Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2021, № 4 (104) https://doi.org/10.33108/visnyk_tntu2021.04
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 631.361.2

METHOD OF STEP-BY-STEP DEVELOPMENT OF A MATHEMATICAL MODEL OF THE PROCESS OF SEPARATING IMPURITIES FROM ROOT CROPS

Maria Pankiv[1]; Mykola Pidhurskyi[1]; Mykhailo Pylypets[1]; Myroslav Burda[2]

[1]Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine
[2]Ivano-Frankivsk National Technical University of Oil and Gas, Ivano-Frankivsk, Ukraine

Summary*. Harvesting root crops, such as large sugar and fodder beetroots, and long-term chicory roots is a technologically complex and ambiguous technological process. It consists of different structural successive technological operations of pruning, digging roots, cleaning the dug heap from impurities, loading clean roots into the hopper or in vehicles moving near the root harvester. The aim of the study is to increase the efficiency of the process of harvesting roots by analyzing existing approaches to mathematical simulation of the technological process of separating impurities from roots. The developed mathematical model allows describing at the highest-level more precisely the process of gradual separation of variously structured components of impurities from root crops by each cleaning working body, which are constituent units of technical systems of root-harvesting machines. The proposed mathematical model can be used to optimize the parameters of the working bodies and other processes, in particular for the separation of the harvested grain heap, preparatory processes of seed, and so on.*

Keywords*: root harvesting machine, treatment system, working bodies, harvesting conditions, impurity components, component supply, impurity separation, separation area, and soil and plant impurities.*

https://doi.org/10.33108/visnyk_tntu2021.04.074 *Received 01.09.2021*

Introduction. The design of machines for harvesting root crops in different soil and climatic conditions is a rather complex scientific problem, but also – a design development [1].

To solve this problem successfully, the cleaning working bodies of the root-harvesting machine must be characterized by adaptability, which provides the ability to adapt to changes in different structured natural and climatic conditions of root crops and their biological and agro physical features. Thus, it is necessary to provide the necessary adaptive settings and change of the design and kinematic parameters of the working bodies of root-harvesting machines for specific conditions of root crop harvesting [2, 3].

As a rule, this leads to the design complication, to the increase in metal content and cost of the machine. Therefore, the working bodies of root-harvesting machines should be not only universal, but also simple in design and available in the layout of the spatial arrangement [4].

Development and optimization of parameters of new working bodies and machines in general requires step-by-step analysis and generalization of existing technologies, methods of root harvesting, design features of modern technical means and working bodies, identification of their advantages and disadvantages, creation of technological process theory, optimization criteria calculation [5].

To solve the problem of improving the efficiency of root harvesting techniques due to the analysis and synthesis of complex structures of technical means or technical systems and, accordingly, technological processes of their work, it is necessary to apply the basic principles of scientific research.

Existing research methods are used to effectively solve this problem. One of the

Corresponding author: Maria Pankiv; e-mail: pankiv@tntu.edu.ua common research methods is mathematical simulation of the functioning of technically complex dynamic systems. Simulation allows to describe processes and phenomena on the basis of the created effective analogue – mathematical model.

Analysis of recent research and publications. To describe the functioning of technical systems, as a rule, in most cases, methods of developing empirical and analytical mathematical models are used, or methods of empirical and analytical simulation [6, 7].

The method of empirical simulation is based on the implementation of experimental research and processing of the results. Especially empirical simulation should be used in the study of complex systems. In this case, the planning and implementation of experimental studies of the technical system with the measurement of parameters and subsequent statistical processing of the experimental data are carried out. The use of experimental research and empirical simulation can reduce costs in the study of technical systems, and allows to achieve the required accuracy of models [8, 9].

In general, the empirical model obtained due to the experimental studies is a «black box», where the input parameters are managed controlled factors, managed uncontrolled factors and unmanaged uncontrolled factors, and the output parameters – the response function. Based on experimental data processing, a dependence is obtained that mathematically connects the response function with input factors, which is an empirical model of the system [10].

When developing an empirical model, the type of approximating dependence should be determined at first, and then, the numerical values of the coefficients of the model should be found. It is quite difficult and sometimes impossible to draw a line that passes precisely through the experimental points. To solve such a problem, it is necessary to select from the set of possible lines the one that will pass the most perfectly between the experimental points (which approximates the experimental data, is more accurately aligns the polyline built on the experimental points). In this case, there is a problem of finding the function and its coefficients, which will provide the maximum approximation [11].

The problem of approximation is carried out by applying mathematical (analytical) approaches based on known methods, which differ in both algorithm and accuracy of calculations. Based on the results of experimental research and processing of experimental data, numerical values of the model coefficients are determined [12, 13].

In general, to determine the dependence that regulates the relationship between input and output values, it is best to use a functional method that involves the use of known mathematical relationships, such as algebraic functions of linear, power, exponential and logarithmic nature, etc. [15].

Theoretical models differ from empirical ones, first, for information needed to build them. In empirical models, the source information is used only to select environmental factors whose impact on the system will be considered in the model. Theoretical models are based on ideas about the described phenomena that belong to the mechanisms of technical systems [16].

Theoretical models are developed on the basis of the application of mathematical theoretical formulas, which are based on and describe the fundamental laws of mechanics, electricity, thermodynamics, etc. For example, the law of conservation of mass, the law of conservation of energy, thermodynamic equations, and so on. The initial theoretical information about the nature of the processes under consideration allows you to more reasonably choose the type of functions to describe them. Theoretical simulation refers to basic research.

At the same time, in experimental research there are a number of problems that do not allow for a thorough study and analysis of technical systems. The obtained mathematical model is not universal, but can only describe the functioning of the specified process of the technical system within certain limits, which are set by the experimenter and are investigated experimentally [17].

Therefore, based only on conservation laws, it is not possible to build a closed mathematical model of a complex technical system, because mechanisms of many processes are insufficiently studied, while a number of values always remains uncertain, in particular different correction factors models.

Theoretical research is based on the acceptance of some assumptions or simplification of the nature of technological processes that are present during the operation of technical systems.

Semi-empirical models are a partial combination of theoretical and empirical simulation results. The developed analytical dependences are supplemented by empirical models of individual simplified at the theoretical level of microprocesses, and thus, a semi-empirical mathematical model is formed, which more fully and at a higher level describes the phenomena studied in general.

These simplifications are taken into account by introducing correction factors, which at the theoretical level are almost impossible to determine. To determine them, you have to both collect empirical information and process it using mathematical statistics, or conduct specific experimental studies [18].

Implementation of statistical simulation is possible with preliminary analytical research and collection of information on the indicators of the studied system and its subsequent statistical processing and obtaining probabilistic characteristics [19].

First, it is necessary to analyze the object of research based on system analysis and substantiate the quantitative values that will be studied in the simulation, taking into account the peculiarities of the technical system. These indicators must be divided into input and output.

In the process of developing a statistical model, it is necessary to obtain a set of deterministic or stochastic relations between input and output values in the form of equations. In this case, the known results of theoretical and experimental studies, accepted assumptions, etc. are used. The obtained statistical model is analyzed on the basis of the chosen laws of distribution of random variable, methods of mathematical statistics and statistical analysis, and on the received parity define values of initial sizes.

Because of statistical simulation, you can test the hypotheses, summarize existing information, as well as formulate conclusions about the system under study and the possibility of further application. For more effective implementation of statistical simulation in the study of technical systems, a personal computer with the appropriate software packages is used.

The objective of the article is to improve the efficiency of root crop collection by developing a step-by-step mathematical model that functionally describes the technological process of separating impurities from root crops.

Statement of the problem. Existing models that describe the functional dependence of impurity separation processes (soil and plant) are single-stage or generalizing ones [20–22]. Based on them, the process of separating impurities from root crops is considered from the standpoint of simultaneous and one-time flow of the process along the entire path of movement of root components and impurities on the working surfaces of treatment systems. This significantly narrows the mathematical description of the process of separating impurities from root crops and does not accurately describe the existing real process of cleaning the heap of root crops from impurities.

Based on previous studies, the separation of impurities from root crops actually occurs at each successive conditional segment or a certain conditional area during the movement of the heap on the cleaning surface of each area and the total time of movement of the heap along the entire length of the cleaning surface of each working body and treatment system. [23, 24].

According to Fig. 1, a complex dynamic cleaning system is taken as a basis. It constructively combines the schemes of treatment combined working bodies, which are mainly used to separate impurities from the roots of modern root harvesting machines.

Let us consider the process of purification of the heap components, or the process of separation of their components of impurities from the roots, which enters the complex dynamic cleaning system shown in Fig. 1. Conventionally, we believe that the treatment system has j = 1, 2, …, n combined treatment working bodies: the first (loading conveyor 1), the second (cleaning slide 2),…, n cleaning working body (right and left auger system 3 and 4), or j stages of cleaning.

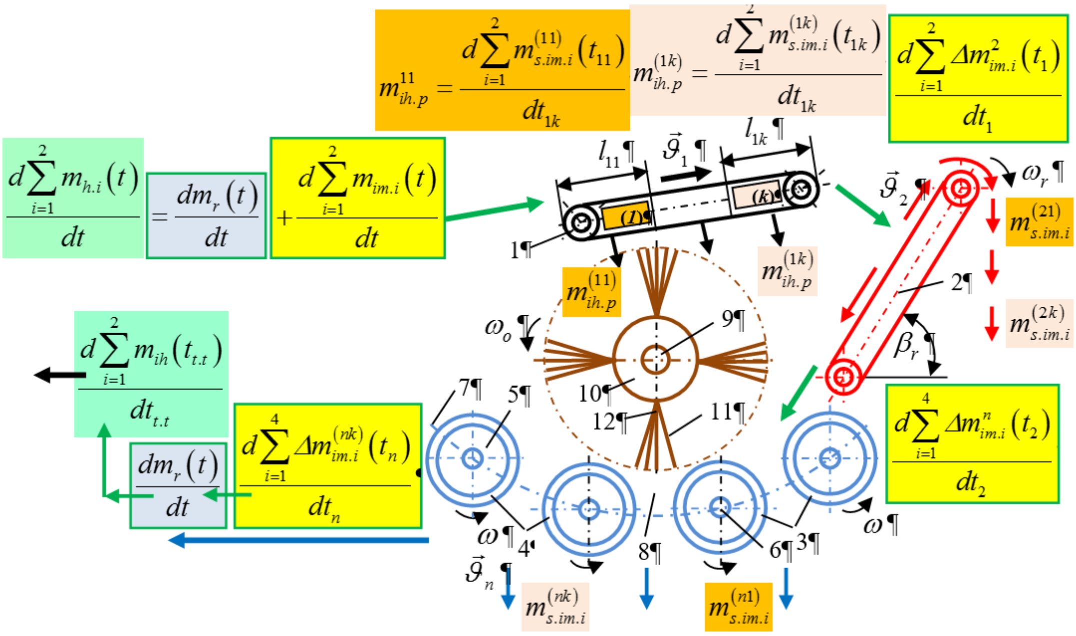

Figure 1. Constructive scheme of the treatment system: 1 – loading conveyor; 2 – cleaning slide; 3, 4 – right and left auger system; 5 – auger; 6 – axis of rotation; 7 – the lower branch of the ellipse; 8 – gutter of the working channel; 9 – cleaning shaft; 10 – drum; 11 – elastic cleaning elements; 12 – tufts of hair

It is necessary to develop a mathematical model that describes the step-by-step process of separation of impurities from roots on a separate j working body of the treatment system and a mathematical model of the process of cleaning roots from impurities by means of complex cleaning system as a whole.

Presentation of the main material. Conventionally, the cleaning system has j working bodies (Fig. 1); on these bodies, the roots are cleaned from impurities. The system receives the total mass of the components of the heap, which is denoted by $\frac{d\sum_{i=1}^{2} m_{h.i}(t)}{dt}$. The components of the heap are roots and impurities. In addition, the impurities are in a free, root-bound and bound state.

Then

$$\frac{d\sum_{i=1}^{2} m_{h.i}(t)}{dt} = \frac{dm_r(t)}{dt} + \frac{d\sum_{i=1}^{2} m_{im.i}(t)}{dt} = \frac{dm_r(t)}{dt} + \frac{dm_f(t)}{dt} + \frac{dm_b(t)}{dt}, \tag{1}$$

if $m_{im.i}$, m_r, m_f, m_b – respectively, the total mass of impurities, the mass of roots, free impurities and bound impurities that enter the treatment system.

To develop a step-by-step mathematical model, we conditionally divide the total length of the cleaning surface of each j working body into q = 1, 2,…, k sections (Fig. 1), where the process of separating impurities from roots occurs. We assume that the mass of «pure» roots after their passage in all q areas of each j working body remains constant; or the input mass of roots $\frac{dm_r(t)}{dt}$ is equal to the original mass of roots after the process of cleaning by the treatment system as a whole, is $\frac{dm_r(t)}{dt}=\frac{dm_r^{(nk)}(t_{nk})}{dt_{nk}}=const$; or in the process of cleaning, the loss of root crops on the working bodies of the treatment system are absent.

Then equation (1) can be written as

$$\frac{d\sum_{i=1}^{2} m_{im.i}(t)}{dt}=\frac{dm_f(t)}{dt}+\frac{dm_b(t)}{dt}. \tag{2}$$

We assume that during the movement of impurity components in the treatment system, the process of cleaning roots from impurities occurs at each individual n working body.

At the same time, according to the design features of each individual working body of the treatment system, the separation of free components of impurities (free soil and free plant residues – weeds and lost during harvesting tops) occurs by sifting (separation) through the gaps between the rods loading conveyor, removal of free impurities by the working branch of the cleaning slide 2, sieving of free soil and free plant impurities in the gaps between the screws 5 of the right 3 and left 4 of the auger system, the axes of rotation 6 of which are located on the lower branch 7 of the ellipse and form a chute 8 of a working channel.

Separation of bound impurities occurs by scraping the sticky soil from the surface of the root body and the remnants of the bud from the root heads by screw turns 5 and elastic cleaning elements 11, which form bundles of pile 12 mounted on the drum 10 of the cleaning shaft 9.

Let us denote the total mass amount of separated impurities on one separate j working body of the treatment system $\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(j)}(t_j)}{dt_j}$, where j = 1, 2, , n; t_j – the total time of finding the components of the heap on a separate j working body of the treatment system. Here, the upper index in parentheses (j) corresponds to the designation of the number of a specific working body from 1 to n, on which the process of cleaning roots from impurities directly takes place.

Then

$$\left.\begin{array}{l}
\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(1)}(t_1)}{dt_1}=\frac{\sum_{i=1}^{2} m_{s.i}^{(1)}(t_1)}{dt_1}+\frac{\sum_{i=1}^{2} m_{v.i}^{(1)}(t_1)}{dt_1}=\frac{dm_{1s}^{(1)}(t_1)}{dt_1}+\frac{dm_{2s}^{(1)}(t_1)}{dt_1}+\frac{dm_{3s}^{(1)}(t_1)}{dt_1}+\frac{dm_{4s}^{(1)}(t_1)}{dt_1};\\
\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}(t_2)}{dt_2}=\frac{\sum_{i=1}^{2} m_{s.i}^{(2)}(t_2)}{dt_2}+\frac{\sum_{i=1}^{2} m_{v.i}^{(2)}(t_2)}{dt_2}=\frac{dm_{1s}^{(2)}(t_2)}{dt_2}+\frac{dm_{2s}^{(2)}(t_2)}{dt_2}+\frac{dm_{3s}^{(2)}(t_2)}{dt_2}+\frac{dm_{4s}^{(2)}(t_2)}{dt_2};\\
\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots;\\
\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(n)}(t_n)}{dt_n}=\frac{\sum_{i=1}^{2} m_{s.i}^{(n)}(t_n)}{dt_n}+\frac{\sum_{i=1}^{2} m_{v.i}^{(n)}(t_n)}{dt_n}=\frac{dm_{1s}^{(n)}(t_n)}{dt_n}+\frac{dm_{2s}^{(n)}(t_n)}{dt_n}+\frac{dm_{3s}^{(n)}(t_n)}{dt_n}+\frac{dm_{4s}^{(n)}(t_n)}{dt_n}
\end{array}\right\}, \tag{3}$$

if $m_{s.i}^{(1)},m_{s.i}^{(2)},...,m_{s.i}^{(n)}$, $m_{v.i}^{(1)},m_{v.i}^{(2)},...,m_{v.i}^{(n)}$ – accordingly, the total mass of separated soil and plant impurities on 1, 2, … , the n working body of the treatment system; $m_{1s}^{(1)},m_{1s}^{(2)},...,m_{1s}^{(n)}$,

$m_{2s}^{(1)},m_{2s}^{(2)},...,m_{2s}^{(n)}$ – respectively, the mass of separated free soil and free plant impurities on 1, 2, … , the *n* working body of the treatment system; $m_{3s}^{(1)},m_{3s}^{(2)},...,m_{3s}^{(n)}$, $m_{4s}^{(1)},m_{4s}^{(2)},...,m_{4s}^{(n)}$ – respectively, the mass of the separated sticky soil on the roots and the remnants of the bud on the heads of the roots on 1, 2, … , the *n* working body of the treatment system; $t_1,t_2,...,t_n$ – the total residence time of the heap components on 1, 2, … , the *n* working body of the treatment system.

At the first stage, we will consider the process of separation of impurity components in the first (*1*) section of root crop cleaning by loading conveyor 1, Fig. 1.

Then on each q section of the loading conveyor, due to sifting, only two components of free impurity (free soil and free vegetable impurity) are separated by the total mass quantity, which we will designate through $m_{s.im}^{(1q)} = \frac{d\sum\limits_{i=1}^{2} m_{s.im.i}^{(1q)}\left(t_{1q}\right)}{dt_{1q}}$, where q = 1, 2, … , k.

Then the total number of separated components of free impurities by the loading conveyor 1 (Fig. 1), which are separated at each *q* section of the loading conveyor, taking into account the first equation (3) will be

$$\frac{d\sum\limits_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_1\right)}{dt_1} = \frac{dm_{1s}^{(11)}\left(t_{11}\right)}{dt_{11}} + \frac{dm_{1s}^{(12)}\left(t_{12}\right)}{dt_{12}} +,...,+ \frac{dm_{1s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}} + \frac{dm_{2s}^{(11)}\left(t_{11}\right)}{dt_{11}} + \frac{dm_{2s}^{(12)}\left(t_{12}\right)}{dt_{12}} +,...,+ \frac{dm_{2s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}}. \qquad (4)$$

Taking into account the accepted assumptions, the total mass of components of impurities entering the first (*1*) section of the loading conveyor 1 (Fig. 1), which is denoted by $\frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(1)}\left(t\right)}{dt}$ equals to the total mass of components of impurities $\frac{d\sum\limits_{i=1}^{2} m_{im.i}\left(t\right)}{dt}$, entering the treatment system, is

$$\frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(1)}\left(t\right)}{dt} = \frac{d\sum\limits_{i=1}^{2} m_{im.i}\left(t\right)}{dt}. \qquad (5)$$

Then the total mass of impurity components, which enters the first (*1*) section of the cleaning slide 2 (Fig. 1) $\frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(2)}\left(t_1\right)}{dt_1}$, which is denoted by equals the difference between the total mass of impurity components $\frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(1)}\left(t\right)}{dt}$ and $\frac{d\sum\limits_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_1\right)}{dt_1}$, which, respectively, enters the loading conveyor 1 and separated from the roots on each *q* section of the loading conveyor 1, which is denoted by $\frac{d\sum\limits_{i=1}^{2} \Delta m_{im.i}^{(2)}\left(t_1\right)}{dt_1}$, ie

$$\frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(2)}\left(t_1\right)}{dt_1} = \frac{d\sum\limits_{i=1}^{2} m_{im.i}^{(1)}\left(t\right)}{dt} - \frac{d\sum\limits_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_1\right)}{dt_1} = \frac{d\sum\limits_{i=1}^{2} \Delta m_{im.i}^{(2)}\left(t_1\right)}{dt_1}. \qquad (6)$$

Accordingly, by analogy (4) and (6) we can write that the total number of separated components of free impurities by the cleaning slide 2 (Fig. 1), which are separated at each *q* section of the cleaning slide taking into account the second equation (3), the total mass the number of impurity components entering the first (*1*) section of the right 3 and left 4 auger system and the total number of separated components of free and bound impurities by auger systems and cleaning elements 12 of the cleaning shaft 9, which are separated on each *q* section of the right and the left system of screws, taking into account the *n* equation (3), will be:

$$\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}\left(t_2\right)}{dt_2}=\frac{dm_{1s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{1s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\dots,+\frac{dm_{1s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}+\frac{dm_{2s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{2s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\dots,+\frac{dm_{2s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}; \quad (7)$$

$$\frac{d\sum_{i=1}^{2} m_{im.i}^{(n)}\left(t_{n-1}\right)}{dt_{n-1}}=\frac{d\sum_{i=1}^{2} m_{im.i}^{(2)}\left(t_1\right)}{dt_1}-\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}\left(t_2\right)}{dt_2}-,\dots,-\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}\left(t_{n-1}\right)}{dt_{n-1}}=\frac{d\sum_{i=1}^{2} \Delta m_{im.i}^{(n)}\left(t_{n-1}\right)}{dt_{n-1}}; \quad (8)$$

$$\begin{aligned}\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(n)}\left(t_n\right)}{dt_n}&=\frac{dm_{1s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{1s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{1s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{2s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{2s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{2s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+. \\ &+\frac{dm_{3s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{3s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{3s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{4s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{4s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{4s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}\end{aligned} \quad (9)$$

Thus:

- the total mass of separated components of impurities, which separated on each *q* section of each *j* working body of the treatment system for the total time $t_{t.t}=t_1+t_2+,\dots,+t_n$ of the components of impurities on the working bodies of the treatment system (time of cleaning the impurity heap) will be equal to the sum of separated components on each *j* working body of the treatment system, and in accordance with (4), (6) and (8) will be determined by the formula

$$\frac{d\sum_{i=1}^{n} m_{s.im.i}^{(n)}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_1\right)}{dt_1}+\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}\left(t_2\right)}{dt_2}+,\dots,+\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(n)}\left(t_n\right)}{dt_n}; \quad (10)$$

- substituting the values of (4), (7) and (9) in equation (10), we obtain

$$\begin{aligned}\frac{d\sum_{i=1}^{n} m_{s.im.i}^{(n)}\left(t_{t.t}\right)}{dt_{t.t}}&=\frac{dm_{1s}^{(11)}\left(t_{11}\right)}{dt_{11}}+\frac{dm_{1s}^{(12)}\left(t_{12}\right)}{dt_{12}}+,\dots,+\frac{dm_{1s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}}+\frac{dm_{2s}^{(11)}\left(t_{11}\right)}{dt_{11}}+\frac{dm_{2s}^{(12)}\left(t_{12}\right)}{dt_{12}}+,\dots,+\frac{dm_{2s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}}+ \\ &+\frac{dm_{1s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{1s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\dots,+\frac{dm_{1s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}+\frac{dm_{2s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{2s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\dots,+\frac{dm_{2s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}+ \\ &+\frac{dm_{1s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{1s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{1s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{2s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{2s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{2s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+ \\ &+\frac{dm_{3s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{3s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{3s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{4s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{4s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\dots,+\frac{dm_{4s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}\end{aligned}; \quad (11)$$

- the total mass of components of impurities remaining after their separation in each *q* section of each *j* working body of the treatment system during the time $t_{t.t}$ of cleaning the heap from impurities and which will be supplied to the next transport-technological systems of the root-harvesting machine will be equal to the difference of components of impurities entering the treatment system and the total mass of separated components of impurities that have separated in each *q* section of each *j* working body of the treatment system, and according to (2) and (10) will be determined by the formula

$$\frac{d\sum_{i=1}^{2} m_{im.i}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt}-\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(n)}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{d\sum_{i=1}^{2} \Delta m_{im.i}^{(nk)}\left(t_{n}\right)}{dt_{n}}, \tag{12}$$

or

$$\frac{d\sum_{i=1}^{2} m_{im.i}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt}-\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_{1}\right)}{dt_{1}}+\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(2)}\left(t_{2}\right)}{dt_{2}}+,\ldots,+\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(n)}\left(t_{n}\right)}{dt_{n}}=\frac{d\sum_{i=1}^{2} \Delta m_{im.i}^{(nk)}\left(t_{n}\right)}{dt_{n}}. \tag{13}$$

Accordingly, the total mass quantity of the heap, which will arrive on the following transport and technological systems of the root-harvesting machine, will be defined by the formula

$$\frac{d\sum_{i=1}^{2} m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{dm_{r}\left(t\right)}{dt}+\frac{d\sum_{i=1}^{2} m_{im.i}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{d\sum_{i=1}^{2} \Delta m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}}. \tag{14}$$

Taking into account (13) and (4), (7), (9), equation (14) will have the final form:

$$\frac{d\sum_{i=1}^{2} m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}}=\frac{dm_{r}\left(t\right)}{dt}+\frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt}-\left(\frac{d\sum_{i=1}^{2} m_{s.im.i}^{(1)}\left(t_{1}\right)}{dt_{1}}+\frac{d\sum_{i=1}^{3} m_{s.im.i}^{(2)}\left(t_{2}\right)}{dt_{2}}+,\ldots,+\frac{d\sum_{i=1}^{4} m_{s.im.i}^{(n)}\left(t_{n}\right)}{dt_{n}}\right). \tag{15}$$

$$\begin{aligned}\frac{d\sum_{i=1}^{2} m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}}&=\frac{dm_{r}\left(t\right)}{dt}+\frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt}-\\&-\left[\begin{aligned}&\frac{dm_{1s}^{(11)}\left(t_{11}\right)}{dt_{11}}+\frac{dm_{1s}^{(12)}\left(t_{12}\right)}{dt_{12}}+,\ldots,+\frac{dm_{1s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}}+\frac{dm_{2s}^{(11)}\left(t_{11}\right)}{dt_{11}}+\frac{dm_{2s}^{(12)}\left(t_{12}\right)}{dt_{12}}+,\ldots,+\frac{dm_{2s}^{(1k)}\left(t_{1k}\right)}{dt_{1k}}+\\&+\frac{dm_{1s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{1s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\ldots,+\frac{dm_{1s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}+\frac{dm_{2s}^{(21)}\left(t_{21}\right)}{dt_{21}}+\frac{dm_{2s}^{(22)}\left(t_{22}\right)}{dt_{22}}+,\ldots,+\frac{dm_{2s}^{(2k)}\left(t_{2k}\right)}{dt_{2k}}+\\&+\frac{dm_{1s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{1s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\ldots,+\frac{dm_{1s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{2s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{2s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\ldots,+\frac{dm_{2s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\\&+\frac{dm_{3s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{3s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\ldots,+\frac{dm_{3s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}+\frac{dm_{4s}^{(n1)}\left(t_{n1}\right)}{dt_{n1}}+\frac{dm_{4s}^{(n2)}\left(t_{n2}\right)}{dt_{n2}}+,\ldots,+\frac{dm_{4s}^{(nk)}\left(t_{nk}\right)}{dt_{nk}}\end{aligned}\right].\end{aligned} \tag{16}$$

The obtained differential equation (16) is a mathematical model that generally describes the step-by-step process of separating impurity components from root crops depending on the time t_{jq} the impurity component is in each q section of each j combined working body of a complex dynamic cleaning system.

The time t_{jq} of the component of impurities on each q section of each j of combined working body is expressed through the length of each q section l_{jq} and the speed of movement ϑ_j of the components of impurities on each j working body, thus $t_{jq} = l_{jq} / \vartheta_{jq}$.

Then the differential equation (16) can be written in the form

$$\frac{d\sum_{i=1}^{2} m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}} = \frac{dm_r\left(t\right)}{dt} + \frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt} -$$

$$-\left[\begin{array}{l}
\dfrac{dm_{1s}^{(11)}\left(\frac{l_{11}}{\vartheta_1}\right)}{d\,\frac{l_{11}}{\vartheta_1}} + \dfrac{dm_{1s}^{(12)}\left(\frac{l_{12}}{\vartheta_1}\right)}{d\,\frac{l_{12}}{\vartheta_1}} +,\ldots,+ \dfrac{dm_{1s}^{(1k)}\left(\frac{l_{1k}}{\vartheta_1}\right)}{d\,\frac{l_{1k}}{\vartheta_1}} + \dfrac{dm_{2s}^{(11)}\left(\frac{l_{11}}{\vartheta_1}\right)}{d\,\frac{l_{11}}{\vartheta_1}} + \dfrac{dm_{2s}^{(12)}\left(\frac{l_{12}}{\vartheta_1}\right)}{d\,\frac{l_{12}}{\vartheta_1}} +,\ldots,+ \dfrac{dm_{2s}^{(1k)}\left(\frac{l_{1k}}{\vartheta_1}\right)}{d\,\frac{l_{1k}}{\vartheta_1}} + \\
+ \dfrac{dm_{1s}^{(21)}\left(\frac{l_{21}}{\vartheta_2}\right)}{d\,\frac{l_{21}}{\vartheta_2}} + \dfrac{dm_{1s}^{(22)}\left(\frac{l_{22}}{\vartheta_2}\right)}{d\,\frac{l_{22}}{\vartheta_2}} +,\ldots,+ \dfrac{dm_{1s}^{(2k)}\left(\frac{l_{2k}}{\vartheta_2}\right)}{d\,\frac{l_{2k}}{\vartheta_2}} + \dfrac{dm_{2s}^{(21)}\left(\frac{l_{21}}{\vartheta_2}\right)}{d\,\frac{l_{21}}{\vartheta_2}} + \dfrac{dm_{2s}^{(22)}\left(t_{22}\right)}{d\,\frac{l_{22}}{\vartheta_2}} +,\ldots,+ \dfrac{dm_{2s}^{(2k)}\left(\frac{l_{2k}}{\vartheta_2}\right)}{d\,\frac{l_{2k}}{\vartheta_2}} + \\
+ \dfrac{dm_{1s}^{(n1)}\left(\frac{l_{n1}}{\vartheta_3}\right)}{d\,\frac{l_{n1}}{\vartheta_3}} + \dfrac{dm_{1s}^{(n2)}\left(\frac{l_{n2}}{\vartheta_3}\right)}{d\,\frac{l_{n2}}{\vartheta_3}} +,\ldots,+ \dfrac{dm_{1s}^{(nk)}\left(\frac{l_{nk}}{\vartheta_3}\right)}{d\,\frac{l_{nk}}{\vartheta_3}} + \dfrac{dm_{2s}^{(n1)}\left(\frac{l_{n1}}{\vartheta_3}\right)}{d\,\frac{l_{n1}}{\vartheta_3}} + \dfrac{dm_{2s}^{(n2)}\left(\frac{l_{n2}}{\vartheta_3}\right)}{d\,\frac{l_{n2}}{\vartheta_3}} +,\ldots,+ \dfrac{dm_{2s}^{(nk)}\left(\frac{l_{nk}}{\vartheta_3}\right)}{d\,\frac{l_{nk}}{\vartheta_3}} + \\
+ \dfrac{dm_{3s}^{(n1)}\left(\frac{l_{n1}}{\vartheta_3}\right)}{d\,\frac{l_{n1}}{\vartheta_3}} + \dfrac{dm_{3s}^{(n2)}\left(\frac{l_{n2}}{\vartheta_3}\right)}{d\,\frac{l_{n2}}{\vartheta_3}} +,\ldots,+ \dfrac{dm_{3s}^{(nk)}\left(\frac{l_{nk}}{\vartheta_3}\right)}{d\,\frac{l_{nk}}{\vartheta_3}} + \dfrac{dm_{4s}^{(n1)}\left(\frac{l_{n1}}{\vartheta_3}\right)}{d\,\frac{l_{n1}}{\vartheta_3}} + \dfrac{dm_{4s}^{(n2)}\left(\frac{l_{n2}}{\vartheta_3}\right)}{d\,\frac{l_{n2}}{\vartheta_3}} +,\ldots,+ \dfrac{dm_{4s}^{(nk)}\left(\frac{l_{nk}}{\vartheta_3}\right)}{d\,\frac{l_{nk}}{\vartheta_3}}
\end{array}\right]. \qquad (17)$$

For the real (practical) application of the developed mathematical model (17) we will compare (write down) the total supply of heap components and the total supply of impurity components to the working bodies of the treatment system through adequate second feed $Q_{i\partial}^{(jq)}$ (kg / s), while:

$$\sum_{i=1}^{2} Q_{h.i} = \left(\frac{d\sum_{i=1}^{2} m_{h.i}\left(t_{t.t}\right)}{dt_{t.t}}\right) / t_{t.t}\text{, } Q_r = \left(\frac{dm_r\left(t\right)}{dt}\right) / t\text{, } \sum_{i=1}^{2} Q_{im.i} = \left(\frac{d\sum_{i=1}^{2} m_{im.i}\left(t\right)}{dt}\right) / t\text{, } Q_{s.im.i}^{(jq)} = \left(\frac{dm_{s.im.i}^{(jq)}\left(t_{jq}\right)}{dt_{jq}}\right) / t_{jq} \qquad (18)$$

Then the differential equation (16) according to (17) is deduced

$$\sum_{i=1}^{2} Q_{h.i} = Q_r + \sum_{i=1}^{4} Q_{im.i} - \left[\begin{array}{l}
Q_{1s}^{(11)} + Q_{1s}^{(12)} +,\ldots,+ Q_{1s}^{(1k)} + Q_{2s}^{(11)} + Q_{2s}^{(12)} +,\ldots,+ Q_{2s}^{(1k)} + \\
+ Q_{1s}^{(21)} + Q_{1s}^{(22)} +,\ldots,+ Q_{1s}^{(2k)} + Q_{2s}^{(21)} + Q_{2s}^{(22)} +,\ldots,+ Q_{2s}^{(2k)} + \\
+ Q_{1s}^{(n1)} + Q_{1s}^{(n2)} +,\ldots,+ Q_{1s}^{(nk)} + Q_{2s}^{(n1)} + Q_{2s}^{(n2)} +,\ldots,+ Q_{2s}^{(nk)} + \\
+ Q_{3s}^{(n1)} + Q_{3s}^{(n2)} +,\ldots,+ Q_{3s}^{(nk)} + Q_{4s}^{(n1)} + Q_{4s}^{(n2)} +,\ldots,+ Q_{4s}^{(nk)}
\end{array}\right]. \qquad (19)$$

The second feed of each separated component of impurities is expressed as the difference between the input amount of the component of impurities on each *q* area of each *j* working body of the treatment system and the output amount of the component of impurities on each *q* section of each *j* working body of the treatment system.

$$\begin{aligned} Q_{s.im.i}^{(jq)} &= Q_{inc.im.com.i}^{(jq)} - Q_{out.im.com.i}^{(jq)} = \\ &= \frac{Q_{s.im.i}^{(jq)}}{Q_{inc.im.com.i}^{(jq)}} = \frac{Q_{inc.im.com.i}^{(jq)}}{Q_{inc.im.com.i}^{(jq)}} - \frac{Q_{out.im.com.i}^{(jq)}}{Q_{inc.im.com.i}^{(jq)}} = Q_{inc.im.com.i}^{(jq)}\left(1-\mu_{im.i}^{(jq)}\right), \end{aligned} \tag{20}$$

if $Q_{inc.im.com.i}^{(jq)}$ – second supply of the *i* component of impurities on *q* area of each *j* working body of the treatment system, kg/s;

$\mu_{im.i}^{(jq)}$ – coefficient that determines the degree of separation of the *i* component of impurities on the *q* section of each *j* working body of the treatment system.

Then equation (19) is deduced

$$\begin{aligned} &\sum_{i=1}^{2} Q_{h.i} = Q_r + \sum_{i=1}^{4} Q_{im.i} - \\ &-\left[\begin{aligned} &Q_{inc.f.s}^{(11)}\left(1-k_{1s}^{(11)}\right) + Q_{inc.f.s}^{(12)}\left(1-k_{1s}^{(12)}\right)+,\ldots,+Q_{inc.f.s}^{(1k)}\left(1-k_{1s}^{(1k)}\right) + Q_{inc.f.v}^{(11)}\left(1-k_{2s}^{(11)}\right) + Q_{inc.f.v}^{(12)}\left(1-k_{2s}^{(12)}\right)+,\ldots,+ \\ &+Q_{inc.f.v}^{(1k)}\left(1-k_{2s}^{(1k)}\right) + Q_{inc.f.s}^{(21)}\left(1-k_{1s}^{(21)}\right) + Q_{inc.f.s}^{(22)}\left(1-k_{1s}^{(22)}\right)+,\ldots,+Q_{inc.f.s}^{(2k)}\left(1-k_{1s}^{(2k)}\right) + Q_{inc.f.v}^{(21)}\left(1-k_{2s}^{(21)}\right) + \\ &+Q_{inc.f.v}^{(22)}\left(1-k_{2s}^{(22)}\right)+,\ldots,+Q_{inc.f.v}^{(2k)}\left(1-k_{2s}^{(2k)}\right) + Q_{inc.f.s}^{(n1)}\left(1-k_{1s}^{(n1)}\right) + Q_{inc.f.s}^{(n2)}\left(1-k_{1s}^{(n2)}\right)+,\ldots,+Q_{inc.f.s}^{(nk)}\left(1-k_{1s}^{(nk)}\right) + \\ &+Q_{inc.f.v}^{(n1)}\left(1-k_{2s}^{(n1)}\right) + Q_{inc.f.v}^{(n2)}\left(1-k_{2s}^{(n2)}\right)+,\ldots,+Q_{inc.f.v}^{(nk)}\left(1-k_{2s}^{(nk)}\right) + Q_{inc.s.s}^{(n1)}\left(1-k_{3s}^{(n1)}\right) + Q_{inc.s.s}^{(n2)}\left(1-k_{3s}^{(n2)}\right) + \\ &+,\ldots,+Q_{inc.s.s}^{(nk)}\left(1-k_{3s}^{(nk)}\right) + Q_{inc.l.h}^{(n1)}\left(1-k_{4s}^{(n1)}\right) + Q_{inc.l.h}^{(n2)}\left(1-k_{4s}^{(n2)}\right)+,\ldots,+Q_{inc.l.h}^{(nk)}\left(1-k_{4s}^{(nk)}\right) \end{aligned}\right] \end{aligned} \tag{21}$$

The coefficients $\mu_{im.i}^{(jq)}$ that determine the degree of separation of the *i* component of impurities on the *q* section of each *j* working body of the treatment system are determined experimentally in the field real conditions of root crop harvesting. Each coefficient $\mu_{im.i}^{(jq)}$ is also dependent on many objective and subjective factors or factors that regulate the agrophysical properties and characteristics of the soil environment and roots, agro-climatic conditions of root crops, characteristics of the agrophysical state of the field at harvest time, physical properties and characteristics of working bodies and their structural and kinematic parameters, etc.

Conclusion. The proposed method of developing a mathematical model of step-by-step separation of impurity components from root crops allows to optimize technological and structural and kinematic parameters of the working bodies of complex dynamic cleaning systems, both at the analytical and empirical levels.

Further analysis of the obtained mathematical model (17), by integrating it into parts within the established limits of integration allows to determine the total separation time of impurity components on each working body and the treatment system as a whole, and the degree of separation of impurity components. The function of optimizing the parameters of the working bodies is the minimized quality indexes of the treatment system in accordance with the agronomic requirements for the process of harvesting roots. The analytical solution and experimental results of the proposed models allow to optimize the required minimum length of each treatment working body and the required minimum total length of the treatment system as a whole.

References

1. Baranovsky V. M. Osnovni etapy ta suchasni tendentsii rozvytku korenezbyralnykh mashyn. Visnyk Ternopilskoho natsionalnoho tekhnichnoho universytetu. 2006. No. 11 (2). P. 67–75. [In Ukrainian].
2. Dubrovyn V., Golub G., Baranovsky V., Teslyuk V. Identifikatsiya protsessa razrabotki adaptirovannoy korneuborochnoy mashiny, Commission of motorization and energetics in agriculture, MOTROL. 2013. No. 15 (3). P. 243–255. [In Russian].
3. Baranovsky V. M., Pidhurskij M. I., Pankiv M. R. Metodolohichni ta konstruktyvno-tekhnolohichni aspekty rozrobky adaptovanykh korenezbyralnykh mashyn. Visnyk Ternopilskoho natsionalnoho tekhnichnoho universytetu. 2014. No. 2 (74). P. 106–113. [In Ukrainian].
4. Pogorely L. V., Tatianko N. V. Sveklouborochnyie mashinyi: istoriya, konstruktsiya, teoriya, prognoz. K.: Feniks, 2004. 231 p. [In Russian].
5. Baranovsky V. M. Konstruktyvno-tekhnolohichni pryntsypy adaptyzatsii transportno-ochysnoho kombinovanoho robochoho orhana korenezbyralnykh mashyn. Silskohospodarski mashyny. 2005. No. 13. P. 18–24. [In Ukrainian].
6. Špokas L., Adamchuk V., Holovach I., Prysiazhny V. Rozrobka vdoskonalenoho sposobu ochyshchennia koreneplodiv zbyralnoi mashyny, Zbirnyk naukovykh prats Vinnytskoho natsionalnoho ahrarnoho universytetu. Seriia “Tekhnichni nauky”. 2012. No. 11, I (65). P. 133–141. [In Ukrainian].
7. Ramsh V. Iu, Baranovsky V. M., Pankiv M. R., Herasymchuk H. A. Analiz tendentsii rozvytku robochykh orhaniv dlia separatsii vorokhu koreneplodiv. Naukovi notatky. 2011. 31. P. 298–305. [In Ukrainian]. DOI: https://doi.org/10.1016/j.jsames.2011.02.003
8. Baranovsky V., Tesliuk V., Lukach V., Ikalchyk M., Kushnirenko A., Kulyk V. The results of root crop cleaner experimental research. Scientific Journal of the Ternopil National Technical University. 2021. No. 1 (101). P. 47–55. DOI: https://doi.org/10.33108/visnyk_tntu2021.01.047
9. Baranovsky V. M. Rezultaty teoretychno-eksperymentalnykh doslidzhen sekundnoi podachi vorokhu koreneplodiv. Mekhanizatsiia silskohospodarskoho vyrobnytstva. 2008. No. 1. P. 111–120. [In Ukrainian].
10. Baranovsky V., Truchanska O., Pankiv M., Bandura V. Research of a contact impact of a root crop with a screw auger. Research in Agricultural Engineering. 2020. 66. P. 33–42. DOI: https://doi.org/10.17221/75/2017-RAE
11. Baranovsky V., Pankiv M., Dubchak N. Experimental research of stripping the leaves from root crops. Acta Technologica Agriculturae. 2017. 20. 3. P. 69–73. DOI: https://doi.org/10.1515/ata-2017-0014
12. Baranovsky V. M., Potapenko M. V. Theoretical analysis of the technological feed of lifted root crops. INMATEH: Agricultural Engineering. 2017. 51 (1). P. 29–38.
13. Mou X., Ou Y., Liu Q., Feng J., Li Y. Kinematic analysis and experiments of elastic dentations in process of sugarcane leaf sheath stripping. Agricultural Mechanics Report. Journal of Shandong Agricultural University. 2014. 2. P. 122–129.
14. Voytiuk D. G., Baranovsky V. M., Bulgakov V. M. Silskohospodarski mashyny. Osnovy teorii ta rozrakhunku: pidruchnyk / za red. D. H. Voitiuka. K.: Vyshcha osvita, 2005. 361 p. [In Ukrainian].
15. Baranovsky V. M., Solomka V. O., Onyshchenko V. B. Vybir parametriv pry konstruiuvanni hvyntovoho konveiera. Visnyk KhDTUSH. 2001. Vol. 8 (2). P. 209–215. [In Ukrainian].
16. Hevko R. B., Tkachenko R. I., Synii S. V., Flonts I. V. Development of design and investigation of operation processes of small-sclale root crop and potato harvesters. INMATEH: Agricultural engineering. 2016. 49 (2). P. 53–60.
17. Hevko R., Brukhanskyi R., Flonts I., Synii S., Klendii O. Advances in methods of cleaning root crops. Bulletin of theTransilvania University of Brasov. 2018. II. 11 (60). P. 127–138.
18. Gritsay Yu., Baranovsky V., Marainenko S. Experimental studies of the homogeneity coefficient of crushed particles of root crops. Scientific Journal of TNTU. 2019. 2 (94). P. 80–89. DOI: https://doi.org/10.33108/visnyk_tntu2019.02.080
19. Baranovsky V. M. Konstruktyvno-tekhnolohichni pryntsypy zastosuvannia adaptyvnoho vykopuvalnoho robochoho orhanu korenezbyralnoi mashyny. Naukovyi visnyk NAU. Zb. nauk. prats. 2004. No. 73. P. 249–255. [In Ukrainian].
20. Berezhenko Eu., Pankiv M., Jobbagy Ja., Berezhenko B.. Experimental research of the module for gathering plant of chicory roots. Eugene Berezhenko. Scientific Journal of the Ternopil National Technical University. 2021. 1 (101). P. 56–67. DOI: https://doi.org/10.33108/visnyk_tntu2021.01.056
21. Hevko R. B., Tkachenko I. G., Rogatynskyi R. M., Synii S. V., Flonts I. V., Pohrishchuk B. V. Impact of parameters of an after-cleaning conveyor of a root crop harvester on its performance. INMATEH: Agricultural engineering. 2019. 59 (3). P. 41–48. DOI: https://doi.org/10.35633/INMATEH-59-05
22. BaranovskyV. M. Konstruktyvno-tekhnolohichni pryntsypy adaptyzatsii transportno-ochysnoho kombinovanoho ochysnoho robochoho orhana korenezbyralnykh mashyn. Naukovyi visnyk NAU. 2004. 73. P. 249–255. [In Ukrainian]. DOI: https://doi.org/10.1016/j.vacuum.2003.12.010

23. Baranovsky V., Skalskiy O. Digging of chicory root crops by a combined digger. Scientific Journal of TNTU. 2018. 2 (90). P. 115–123. DOI: https://doi.org/10.33108/visnyk_tntu2018.02.115
24. Jobbagy J., Gabaj D., Arvay J. Evaluation of selected agro-physical properties of a root vegetable. In Acta Technologica Agriculturae. 2011. 14. 3. P. 61–65.

Список використаної літератури

1. Барановський В. М. Основні етапи та сучасні тенденції розвитку коренезбиральних машин. Вісник Тернопільського національного технічного університету. 2006. № 11 (2). С. 67–75.
2. Дубровин В., Голуб Г., Барановский В., Теслюк В. Идентификация процесса разработки адаптированной корнеуборочной машины. Commission of motorization and energetics in agriculture, MOTROL. 2013. № 15 (3). P. 243–255.
3. Барановський В. М., Підгурський М. І., Паньків М. Р. Методологічні та конструктивно-технологічні аспекти розробки адаптованих коренезбиральних машин. Вісник Тернопільського національного технічного університету. 2014. № 2 (74). С. 106–113.
4. Погорелый Л. В., Татьяко Н. В. Свеклоуборочные машины: история, конструкция, прогноз. К.: Феникс, 2004. 231 с.
5. Барановський В. М. Конструктивно-технологічні принципи адаптації транспортно-очисного комбінованого робочого органу коренезбиральних машин. Сільськогосподарські машини. 2013. № 13. С. 18–24.
6. Шпокас Л., Адамчук В., Головач І., Присяжний В. Розробка вдосконаленого способу очищення коренеплодів збиральних машин. Збірник наукових праць Вінницького національного аграрного університету. Серія «Технічні науки». 2012. № 11. Серія І (65). С. 133–141.
7. Рамш В. Ю., Барановський В. М., Паньків М. Р., Герасимчук Г. А. Аналіз тенденцій розвитку робочих органів для сепарації вороху коренеплодів. Наукові нотатки. 2011. № 31. С. 298–305. DOI: https://doi.org/10.1016/j.jsames.2011.02.003
8. Baranovsky V., Tesliuk V., Lukach V., Ikalchyk M., Kushnirenko A., Kulyk V. The results of root crop cleaner experimental research. Scientific Journal of the Ternopil National Technical University. 2021. No. 1 (101). P. 47–55. DOI: https://doi.org/10.33108/visnyk_tntu2021.01.047
9. Барановський В. М. Результати теоретично-експериментальних досліджень секундної подачі вороху коренеплодів. Механізація сільськогосподарського виробництва. 2008. № 1. С. 111–120.
10. Baranovsky V., Truchanska O., Pankiv M., Bandura V. Research of a contact impact of a root crop with a screw auger. Research in Agricultural Engineering. 2020. No. 66. P. 33–42. DOI: https://doi.org/10.17221/75/2017-RAE
11. Baranovsky V., Pankiv M., Dubchak N. Experimental research of stripping the leaves from root crops. Acta Technologica Agriculturae. 2017. Vol. 20. No. 3. P. 69–73. DOI: https://doi.org/10.1515/ata-2017-0014
12. Baranovsky V. M., Potapenko M. V. Theoretical Analysis of the Technological Feed of Lifted Root Crops. INMATEH: Agricultural Engineering. 2017. Vol. 51 (1). C. 29–38.
13. Mou X., Ou Y., Liu Q., Feng J., Li Y. Kinematic analysis and experiments of elastic dentations in process of sugarcane leaf sheath stripping. Agricultural Mechanics Report. Journal of Shandong Agricultural University. 2014. Vol. 2. P. 122–129.
14. Войтюк Д. Г., Барановський В. М., Булгаков В. М. Сільськогосподарські машини. Основи теорії та розрахунку: підручник / за ред. Д. Г. Войтюка. К.: Вища освіта, 2005. 464 с.
15. Барановський В. М., Соломка В. О., Онищенко В. Б. Вибір параметрів при конструюванні гвинтового конвеєра. Вісник ХДТУСГ. 2001. № 8 (2). С. 209–215.
16. Hevko R. B., Tkachenko R. I., Synii S. V., Flonts I. V. Development of design and investigation of operation processes of small-sclale root crop and potato harvesters. INMATEH: Agricultural engineering. 2016. Vol. 49 (2). P. 53–60.
17. Hevko R. B., Tkachenko R. I., Synii S. V., Flonts I. V. Development of design and investigation of operation processes of small-sclale root crop and potato harvesters. INMATEH: Agricultural engineering. 2016. 49 (2). P. 53–60.
18. Gritsay Yu., Baranovsky V., Marainenko S. Experimental studies of the homogeneity coefficient of crushed particles of root crops. Scientific Journal of TNTU. 2019. 2 (94). P. 80–89. DOI: https://doi.org/10.33108/visnyk_tntu2019.02.080
19. Барановський В. М. Конструктивно-технологічні принципи застосування адаптованого викопувального робочого органу коренезбиральної машини. Науковий вісник НАУ. Зб. наук. праць. 2004. № 73. С. 249–255.
20. Berezhenko Eu., Pankiv M., Jobbagy Ja., Berezhenko B.. Experimental research of the module for gathering plant of chicory roots. Eugene Berezhenko. Scientific Journal of the Ternopil National Technical University. 2021. 1 (101). P. 56–67. DOI: https://doi.org/10.33108/visnyk_tntu2021.01.056

21. Hevko R. B., Tkachenko I. G., Rogatynskyi R. M., Synii S. V., Flonts I. V., Pohrishchuk B. V. Impact of parameters of an after-cleaning conveyor of a root crop harvester on its performance. INMATEH: Agricultural engineering. 2019. 59 (3). P. 41–48. DOI: https://doi.org/10.35633/INMATEH-59-05
22. Барановський В. М. Конструктивно-технологічні принципи адаптизації транспортно-очисного комбінованого очисного робочого органа коренезбиральних машин. Науковий вісник НАУ. 2004. Том 73. С. 249–255. DOI: https://doi.org/10.1016/j.vacuum.2003.12.010
23. Baranovsky V., Skalskiy O. Digging of chicory root crops by a combined digger. Scientific Journal of TNTU. 2018. 2 (90). P. 115–123. DOI: https://doi.org/10.33108/visnyk_tntu2018.02.115
24. Jobbagy J., Gabaj D., Arvay J. Evaluation of selected agro-physical properties of a root vegetable. In Acta Technologica Agriculturae. 2011. 14. 3. P. 61–65.

УДК 631.361.2

МЕТОД ПОЕТАПНОГО РОЗРОБЛЕННЯ МАТЕМАТИЧНОЇ МОДЕЛІ ПРОЦЕСУ ВІДОКРЕМЛЕННЯ ДОМІШОК ВІД КОРЕНЕПЛОДІВ

Марія Паньків; Микола Підгурський;
Михайло Пилипець; Мирослав Бурда

Тернопільський національний технічний університет імені Івана Пулюя,
Тернопіль, Україна
Івано-Франківський національний технічний університет нафти і газу,
Івано-Франківськ, Україна

Резюме. *Збирання коренеплодів, наприклад таких, як великорозмірні коренеплоди цукрових і кормових буряків, довгоплідні коренеплоди цикорію є технологічно складним і неоднозначним технологічним процесом, який має свої різнотипні або різноструктурні послідовні технологічні операції зрізування гички, викопування коренеплодів, очищення викопаного вороху від домішок, завантаження чистих коренеплодів у бункер або в транспортні засоби, які рухаються поруч з коренезбиральною машиною. Підвищення процесів ефективності відокремлення домішок від коренеплодів є актуальною науковою проблемою, вирішення якої значно покращує якість сировини для переробки коренеплодів і якість виробленої з неї продукції. Метою дослідження є підвищення ефективності процесу збирання коренеплодів шляхом аналізу існуючих підходів до математичного моделювання технологічного процесу сепарації, або відокремлення домішок від коренеплодів. Наведено викладення аналізу існуючих математичних моделей, які застосовуються для описування процесів роботи технічно складних систем і подальшої оптимізації раціональних параметрів їх робочих органів і технологічних показників машин загалом. На основі проведеного аналізу запропоновано розроблення математичних моделей, які описують процеси функціонування складних технічних систем проводити з застосуванням методу поетапного аналізу процесу відокремлення домішок від коренеплодів за певний проміжок часу або на певному проміжку шляху переміщення компонентів вороху (коренеплодів і домішок) по всій довжині очисної поверхні кожного робочого органу. Розроблена математична модель дозволяє на вищому рівні точніше описувати процес поетапного відокремлення різноструктурованих компонентів домішок від коренеплодів кожним очисним робочим органом, які є складовими одиницями технічних систем коренезбиральних машин. Запропонована математична модель може бути застосована для оптимізації параметрів робочих органів та інших процесів, наприклад, для сепарації зібраного зернового вороху, підготовчих процесів посівного матеріалу тощо.*

***Ключові слова**: коренезбиральна машина, очисна система, робочі органи, умови збирання, компоненти домішок, подача компонентів, відокремлення домішок, ділянка відокремлення, грунтові та рослинні домішки.*

https://doi.org/10.33108/visnyk_tntu2021.04.074 *Отримано 01.09.2021*