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On the Question of Constructing a Model for Assessing Production Efficiency when the Quality of Sugar Beet Changes During Storage

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Abstract: The performance of sugar beet factories depends significantly on the quality of the processed raw materials, which is influenced by climatic factors during vegetation and storage. Associated microflora, whose activity is also determined by ambient temperature and humidity, plays a key role. Under the influence of microorganisms, not only is beet sucrose consumed but also non-sugars, which are harmful to production, accumulate. Based on statistical data from sugar factories, the influence of climatic factors on the condition of sugar beet roots as a biosystem, in conjunction with associated microflora, is substantiated. The dynamics of sucrose losses during storage and delivery of raw materials for processing are presented. Laboratory analyses performed regularly in the factory laboratory revealed indicators characterizing the impact of raw material quality on technological processes. A mathematical model has been constructed that allows for the prediction of limestone consumption in production as one of the most important indicators of production efficiency, determining the degree of purification of sugar solutions, the yield and quality of finished products.

1 INTRODUCTION

The technological process of sugar beet root processing is characterized by a sequence of industrial operations and is multi-stage. The main production stages include:

- receiving and storing beets;
- transporting beets to the plant and removing impurities;
- sucrose extraction;
- removing impurities from the raw juice and condensing it;
- obtaining crystalline sugar and processing intermediate products;
- drying and packaging the finished product.

The transition from the previous stage to the next occurs sequentially. The quality of the intermediate products at the previous stage influences the process modes and product quality in subsequent operations.

The sugar beet root processing business process is shown in Figure 1 as an IDEF0 diagram. This approach provides a structured visualization of the functioning of the entire sugar production system.

Sugar production requires consideration of a large number of parameters that are interrelated and mutually influence each other. Determining the importance of parameters is virtually impossible, from the operations of receiving raw materials (root crops) to the production and packaging of the finished product. Parameters must be taken into account, starting from the quality of the beets, characterized by their technical ripeness, sugar content, turgor state, and degree of contamination, and ending with the concentration of non-sugars in beet juice. The suitability of sugar beets as raw materials for storage and industrial processing is determined by GOST 33884-2016.

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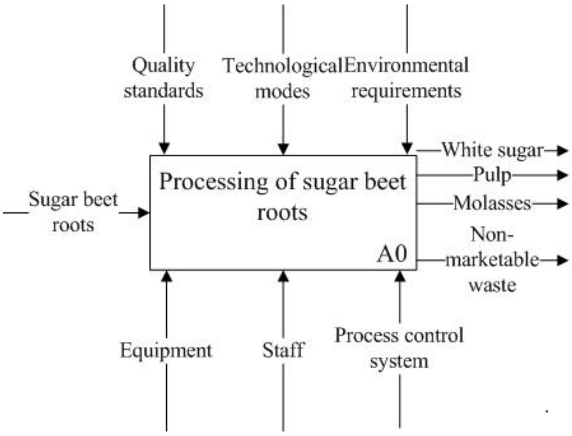


Figure 1: Context diagram of the main business process.

The decomposition of the context diagram in Figure 1 in accordance with the main stages of the process is presented in Figure 2, which helps to see the interrelations between the stages of processing the raw materials, identify bottlenecks and dependencies between raw materials, equipment and personnel. .

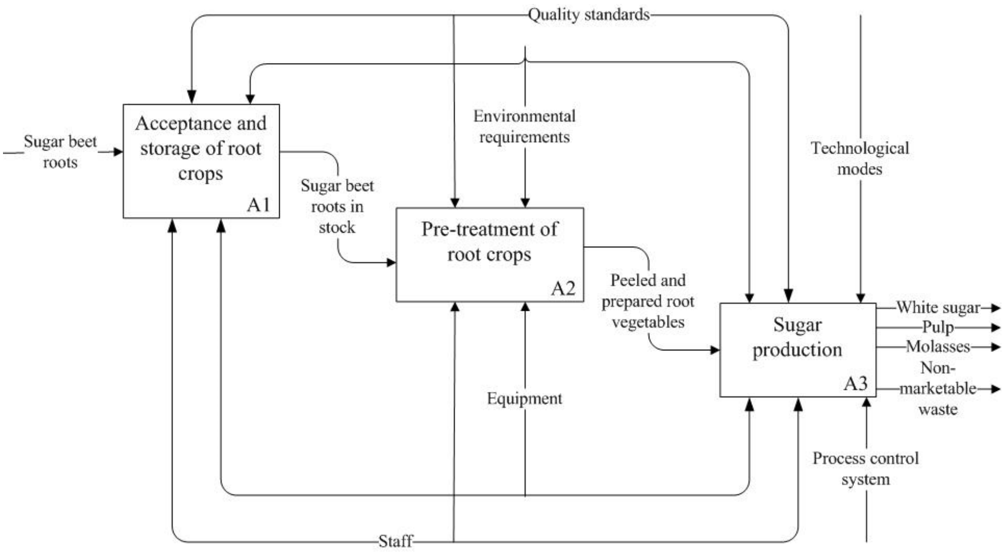


Figure 2: Decomposition of the business process context diagram.

The quality and yield of white sugar are determined not only by the technological quality of the root crops, but also by the nature and volume of sucrose losses due to mechanical damage during harvesting and transportation, wilting, freezing, and thawing during storage. Mechanically damaged root crops increase their respiration rate during storage and are more easily attacked by microorganisms. Wilting leads to increased respiration, which increases sugar losses and weakens resistance to microorganisms.

Various researchers and practitioners in this field have shown great interest in the sugar production process. In their source, Kalinin A.T. and Kalinin A.A. discuss issues of improving the technological quality of sugar beet. In their recommendations, Kornienko A.V., Nanaenko A.K., and Mazepin M.G. provide examples of modern sugar beet production technologies.

To effectively implement and account for requirements for the physical condition of raw materials, GOSTs, standards, and technical requirements have been developed. These regulatory documents define the percentage of beet pulp containing impurities such as blooming, wilted, frostbitten, or severely damaged root crops, which can reduce their shelf life and complicate processing. Sugar beets that do not meet these standards are considered substandard. Substandard root crops are hotbeds for pathogenic microflora and spread diseases to healthy ones.

Spoilage of raw materials is caused by a complex of microorganisms, predominantly over 150 species of fungi. Root crops damaged by wilting or freezing are particularly susceptible to attack. Acids and toxins released by microorganisms penetrate healthy tissue, then onto healthy roots. The tissues thus destroyed are easily colonized by other saprophytic fungi and bacteria, further degrading the quality of the raw material. This process is a chain reaction.

Thus, storage stability and efficient processing of root crops are achieved when beets meet certain parameters [3, 6]. Losses at beet processing plants during storage and processing are highly dependent on the initial technical characteristics of the root crops.

2 MATERIALS AND METHODS OF RESEARCH

During post-harvest storage of root crops, a complex biosystem is formed, consisting of sugar beets and microbial populations on their surface. The behavior of this biosystem depends on abiotic influences that alter the nature of biotic interactions. Among the complex of factors influencing the interactions between rot pathogens and the sugar beet plant, temperature and relative humidity are of great importance. As previously demonstrated, temperature influences the mycelial growth of rot pathogens and the development of the disease (Fig. 3), while the possibility of root crop infection depends on humidity.

In previous studies, the authors of the article, based on experimental data, obtained mathematical models of the growth of some pathogen populations (Ph. betae, A. tenuis, S. sclerotiorum, Fusarium sp., B. cinerea and P. expandum) (Fig. 3). Harvested beet roots and rot pathogens during storage form a system in which a struggle for existence and survival occurs. In this context, interest arises; this simple statistical interaction of rot pathogen populations, obtained as a result of similar abiotic conditions, arises. Abiotic conditions in this case are determined by the specifics of beet root storage.

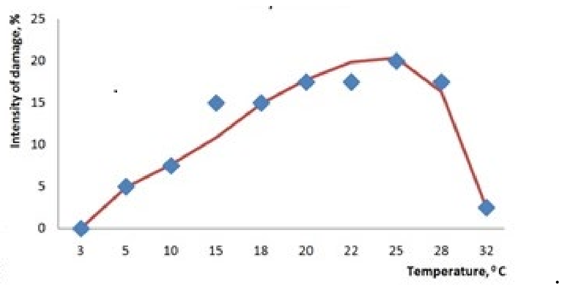


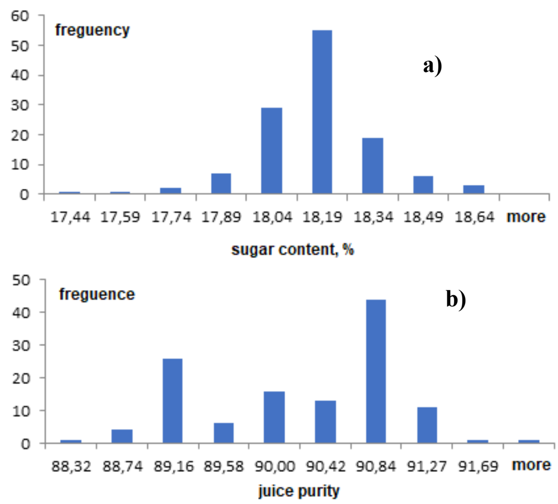
Figure 3: Intensity of root crop damage by the fungus P.expansum.

Thus, it is necessary to clearly establish the dependence of sugar production efficiency on the processes occurring in the biosystem during storage.

The first important condition for the existence of a biosystem is a uniform nutritional status. All microorganisms use sugar beet sucrose as an energy source, therefore, they are indirectly connected through the sugar beet organism. This allows the model to be built using the dynamics of sucrose losses both during raw material storage and during processing.

Sucrose losses are determined at all stages of the sugar production process in the company's raw material and plant laboratories based on the qualitative characteristics of raw materials, semi-finished products, production waste, and finished products. The number of parameters studied exceeds 120 and requires the use of specialized mathematical apparatus.

The laboratory results obtained under the production conditions of a specific enterprise were processed using regression analysis.



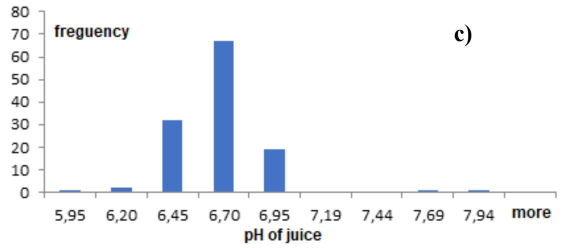


Figure 4: Histograms of laboratory data distribution: a) sugar content; b) cell sap purity; c) cell sap pH.

To understand the impact of root crop damage intensity and overall quality on sugar production efficiency, limestone consumption (%) was selected. Root crop sugar content (%), cell sap purity, and pH were selected as input parameters characterizing raw material quality and influencing finished product quality and yield. Laboratory test results were preprocessed, and their consistency was determined. A visualization of the results is presented in Figure 4.

The histograms shown in Figure 4 indicate that there are no outliers or biases in the laboratory values. The numerical values from the studies can be used to construct a regression model.

To assess the consistency of process quality parameters (beet sugar content, %; cell sap purity, %; and cell sap pH), we use correlation analysis. This method is based on calculating the Pearson correlation coefficient. We use the following notations: Y is limestone consumption, %; $X1$ is sugar content, %; $X2$ is juice purity; and $X3$ is cell sap pH. The results of the correlation analysis are presented in Table 1.

Thus, from the obtained data of the correlation it follows that the Pearson coefficient in modulus lies in the range from 0.11 to 0.24, i.e. does not exceed 0.25. Consequently, the use of variables $X1$, $X2$ and $X3$ in constructing the regression model is appropriate.

Table 1: Correlation of variables.

	Y	***X1***	***X2***	***X3***
Y	1			
X1	-0,18599	1		
X2	0,194917	-0,23851	1	
X3	0,209394	-0,16832	-0,1127	1

3 RESEARCH RESULTS AND THEIR DISCUSSION

Rotten root crops have low sugar content and high levels of reducing, mineral, soluble nitrogenous, and pectin substances. These non-sugars negatively impact technological processes during processing of substandard raw materials, as they promote accelerated sucrose decomposition and increased coloration of semi-finished products, increase viscosity and scale formation, and increase sugar losses in molasses and its yield. It has been established that it is impossible to obtain commercial sugar when the rotten matter content in beets is 8-10%.

In real sugar factories, microbiological monitoring of individual pathogens is generally lacking, but their impact is assessed using a summary characteristic — the percentage of rotten matter. This is determined during the acceptance of sugar beets at the plant. As noted earlier, all sugar beet pathogens share a common nutrient—the consumption of sucrose. Therefore, their harmfulness at a specific plant can be assessed using the "Sucrose Loss" indicator, which is the difference in sucrose content between the acceptance of beets and their transfer for processing (Fig. 5) [Data from Soyuzrossakhar].

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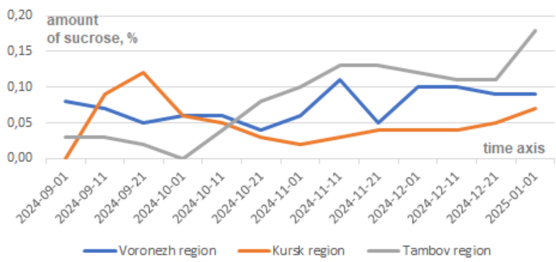

Figure 5: Dynamics of average daily sucrose losses in root crops during the 2024 production season

An analysis of statistical data shows that during the initial processing period, when air temperatures significantly exceed the optimal storage temperature for root crops (0 to +3°C), favorable conditions for microbiological spoilage of beets are created, which is particularly noticeable at factories in the Voronezh and Kursk regions. A decrease in ambient air temperature reduces the rate of root respiration and microbial growth, and sucrose losses are reduced. However, the onset of frost has a detrimental effect on the condition of beets: their immunity is weakened, and secondary microflora begins to actively develop in frost-affected areas, increasing sucrose losses.

In the Tambov region, sucrose losses increase gradually throughout the production season, but the same patterns apply. Low losses during the initial period of plant operation are due to the lack of storage of root crops or their small volume, when the crop is sent directly from the field for processing. Storing part of the crop directly in the field leads to a decrease in root crop quality due to the absence of preliminary purification from impurities and high crowding, creating conditions for microbiological processes.

The impact of sucrose losses during storage and delivery for processing on plant operations can be assessed based on the consumption of equivalent fuel and limestone, as well as the sugar content of molasses. The analysis was conducted for a specific sugar refinery in the Central Black Earth Region (Table 2).

Plant performance indicators show that sucrose losses during storage are increasing gradually, due to the factors mentioned above, including high temperatures in the region in October 2024. Lower temperatures put microflora into a sedative state, reducing root respiration, and reducing losses. However, total sucrose losses during storage and transportation remain high, as microbially damaged and frost-damaged root vegetables rapidly lose sugar during transport to the plant.

Table 2: Average daily losses of sucrose during storage and transportation at a sugar plant in the Central Black Earth Region in the 2024/25 season (plant data)

Indicator	01.09	11.09	21.09	01.10	11.10	21.10	01.11	11.11	21.11	01.12	11.12
Average daily sucrose losses during storage, %	0,01	0,01	0,03	0,06	0,08	0,08	0,06	0,06	0,04	0,03	0,01
Average daily sucrose losses during storage and transportation, %	0,07	0,09	0,10	0,09	0,14	0,16	0,21	0,19	0,17	0,15	0,12
Sucrose losses in molasses, %	2,11	1,81	2,03	1,93	2,13	2,03	1,99	2,07	2,01	2,00	2,19
Consumption of fuel equivalent, %	2,82	2,68	2,65	2,70	2,73	2,76	2,79	2,81	2,82	2,84	2,84
Consumption of limestone, %	4,1	2,88	2,62	2,57	2,54	2,60	2,65	2,64	2,68	2,70	2,71

Molasses, a waste product, is the largest source of sucrose losses in production. During beet processing, molasses contains all non-sugars that are not removed by modern purification methods, as well as those newly formed during the process as secondary degradation products. Almost all of these have a negative impact on sucrose crystallization and white sugar yield. The sucrose content in molasses depends not only on the quality of the raw materials but also on the overall process organization, and therefore serves as an indirect indicator of production efficiency.

Fuel consumption is one of the most important production characteristics and increases as the quality of raw materials declines.

Microbial waste products primarily consist of reducing substances, organic acids, and a wide range of soluble compounds. Purity is used to quantify the content of non-sugars, and to remove them from sugar solutions, the diffusion juice is treated with lime milk and carbonation gas, which are obtained directly at the sugar factory by calcining limestone. Lime consumption correlates well with sucrose losses and can be used as an output parameter when constructing a model.

To construct the model, we use the previously adopted parameters and notations: output parameter Y is limestone consumption, %; independent input parameters $X1$ is sugar content, %; $X2$ is juice purity; and $X3$ is cell sap pH. Because Since the influence of three input parameters is being studied, we will consider two regression model structures: linear and incomplete quadratic.

The structure of the linear model is as follows (1):

$$Y(X1, X2, X3) = A1 \cdot X1 + A2 \cdot X2 + A3 \cdot X3 \qquad (1)$$

The structure of the incomplete quadratic model is (2)

The least-squares method was used to determine the regression coefficients. The criterion for this method is the minimum error of the squared difference between Y obtained in the laboratory and Y calculated using one of the models, the structures of which are given above (1) and (2). Model quality was determined by the coefficient of determination.

The results of laboratory analyses obtained in the production environment were processed using the

$$
\begin{aligned}
& Y(X1, X2, X3) = \\
& = A1 \cdot X1 + A2 \cdot X2 + \\
& + A3 \cdot X3 + A4 \cdot X1 \cdot X2 + \\
& + A5 \cdot X2 \cdot X3 + A6 \cdot X1 \cdot X3
\end{aligned}
\qquad (2)
$$

"Data Analysis" add-in of the built-in regression module of MS Excel. The following results were obtained (Figure 7).

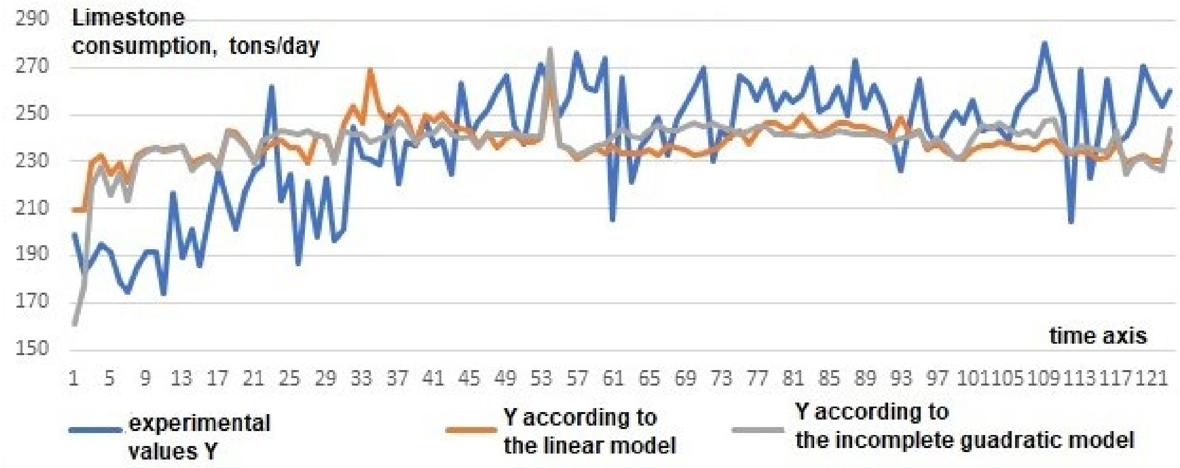

Figure 7: Visualization of computer simulation results.

The least-squares method was used to determine the regression coefficients. The criterion for this method is the minimum error of the squared difference between Y obtained in the laboratory and Y calculated using one of the models, the structures of which are given above (1) and (2). Model quality was determined by the coefficient of determination.

The results of laboratory analyses obtained in the production environment were processed using the "Data Analysis" add-in of the built-in regression module of MS Excel. The following results were obtained (Figure 7)

The R^2 coefficient of determination for the linear model (1) is 0,99.

The R^2 coefficient of determination for the incomplete quadratic model (2) is 0,989.

Numerical values of the coefficients of the linear model (1): $A1$=-19,916; $A2$=5,055; $A3$=21,9.

Numerical values of the incomplete quadratic model (2): A1=-133,18; A2=8,864; $A3$=3599,839; $A4$=14,452; $A5$=-40,461; $A6$=3,305.

4 CONCLUSIONS

This article presents information characterizing sugar beet production as a set of complex technological operations dependent on the quality of the processed raw materials and the level of their organization. Based on statistical data from sugar refineries, the influence of climatic factors on the condition of sugar beet roots as a biosystem, along with associated microflora, is substantiated. The dynamics of sucrose losses during storage and delivery of raw materials for processing are presented. Based on the results of laboratory analyses performed in the refinery's laboratory on an ongoing basis, indicators characterizing the impact of raw material quality on production processes are identified. A mathematical model has been developed to predict limestone consumption in production, as one of the most important indicators of raw material processing efficiency.

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