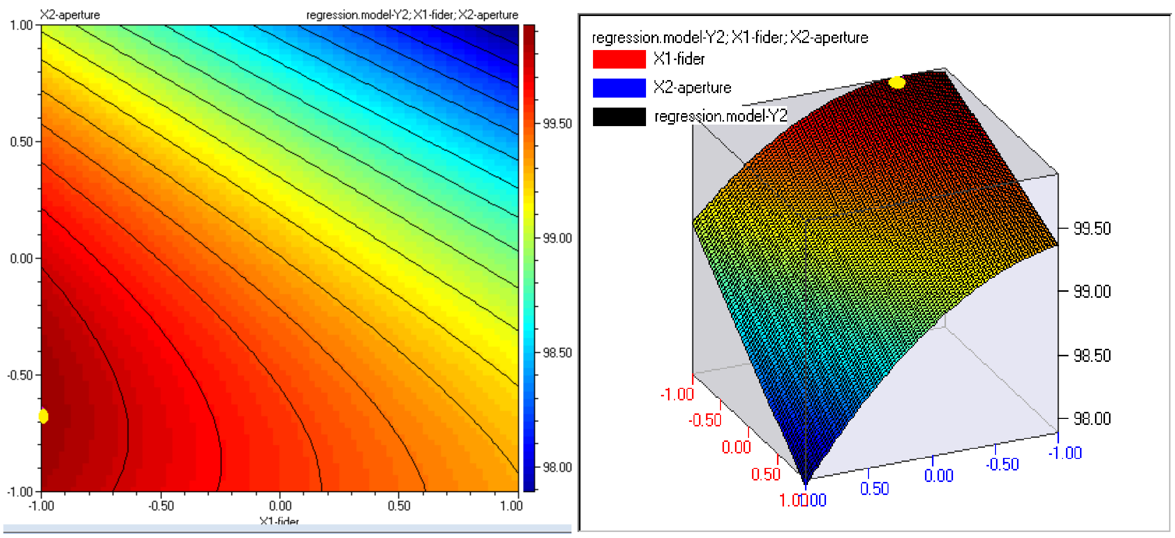

Figure 7: Diagram of the isolines with equal values and surface of response for the objective function Y_2 – purity of produced Scots pine seeds: Y_2 = max = 99.93 % at X_1 = -1 и X_2 = -0.65

The surface of the function Y_3 (loss of full seeds in the waste) is shown in fig. 8. The minimal losses here appear at levels of the factors X_1 = 1 in coded form and X_1 = 7 in natural form and X_2 = 1 in coded form and X_2 = 12 in natural form, where there are no losses – Y_3 = 0.0%. From this image it can be seen that in the optimal mode, when $Y_1 \rightarrow$ max and $Y_2 \rightarrow$ max, the loss of whole grain seeds is 8%. In the greenhouse production of container saplings, it can be assumed that these losses are a compromise solution.

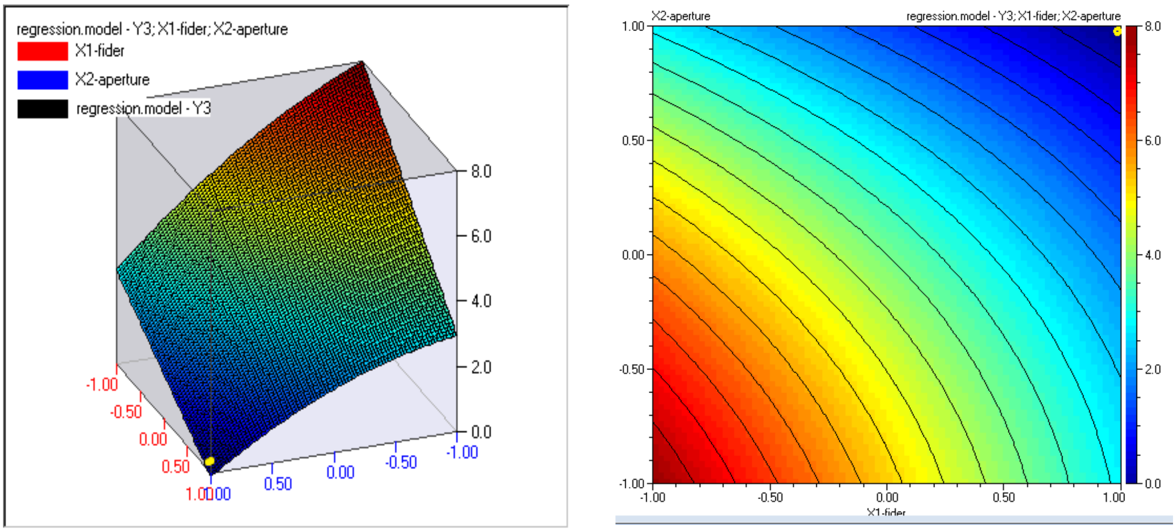

Figure 8: Response surface and isoline plot of the objective function Y_3 – seed loss: $У_3$ = min = 0.0 % at $X_1 = 1$ и $X_2 = 1$

ANALYSIS AND DISCUSSION

The results of the study show that a higher feeder speed also leads to higher productivity. But on the other hand, the lower this speed, the higher the quality of the harvested seeds, which is evident from the graphs of Figures 2 and 3. This is probably due to the smaller amount of processed material that falls into the working aspirator channel and better airflow characteristics, which better sucks out light impurities and empty seeds. As the feeder speed increases, a larger amount of material enters the working channel, which changes the performance of the air flow in the working area of the channel and worsens the quality of the harvested seeds. Within the scope of the studied factor space, it was found that closing the aperture and limiting the cross section of the working channel of the aspirator leads to an increase in the number of full and clean seeds in the yield. This fact is due to the higher speed of air flow in the working channel, which sucks a larger amount of empty and underdeveloped seeds and light impurities. On the other hand, however, the losses of smaller whole-grain seeds in the waste of the aspirator increases

As a result of the research on the operation of a pneumatic separator of BCC Cleaner & Seed Sizer for cleaning Scots pine seeds from indigenous Scots pine seed production plantations in the Rhodopes Mountains, the following facts have been identified:

- To ensure maximum machine productivity and yield of 1st quality Scots pine seeds, in which germination is $Y_1 \geq 90\%$ and purity is $Y_2 \geq 95\%$, the feeder speed must be in level "7" at aperture level "8". In this mode of operation, seed losses are about 2.5%.
- Lower feeder speeds and a closed aperture are suitable for producing seed for exact sowing. The best results are obtained at feeder speed "3" and hood aperture "5". Here the empty seeds are less than 1% and are suitable for greenhouse production of container seedlings. Here, however, the losses of healthy seeds in

the waste are expected to be higher – up to 8%.

- Loss of whole grain seeds decreases below 1% and productivity increases above 13.5 kg/h, with increasing feeder speed above "7" and aperture – above "12". However, this leads to a more significant reduction in the quality of the obtained seeds.

The technological modes for operation of the pneumatic separator are determined according to the set requirements for the quality of Scots pine seeds and the allowable losses of viable seeds. For the production of Scots pine seeds of the 1st quality, the germination must be higher than 90% and the purity – over 95%, provided that the following conditions are met: – $Y_1 \geq 90\%$ and $Y_2 \geq 95\%$. For seed yield of 2nd quality, these parameters are respectively: – Y_1 = 60 to 89% and Y_2 = 85 to 94%. One of the main tasks in the study on the operating modes of the pneumatic separator is not only to obtain seeds of the 1st quality, but also to establish such regimes in which the seeds have the highest possible whole grain and purity, with minimal losses. In order to limit the costs and reduce the price of the container saplings, seeds with the highest germination and whole grain size are suitable for the greenhouse production. The results of the optimization study on the pneumatic separator show that the best technological regimes are established for the feeder at level "3" and the aperture – at level "5".

CONCLUSIONS

The production of container forest saplings requires exact sowing and seeds with the highest sowing qualities. In the conditions of greenhouse production, this is an important factor for limiting the costs of cultivation and reducing the price of the produced saplings. As a result of the study, in the present work are defined functional models for establishing the influence of the working bodies of the pneumatic separator of the seed cleaning machine BCC Cleaner & Seed Sizer on the quality of Scots pine seeds from indigenous seed plantations in the Rhodope Mountains in Bulgaria.

The results of the study show that increasing the speed of the feeder increases the productivity of the machine, but the sowing qualities of the obtained seeds deteriorate. Closing the aperture of the pneumatic separator and limiting the cross section of the working channel leads to an increase in the quality of the seeds, but also to an increase in losses. The obtained regression models were used to optimize the technological regimes of the machine and find the best solutions. As a result of the conducted research, several main technological modes for operation of the pneumatic separator of BCC Cleaner & Seed Sizer have been established:

Mode A. "Maximum quality mode". The whole grain and purity of the obtained seeds is maximally high – $Y_1 \rightarrow max$ и $Y_2 \rightarrow max$: Feeder – level „3“; Aperture – level „5“.
This mode is most suitable for precise sowing in the production of container seedlings. Here there are the largest losses of seeds in the waste (Y_3), but they are negligible compared to the losses of container nests and the costs in the greenhouse.

Mode B. "Minimum seed losses mode": $Y_3 \rightarrow 0$: Feeder – level „7“; Aperture – level „12“

This mode of operation of the machine is justified in the conditions of limited seed yield and poor seed years;

Mode C. "Balanced mode". Yield of first quality Scots pine seeds (Y_1 and $Y_2 \rightarrow$ 1st quality), with high maximum productivity – Y_4 = 13.5kg/h: Feeder – level „7“; Aperture – level „8“

This regime is suitable for the production of seeds for even sowing in the production of saplings with open root system. This mode offers an optimal balance between high productivity, 1st quality seed yield, and relatively low seed loss.

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REFERENCES

BDS 1953:99 (БДС 1953:99). Semena ot gorski darvesni i hrastovi vidove. Pravila za vzemane na probi, (in Bulgarian), Komitet po standartizatsiya i metrologiya.

BDS 208:99 (БДС 208:99). Semena ot gorski darvesni vidove. Posevni kachestva, (in Bulgarian), Komitet po standartizatsiya i metrologiya.

ISTA 2022. International Seed Testing Association. International Rules for Seed Testing. Online ISSN 2310-3665.

VASILEV, V. 1964. Fizikomehanichni svojstva na nyakoi iglolistni darvesni vidove za tyahnoto mehanizirano pochistvane, (in Bulgarian), Gorskostopanska Nauka №6: 3–12.

VUCHKOV, IV., STOYANOV, ST. 1986. Matematichesko modelirane i optimizatsia na tehnologicni obekti, (in Bulgarian), "Tehnika", Sofia.

GLUSCHKOV, S., MARINOV, K., MARKOFF, I. 2009. Construction and technology of small combined machine for cleaning of coniferous seeds, Proceedings of the International Science Conference, 4–5 June 2009, Stara Zagora, Economics and Society development on the Base of Knowledge / Food safety in the European Union, Vol. 1: „Agricultural studies. Plant studies": 498–504.

ZHIGUNOV, A. 2000. Teoriya i praktika vujrishtivanija posadochnogo materiala s zakrita korenova Sistema, (in Russian), SPBNIILH, Sankt Peterburg, 293.

MARINOV, K. 1996. Technological properties of Pinus Silvestris, Pinus Nigricans and Picea Excelsa Seeds, used for their separation, Proceedings of "Second Balkan scientific conference", 3–5 June 1996, Sofia, Vol 1: 212–217.

MARINOV, K. 1998. Izsledvane kachestvoto na separiranite semena, Sbornik nauchni dokladi po "Nadezhdnost, remont i eksploatacia na tehnikata", (in Bulgarian), Ruse University "Angel kanchev", Tom 7: 17–21.

MARINOV, K. 2008. Methodology for research of technological processes for forest seed producing, Proceedings of "XVII International Scientific Conference 'Management and Quality for Yang Scientists", Jundola, 2008: 100–109.

MARINOV, K. 2012. Технологии и машини за оранжерийно производство на фиданки със закрита коренова система. (in Bulgarian) (Technologies and machines for greenhouse production of containerized saplings), „Avangard Prima", Sofia, 110 p.

MARINOV, K., IVANOV, M. 2021. Operating modes optimization of seed cleaning machine for seeds extraction in the Lokorsko forest nursery, Management and Sustainable Development, Vol. 85, №6.

SKRYNNIKOV, B. 1985. K woprosu ob ochistke lesnujih semqn vozdushnujh potok, (in Russian), Izv. vuishih. uch. zavedenij, Lesnoj journal, № 6: 26–30.

SVIRIDOV, L. 1986. Aerodinamicheskie svojstva lesnih semjan i ih primesej, (in Russian), Lesnoj Journal, № 12:70–74.

SVIRIDOV, L., SKRYNNIKOV, B. 1987. O tselesaobraznosti pnevmosortirovaniya semjan hvojnujh porod, (in Russian), Izv. vuishih. uch. zavedenij, Lesnoj journal, № 5:75–76.

ZEMLYANUKHIN, A. SKRYNNIKOV, B., 1990. Povujshenie effektivnosti pnevmoseparirania semjan, (in Russian), Lesnoe hozyaistvo, №2:49–50.