Technology and parameters of cabbage machine harvesting by careful stacking of heads in containers

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Abstract. The most important issue when developing the machine technology of cabbage harvesting is to protect the heads from mechanical damage. In this regard, the article describes a new technology for harvesting cabbage based on a prototype developed by the authors of a multivariate cabbage harvester. This technology of cabbage machine harvesting differs from the known gentle mode of stacking heads in containers on a low-frame trailer accompanying the harvesting unit. The authors first simulated the workflow of this technology using the queuing theory. As a result, a quantitative relationship between the performance indicators of the cabbage harvesting process and the structural and technological parameters of the machine in the studied variant was established. On its basis, rational values of parameters of the machine were defined: the number of jobs at the completion table, the longitudinal conveyor and on the site of the low-frame trailer, respectively, \( n_1 = 2 \), \( n_2 = 4 \), and \( n_3 = 4 \); the length of the conveyor-cutter and the longitudinal conveyor, respectively, was 2.8 and 4 m.

1. Introduction
Harvesting of cabbage is carried out in the late autumn period often in adverse weather conditions with the involvement of a large number of labor. In this regard, close attention was paid to the development of various technical means for harvesting cabbage for several years in Russia and abroad [1]. Notable success in this matter has been achieved in Europe, the United States and other developed countries [2]. In recent years, work has also intensified on the creation of cabbage harvesting equipment in Japan and China [3-6].

Currently, most of the proposed cabbage harvesting machines are in the stage of technical solutions and pilot production, and machines in mass production are also known. Thus, in [7], the structure of the layout scheme of a cabbage harvesting machine is discussed, and sources [8,9] describe patents for cabbage harvesting machines. The work [10] reports on the successful creation of a self-propelled cabbage harvester.

It should be noted that the well-known cabbage harvesting machines, which are quite well worked out and produced serially, are mainly performed with an elevator for unloading of heads in bulk directly into the body of the vehicle or into containers installed in it. At the same time, as our studies show, cabbage heads are damaged to a large extent due to exceeding the height of the fall and the collision rates of the heads of permissible values. For this reason, in our opinion, cabbage harvesting machines with an elevator for the unloading of products are currently of limited use, only for harvesting cabbage intended for short-term storage. Cabbage in most cases is removed manually for long-term storage.
Given the above, the purpose of these studies is to justify a new method of machine technology harvesting cabbage and optimize its basic parameters.

2. Materials and methods
To achieve the goal we simulated the process of cabbage machine harvesting by carefully stacking the heads in containers on a low-frame semi-trailer, and we established a quantitative relationship between the performance indicators of the machine harvesting process and the structural and technological parameters of the harvester in the studied variant.

In our opinion, within the framework of the above, the technology based on the multivariate cabbage harvester proposed by us in the Chuvash State Agricultural Academy (Russia) is of practical interest (figure 1).

![Multivariate cabbage harvester design of the Chuvash State Agricultural Academy (Russia).](image)

This technology of cabbage machine harvesting is as follows. During operation, the harvesting unit moves along the harvested part of the field (figure 2), directing the cutting apparatus 1 along the row to be harvested. In this case, the cutting machine continuously copies the relief of the field. During the work of the cutting device, the cabbage plants are aligned in the longitudinal and transverse planes, as well as in height. Next, the cutting device will approach the cabbage plants and cut them off. The cut heads arrive on a cloth of a belt conveyor at joint action with a clamping conveyor. The flow of cut heads together with cabbage leaves pass through the roller leaf separator and enters the conveyor-cutter 2 (figure 2). Workers inspect cabbages on a conveyor-cutter. In this case, sick and unripe heads are separated from the mainstream, and heads with long stalks (with rosette leaves) are inserted into holes in the plates of the conveyor-cutter, which are subsequently re-cut when meeting with a passive knife. In this case, the rosette leaves are separated from the heads.

Subsequently, the flow of cabbages enters the longitudinal conveyor 3, which allows stretching the flow of cabbages and cabbage leaves along the platform of the accompanying low-frame trailer 4 with interchangeable containers 5 (figure 2). Here, the workers, being on a specially equipped site 6, select the commodity heads for transfer to the workers who are on site 7 and stack them in containers on the accompanying vehicle. The remaining cabbage waste (leaves and unripe heads) is unloaded to the ground at the end of the conveyor. As the containers 5 are filled with cabbage, the transport unit 4 is sent to the vegetable store. Otherwise, it will require a vehicle with empty containers.
Figure 2. Scheme of cabbage machine harvesting by careful stacking of heads in containers on a low-frame trailer: 1 – cutting apparatus, 2 – conveyor-cutter, 3 – longitudinal conveyor, 4 – accompanying low-frame trailer, 5 – interchangeable containers, 6 and 7 – specially equipped sites, 8 – fence.

We would like to note that a longitudinal conveyor is installed instead of elevator as a cabbage harvester unit. In this case, the holes on the frame of the combine for mounting the elevator are used to mounting the named block.

The technological process of cabbage machine harvesting (figure 3) can be considered as the following set of similar tasks: the commercial processing of heads, sorting out the heads on a longitudinal conveyor, and stacking of commodity heads of cabbage in containers.
Such tasks are typical for the Queuing system (hereinafter QS), which in this case can be considered as consisting of three consecutive multi-channel subsystems of QS (figure 3):

a) a subsystem of the commercial processing of head;

b) a subsystem of the bulkhead of the heads on the longitudinal conveyor;

c) subsystems of stacking of commodity heads in containers.

First, we consider the subsystem of commodity completion of cabbage heads. In this subsystem, the flow of non-commodity cut heads entering the conveyor-cutter blade, it is possible to designate the input flow of the subsystem. Workers inspecting and installing the heads in the planting holes of the conveyor-cutter for re-trimming the cabbage stalks replace the channels of the subsystem. This QS subsystem under consideration is multichannel with failures, since when all workers (system channels) inspecting the flow of cabbage on the conveyor-trimmer blade are busy, part of the non-commodity cut heads of cabbage is passed by the workers, and a denial of service may take place.

The total intensity \( \lambda \) of cabbage heading to the cutter when harvesting cabbage with a single-row combine can be determined based on the average working speed \( \vartheta \) of the harvesting unit and the average distance \( A \) between cabbage plants in a row according to the equation (1):

\[
\lambda = \frac{\vartheta}{A}.
\]

In the stream there is only a part of the heads, i.e. non-commodity cut, requiring improvement. Therefore, we determined \( \lambda \) value for the considered subsystem (ISA), taking into account the percentage of non-marketed cabbage heads in the total mass of the stream, in particular, making it equal to 25%. Thus, at \( \vartheta = 0.8 \, \text{m/s}, \, A = 0.5 \, \text{m} \) the intensity of the ISA \( \lambda_1 \) was 0.4 s\(^{-1}\).

The service intensity of one channel can be determined experimentally, based on the service time of \( t_1 \) one cabbage head according to the formula:

\[
\mu_1 = \frac{1}{t_1},
\]

where, \( t = 3 \ldots 4 \, \text{s} \) the intensity of service \( \mu = 0.25 \ldots 0.33 \, \text{s}^{-1} \).

Different states are possible in the considered QS subsystem. The possible states are denoted based on the number of simultaneously occupied channels: \( S_0 \) – all channels are free; \( S_1 \) – one channel is busy, the rest are free; \( S_k \) – \( k \) channels are busy, the rest are free; \( S_{k+1} \) – busy \( k+1 \) channels, the rest are free; and \( S_{n_1} \) – all \( n_1 \) channels are busy.

The graph of the above states is shown in the figure 4. Here, each arrow shows the corresponding intensity of the event flows. Note that according to the arrows from left to right, the system is transferred from one state to another at the same demand intensity, \( \lambda_1 \) according to the arrows from right to left, the
system is transferred from one state to another by a service flow, the intensity of which is multiplied by μ₁ the number of busy channels. For example, let the system be in a state S₀. A stream with intensity λ₁ transfers from S₀ to the S₁ system (as soon as the application arrives, the system jumps from S₀ to S₀). Next, let the system be in the state S₀ (one channel is running). It produces μ₁ services per unit time and then goes back to state S₀, etc.

![Figure 4. The state graph of QS when finalizing the heads of cabbage on the completion table.](image)

In this case, the limiting probabilities of the system states can be expressed by the formulas [1]:

\[
P_0 = \left[ 1 + \frac{\rho_1}{1!} + \frac{\rho_1^2}{2!} + \ldots + \frac{\rho_1^n}{n!} \right]^{-1};
\]

\[
P_1 = \rho_1 P_0;
\]

\[
P_2 = \frac{\rho_1^2}{2!} P_0;
\]

\[
\ldots \ldots \ldots \ldots \ldots ;
\]

\[
P_n = \frac{\rho_1^n}{n!} P_0,
\]

where, \( \rho_1 = \frac{\lambda_1}{\mu_1} \) is the channel load intensity; \( P_0, P_1, P_2, \ldots, P_n \) – respectively the marginal probabilities of states of the system S₀, S₁, S₂, …, Sₙ.

In the QS subsystem, the probability of application denial of service is \( P_1 \) equal to the probability that all channels are busy, i.e. the subsystem is in a state of \( S_{n_1} \). Thus,

\[
P_1 = P_{n_1} = \frac{\rho_1^n}{n!} P_0.
\]

In this case, some of the non-commodity cut heads leave the completion table, without waiting for service, and the probability of servicing applications is found by the equation (5):

\[
P_2 = 1 - P_1 = 1 - \frac{\rho_1^n}{n!} P_0.
\]

Consequently, the percentage of modified non-commodity cut heads can be expressed in the form:

\[
Q = \left( 1 - \frac{\rho_1^n}{n!} \right) \cdot P_0 \cdot 100%.
\]

The results of the calculations of the performance indicators of the QS subsystem under consideration, obtained by equations (1)–(6) for different numbers of service personnel \( n_1 \) are presented in Table 1.

| \( n_1 \) | 1    | 2    | 3    | 4    | 5    |
|----------|------|------|------|------|------|
| \( P_0 \) | 0.412| 0.290| 0.254| 0.243| 0.241|
| \( P_1 \) | 0.588| 0.296| 0.123| 0.042| 0.012|
| \( P_2 \) | 0.412| 0.704| 0.877| 0.958| 0.988|
| \( Q, \% \) | 41.2 | 70.4 | 87.7 | 95.8 | 98.8 |
Next, we considered the functioning of the heading sorting out subsystem on a longitudinal conveyor. The considered QS subsystem, unlike the previous one, can be investigated as multi-channel with delay, since when all the channels (serving workers) are occupied, part of the heads along with cabbage leaves will be passed by the workers to the unloading end of the longitudinal conveyor, where the fence 8 will temporarily delay them, preventing the unloading. However, the number of such heads should be limited, for example, no more than 4, otherwise they may cause congestion in the production line. In this subsystem, the intensity of the input flow will be determined by the formula (1), since the longitudinal conveyor simultaneously receives commodity cut heads and heads after completion: at $\dot{\vartheta} = 0.8$ m/s, $A = 0.5$, $\lambda_2 = 0.8/0.5 = 1.6$ s$^{-1}$.

The intensity of service, in this case, is determined based on the time of heads $t_2$ being sorted out on the longitudinal transport:

$$\mu_2 = \frac{1}{t_2}$$  \hspace{1cm} (7)

where, $t_2 = 2...2.5$ s the intensity of service $\mu_2 = 0.4...0.50$ s$^{-1}$. With these characteristics of flows, a subsystem can be in the following states: $S_0$ – all channels are free, $S_1$ – one channel is busy, the rest are free, $S_{n_2}$ – all $n_2$ channels are busy, $S_{n_2+1}$ – channels $n_2$ are busy, one application is in the queue, and $S_{n_2+r}$ – all $n_2$ channels are busy, applications are queued.

Theoretically, in this case, the number $r$ can be as large as desired, that is, the state graph of the head sorting out subsystem on the longitudinal conveyor can become infinite (figure 5).

![State graph of the QS subsystem during heading sorting out on a longitudinal conveyor.](image)

It should be noted that in the subsystem, the steady-state mode of operation will exist only when $\chi_p = p_2/n_2 < 1$ (here $p_2 = \lambda_2/\mu_2$), and when $\chi_p \geq 1$ the queue in the subsystem will increase infinitely. When $\chi_p < 1$ the limiting probabilities of the above conditions will be determined accordingly [1]:

$$P_0 = \left[1 + \frac{p_2}{n_2} + \frac{p_2^2}{n_2^2} + \cdots + \frac{p_2^{n_2}}{n_2^{n_2}} + \frac{p_2^{n_2+1}}{n_2^{n_2}(n_2-p_2)}\right]^{-1}$$

\[
\begin{align*}
P_1 &= \frac{p_2}{n_2} P_0 \\
P_2 &= \frac{p_2^2}{n_2^2} P_0 \\
P_{n_2} &= \frac{p_2^{n_2}}{n_2^n} P_0 \\
P_{n_2+1} &= \frac{p_2^{n_2+1}}{n_2^{n_2+1}} P_0 \\
&\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\
P_{n_2+r} &= \frac{p_2^{n_2+r}}{n_2^{n_2+r}} P_0 \\
&\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\
&\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\
\end{align*}
\]  \hspace{1cm} (8)

In this case, the average number of applications in the queue (the average number of heads accumulated at the limiter) and the average waiting time for them in the queue can be calculated accordingly:

$$\bar{r} = \frac{p_2^{n_2+1} P_0}{n_2^n (1-\chi)^2}$$  \hspace{1cm} (9)
Results of calculations of indicators of the functioning of the subsystem of QS at a sorting out of heads on the longitudinal conveyor received on formulas (8)–(10) at $\lambda_2=1.6\ \text{s}^{-1}$, $\mu_2=0.45\ \text{s}^{-1}$ are presented in Table 2.

Table 2. Performance indicators for the functioning of the QS subsystem during sorting out commodity heads on a longitudinal conveyor.

| $n_2$ | 4    | 5    | 6    |
|-------|------|------|------|
| $P_0$ | 0.013| 0.024| 0.027|
| $\bar{r}$ | 3.2  | 0.97 | 0.27 |
| $\chi$ | 0.889| 0.711| 0.5925|
| $\bar{t},\text{s}$ | 3.9  | 0.61 | 0.17 |

Finally, let us focus on the subsystem "c" of stacking commodity heads in containers. In this subsystem, the intensity of the input flow $\lambda_3$ is also equal to $\theta/A$ so it should be as close as possible in terms of performance to the previous subsystem. However, it should be noted that in this subsystem there is no waiting area for unserved orders (heads), so the subsystem should be considered as multi-channel with failures.

3. Discussion of results

It can be seen from Table 1 that with an increase in the number of service personnel $n_1$, the percentage of modified heads on the cutting conveyor increases, therefore, in the total mass of heads of cabbage, the content of non-commodity cut heads is reduced. However, it should be noted that the complexity of the process increases. Besides the number of jobs for the staff in the cabbage harvester is limited.

According to Table 1, optimal data should be considered the number of jobs $n_1=2$. At the same time, the percentage of modified non-commodity cut heads is 70.4%, therefore, the longitudinal conveyor will receive a stream containing commodity heads, not lower than 92.6%, if the initial content of non-commodity cut heads in the stream is within 25%.

As can be seen from Table 2, with the increase in the number of service personnel $n_2$ behind the longitudinal conveyor, the average number of applications in the queue $\bar{r}$ is also expected to decrease. For example, when $n_2=4$ – the average number of applications waiting for service, $r \approx 3.2$, when $n_2=5 \bar{r} \approx 1$, and when $n_2=6$ and even less.

As noted above, to eliminate congestion in the subsystem, the number of heads waiting for service on the longitudinal conveyor should not exceed 3...4 pcs. Therefore, according to Table 2, we consider the rational number of personnel serving the longitudinal conveyor $n_2=4$.

Further, taking into account the above, in order to minimize possible service failures of "c" subsystem, we consider it necessary to involve the stacking of heads in containers located on the semi-trailer, the number of workers $n_1$ is not less than in the previous subsystem, that is, not less than 4 people.

According to the found values of the number of service personnel $n_1=2$, $n_2=4$, and $n_3=4$ it is possible to justify the design dimensions of the harvesting machine and the accompanying vehicle.

So, if we take the length of the workplace equal to 1 m, then the length of the conveyor-cutter, taking into account the size of the area for re-trimming heads, should be within 2.8 m, and the length of the longitudinal conveyor and the platform of the accompanying semi-trailer should be at least 4 m.

4. Conclusion

New technology for machine harvesting cabbage by carefully stacking of cabbages in containers on low bed trailers is proposed and modeled.

A quantitative relationship has been established between the efficiency indicators of the process of machine harvesting and the structural and technological parameters of the combine in the studied
variant. On its basis, rational values of parameters are defined: the number of jobs at the completion table, the longitudinal conveyor and on the site of the low loader trailer, respectively, $n_1 = 2$, $n_2 = 4$ and $n_3 = 4$; length of the conveyor-cutter taking into account the sizes of the zone of repeated pruning of heads and length of the longitudinal conveyor are, respectively, equal to 2.8 and 4 m; length of the platform for placement of the service personnel mounted along all platforms of the semi-trailer shall be not less than 4 m.

In this work, scientific novelty is presented proposed technology of cabbage machine harvesting, mathematical models of the process of this technology, the value of the optimal parameters set in the modeling process.

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