

На основі інформаційної структури автоматизованої системи моніторингу якості розроблено систему аналізу інформації про якість формоутворення ПЕТ-тари з можливістю статистичного управління технологічним процесом за допомогою контрольних карт Шухарта. Зокрема, це було здійснено на прикладі запропонованого способу оцінювання якості готових ПЕТ-пляшок за товщиною їх стінки. Отримання високоякісної ПЕТ-тари безпосередньо залежить від ступеня досконалості усіх технологічних стадій, обумовлюючи необхідність створення ефективної системи контролю та управління технологічним процесом формоутворення пляшок з поліетилентерефталату.

Аналіз інформації про якість формоутворення ПЕТ-тари на основі моніторингу інформаційної структури автоматизованої системи дозволить забезпечити оперативне коригування параметри формоутворення з мінімізованим відсотком браку за рахунок організації вибіркового контролю виготовленої продукції. Використання статистичних методів контролю на базі контрольних карт Шухарта забезпечить розробку оригінальних алгоритмів моніторингу якості формоутворення, спрямованих на відстеження порушень технологічних параметрів й створення рекомендацій для підвищення якості процесу та ресурсоефективності.

Для статистичної оцінки причинно-наслідкових зв'язків між основними технологічними параметрами та показниками якості продукції застосовується алгоритм моніторингу якості формоутворення ПЕТ-тари. Це дозволяє забезпечити мінімальний рівень дефектності пляшок в умовах застосування розробленої контрольної карти Шухарта.

Запропонована нечітка когнітивна карта для визначення попереджувально-коригувальних дій, спрямованих на усунення основних причин виникнення дефекту при формоутворенні пляшок з урахуванням взаємозв'язків чинників та їх наслідків на отримувану якість процесу

Ключові слова: алгоритм моніторингу якості, статистичні методи, інформаційна структура, формоутворення, поліетилентерефталат, система управління

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IMPROVING THE QUALITY OF THE TECHNOLOGICAL PROCESS OF PACKAGING SHAPE FORMATION BASED ON THE INFORMATION STRUCTURE OF AN AUTOMATED SYSTEM

M. Sashnova

PhD, Associate Professor*

E-mail: m.sashnova@gmail.com

A. Zahorulko

PhD, Associate Professor

Department of Processes, Devices and Automation of Food Production

Kharkiv State University of Food Technology and Trade

Klochkivska str., 333, Kharkiv, Ukraine, 61051

E-mail: zagorulkoAN@hduht.edu.ua

T. Savchenko

PhD, Associate Professor*

E-mail: Savchenko_tv@ukr.net

S. Gakhovich

PhD, Associate Professor, Senior Researcher

Department of Engineering and Technical Disciplines**

E-mail: s_gakhovich@ukr.net

I. Parkhomenko

PhD, Associate Professor

Department of Cybersecurity and Information Protection

Taras Shevchenko National University of Kyiv

Volodymyrska str., 60, Kyiv, Ukraine, 01033

E-mail: parkhivav@gmail.com

D. Pankov

PhD

Department of Automation and

Computer Technology of Control Systems

National University of Food Technologies

Volodymyrska str., 68, Kyiv, Ukraine, 01601

E-mail: Pankov_dima77@gmail.com

*Department of Software Engineering and Cybersecurity**

**Kyiv National University of Trade and Economics

Kyoto str., 19, Kyiv, Ukraine, 02156

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S. Gakhovich, I. Parkhomenko, D. Pankov

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1. Introduction

Most of the foodstuffs in the packing stages require the use of shape forming packaging made from polyethylene

terephthalate (PET), thereby ensuring the implementation of resource-efficient technologies of their manufacturing through the introduction of waste-free technologies [1]. One of the directions of the resource efficiency of PET-packaging

is the introduction of modern management methods based on economically reasonable innovative solutions using the algorithms for monitoring the resulting quality. The demand for PET-packaging is predetermined by the need to pack food products (beverages, paste-like semi-finished products, powder fractions, etc.) manufactured at resource-efficient equipment [2], emphasizing the importance of obtaining quality packaging that ensures the stabilized technological processes of production.

The quality of PET-packaging is the purpose of the technological process; this directly depends on the degree of its perfection while maintaining strict standards of geometric shapes. The defects in geometric dimensions determine the mechanical heat resistance of packaging, as well as the possibility of using it at automatic bottling lines. The main types of deviations (defects) are uneven wall thickness, external wrinkling, and longitudinal deformation, crystallization, decentralization of a bottle, as well as many others that are often difficult to be defined. Therefore, the complexity of the production process requires the justified analysis of the causes of deviations in order to prevent their repeatability in a minimum time, predetermining the need for constant monitoring and control of the production process of PET-packaging. Thus, improving the quality of the technological process of shape formation of packaging should ensure meeting the requirements put forward by all interested parties. The new standards ISO 9001:2015, ISO 45001:2018 [3, 4] introduce a term of operational control, whose application is aimed at limiting the risk of incompliance.

As part of operational control at existing automation systems, the fulfillment of standards requirements is an urgent task. The difficulty is in the methodology to include the “monitoring, measurement, analysis, and evaluation methods required to ensure the reliability of resource-efficient results obtained” [3]. Given the search for solutions to control the technological parameters at enterprises, it is a relevant task to construct a method of quality control of shape-forming polyethylene terephthalate production while implementing an information structure of the automated system for monitoring the quality of PET-packaging shape formation.

Constant implementation of new standards and their improvement in the monitoring systems of a shape formation technological process makes it possible to ensure a high-quality resource-efficient technological process, thereby emphasizing the expediency and relevance of research in this field. Specifically, the development of control methods over the production quality of shape-forming PET-packaging by introducing an information structure of the automated system to monitor the process quality. In addition, the optimization and implementation of modern techniques of resource-saving management affect the shorter time for the substantiation, selection, and execution of managerial decisions, which is a top priority task at high-quality shape formation. Improving a PET-packaging shape formation monitoring algorithm based on modern control methods would make it possible to predict possible inconsistencies and timely eliminate them, ensuring a reduction of costs at the previous stage of adjustment when changing a formulation. In this case, the application aspect of the obtained scientific result is the possibility to exclude the preliminary phase of adjusting a technological process according to ISO 22514-7:2012 [5] for obtaining initial information about the process.

2. Literature review and problem statement

Papers [6–8] give the proposals and requirements for the constructed technological equipment to produce PET-packaging, specifically, its shape formation while ensuring the manufacturing of high-quality products with a minimum degree of defects. Studies [9, 10] note the need to introduce modern universal matrices of control over the predefined parameters, specifically in the process of molding bottles from polyethylene terephthalate by a dual-stage stretching under pressure with clearly adjusted properties of the system received. However, the cited papers [6–10] did not resolve those issues that are related to resource-saving and minimizing defects in the obtained packaging containers. The reason for this is the objective technological complexity of the implementation and control of the process in real time. One of the ways to solve the above shortcomings is to develop and implement algorithms to monitor the quality of PET-packaging shape formation, based on the application of modern control methods, specifically, the thickness of its walls. Thus, it emphasizes the expediency of more detailed reasonable research in this field.

This approach is used in work [9], which outlines the strategy of parameter selection, developed for the process of two-step stretching under pressure, based on the prognostic model of temperature distribution through neural networks. In this case, the issue of forecasting the temperature of warming the last zone of a workpiece was not resolved under the effect of such factors as a distance, wall thickness, PET stretching rates. The reason for this is the objective difficulties related to heating conditions and temperature distribution in a preform, which has a strong impact on the kinematics of blowing (stretching and functioning) and thus on the distribution of thickness. To solve the above shortcomings, one needs to select the optimum heating temperature because it is necessary to achieve a certain elasticity of the workpiece while the abrupt overheating is unacceptable. That, in turn, makes it possible to argue about the need for research regarding the replacement of the costly, time-consuming, and inefficient test and error method used by operators at factories.

Study [10] noted the influence of uneven temperature distribution on the orientation caused by a two-axial pressure stretching with further influence on the mechanical, optical, and barrier properties of bottles. However, there remain uncertain issues related to the performance characteristics of polymeric product manufacturing equipment at thermal processing. Since the distribution temperature largely depends on the influence exerted by external disturbing factors (the temperature and humidity of work media, etc.), this yields 10...12 % of defects in the finished products. That, in turn, raises an issue about ensuring an automated adjustment of thermal regimes for heating and pressure stretching of preforms.

This approach is described in work [11] reporting a comprehensive study into the performance of different PET brands at 80–110 °C and a deformation rate from 1 s^{-1} to 32 s^{-1} . The obtained results of deformation behavior at a dual-step stretching of PET under pressure confirm the dependence of influence: the formation temperature, deformation rate, stretching coefficient, the deformation mode, and molecular mass, which necessitates further research in this field. This, in turn, proves the expediency of studies aimed at introducing modern monitoring methods based on the anal-

ysis of product state parameters, considering the corrective and preventive measures.

Paper [12] reports a study into the modeling of bottle shape formation using a modern method of 3D-simulation of temperature heating, which makes it possible to obtain the justified behavior at forming. Work [13] gives a strategy for selecting technological parameters, designed for a two-step stretching process under pressure, to minimize the weight of the billets used, based on a predictive model developed using neural networks. In [14], a model was introduced, which employed a finite element method, to commercial packages or to developed proprietary software [15], which implied the distribution of a workpiece temperature. The numerical methods, proposed in the [12–15], to optimize the process of two-step stretching under pressure using simulations imitate the heating and deformation process with approximate forecasts of bottle thickness distribution. However, the authors disregard the tasks of monitoring the quality of production with the possibility of including them in the system of automated quality management, which increases the efficiency of PET bottles shape formation and resource-saving. The reason for this is the difficulty of transferring the results obtained from simulation to the unstable realistic model of the behavior of real-time technological shape formation process, thus predetermining the feasibility of developing a universal quality monitoring algorithm.

Specifically, the estimation of product quality in the existing control systems for automatic blowing equipment: “Nissei ASB GmbH”, “SIG Corpoplast”, “Krupp (Germany)”, “Sidel” (France), “Sidel” (Italy), etc., is predominately empirical, based on an installation’ operator view. Based on this empirical assessment, a decision to change the input inserts is taken in order to improve the quality of the finished product. However, the lack of information about the operator’s actions in case the process leaves the boundaries of control, or the absence of prevention of the deviations from the specified technological norms in the PET shape formation process may lead to defects. Most automated PET bottle blowing systems lack the possibility of a comprehensive assessment of the state of the technological process, the analysis of causes of deviations, and the introduction of corrective actions in the production process in order to prevent their re-occurrence. The above allows us to argue about the expediency of conducting detailed research aimed at the development of monitoring algorithms based on the corrective and preventive actions during the analysis of technological parameters and their impact on the resulting quality.

One way to resolve the above shortcomings is to refer to the concept of [16] to manage quality by transferring the focus from a statement of the defect to its prevention, detection, and analysis of the causes of defects. The above suggests that the automation of production of containers from polyethylene terephthalate based on resource-saving implies the need to complement it with a monitoring system – analysis of information about the quality of PET-packaging, thereby proving the expediency of research. This would make it possible to continuously monitor in dynamics the actual efficiency indices of resource-saving management and resource capacity and, on their basis, to make informed managerial decisions on resource-saving, as well as determine resource-saving reserves.

3. The aim and objectives of the study

The aim of this study is to improve an automated PET-packaging production system by building an informa-

tion structure using modern monitoring algorithms based on the analysis of product status parameters, taking into consideration the corrective and preventive actions. This would make it possible to improve the quality of the technological process of producing polyethylene terephthalate shape forming packaging for food products.

To accomplish the aim, the following tasks have been set:

- to improve the information structure of an automated system to monitor the quality of PET-packaging shape formation, taking into consideration an analysis of the parameters of the product state and corrective-preventive actions;
- to develop a quality monitoring algorithm of PET-packaging shape formation using modern control methods;
- to introduce a technique to estimate the quality of finished PET bottles based on the thickness of their walls.

4. Analysis of the improved structure and the operational algorithm of the PET-packaging quality monitoring system

4.1. The information structure of an automated quality monitoring system of PET-bottles shape formation

The development of a system to monitor the production quality of PET-bottles would warrant the elimination of defects in the shape formation of PET-packaging, associated with the unsatisfactory implementation of its production processes while ensuring the autonomous decision-making. This, in turn, could reduce the overall duration of the production cycle and improve the efficiency of the manufacturing process.

The proposed model of the automated system to monitor the quality of PET-bottles shape formation (Fig. 1) implies the following:

- monitoring, analysis, assessment of the quality of PET bottles shape formation, implemented on the basis of a single software and hardware complex;
- the possibility to manually enter to a database (DB) the results from laboratory-measured parameters of shape-forming PET bottles, which are characterized by the absence of the earlier established methods and means of instrumental control;
- the primary information processing within the functional system: “control – evaluation – management”;
- control and registration of the current values of the functional-technological parameters of quality (the temperature of warming a preform of PET-packaging and the pressure of its blowing), as well as the indication of their deviations from normative values using the methods of statistical analysis of quality [5, 17];

evaluation of the effectiveness of the technological process, executed while using the methodology of statistical control, which implies the following: assessment of the process status, accuracy compared with pre-set requirements, the volume of non-defective and defective PET products;

- a set of measures to control the technological process (TP) (the detection and execution of corrective-preventive actions) to ensure the implementation of qualitative parameters of PET bottles shape formation process in the statistically manageable condition.

The following information flows are proposed in order to simplify the representation of the proposed information structure of an automated system for monitoring the PET-packaging shape formation quality; X – input parameters of the predetermined formulation= $\{P$ – the type of

a polymeric workpiece, Q_r – requirements for the resulting quality of PET-workpieces according to the chosen formulation); C_p – initial configuration of a PET-bottles forming technological line= $\{C_e$ – initial configuration of technological equipment, O_c – initial values of mode parameters}; Y – a task of the technological process= $\{D_e$ – technological equipment configuration, R_c – recommended mode parameters}; X_p – PET-packaging shape formation technological process parameters= $\{T_p$ – the value of current technological parameters}; X_c – control of the defects obtained= $\{D_s$ – data from measuring sensors and V_c – data from visual control}; Y_b – defects in PET bottles= $\{C_d$ – evaluation of defects}; R_m – recommendations for the heating of PET-packaging obtained from the preliminary mathematical modeling and to provide the required initial deformation rate (blowing of PET bottles), depending on the properties of polyethylene terephthalate= $\{T_r$ – the recommended values of mode parameters}; R_s – recommendations for non-standard cases= $\{T_d$ – recommendations for defect elimination}; L_p – laboratory measurements parameters= $\{W_t$ – results of measuring the wall thickness of a bottle}; S_b – assessment of bottle quality= $\{P_s$ – prepared samples to estimate the PET-bottles resulting quality}; S_r – results of studying a PET bottle= $\{Q$ – quality indicators of a bottle}; U – results of the study.

Technical analysis of the examined object will make it possible to justify the resulting structure of the automated system based on two main components: control over a technological process of PET-packaging shape formation and processing of the acquired information about its quality.

One of the main tasks in the functioning of the subsystem to control the technological process of PET-packaging shape formation is to define the recommended mode parameters (R_c) to ensure the obtaining of containers of the required quality (Q_r) while maintaining the permissible restrictive technological parameters (X_p). The resulting system would ensure control over the technological process (TP) both in non-standard cases and in the operational control when using the derived estimated data for a chosen mathematical model of PET-packaging heating (a heating process stage). That would also make it possible to take into consideration those recommendations that relate to the required initial speed of bottle blowing, depending on the properties of polyethylene terephthalate (the stage of a bottle blowing process). The task for an information processing system regarding the quality of the finished PET-packaging is to calculate the quality indicators of polymeric containers (Q) when processing the acquired results of measurements of the thickness of a bottle wall (W_t). In addition, this ensures determining and considering the recommendations for the elimination of possible defects to meet the qualitative requirements for polymeric packaging (Q_r).

For a more informed solution to the control system tasks, the following subsystems are proposed to be additionally used: information on production tasks, operational management, corrective and preventive actions, defect recognition. The subsystem of information about production tasks makes it possible to install the initial configuration of equipment (C_e) and the initial values of regime parameters (O_c) for the predefined type of a polymeric workpiece (P) and with the requirements for the resulting quality of a PET-workpiece according to the operator-preselected formulation (Q_r).

A DB about formulations makes it possible to set the initial configuration while maintaining the optimal qualitative mode parameters due to the presence of the polyethylene terephthalate properties in it, the mathematical models of the stages of PET bottle heating and blowing processes. An operator determines the values for the technological parameters' settings, specifically: the heating temperature, the initial speed of blowing, and a moment when the primary and secondary pressure is supplied. There is also an additional possibility of the sub-systematic operational management of TP in the absence of regime parameters in the DB for formulations or in the presence of influence exerted by random factors (for example, a sharp change in the ambient temperature). The

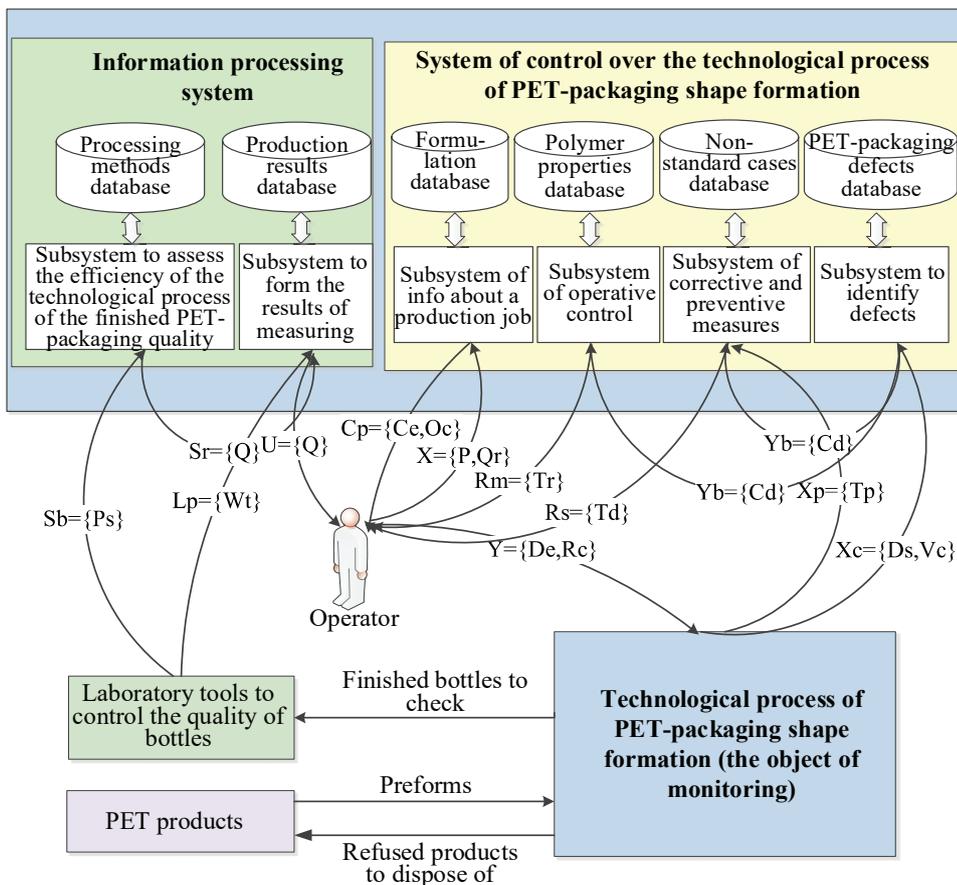


Fig. 1. The information structure of an automated system for monitoring the PET-packaging shape formation quality

defect detection subsystem makes it possible to determine the presence of defects (C_d) and to estimate them based on data acquired, visual control (V_c). In the case of the detection of significant deviations from the specified parameters, the subsystem of control in emergency situations is enabled. The corrective-preventive measure subsystem analyzes the result of defects, their cause (T_d), and the degree of deviation from the technological parameters (T_p) from admissible values, and then provides the operator with recommendations for their elimination. The operational control subsystem gives recommendations to the operator about a change in the regime parameters (T_r) based on technological parameters (T_r) and the estimated data on mathematical modeling.

The use of formulation methods of processing and the data from laboratory measurements, given in a DB of the information processing system, makes it possible to study the required quality indicators of PET-packaging, which cannot be measured during the technological process. To solve the tasks of an information processing system, we propose using the following subsystems: the estimation of technological process effectiveness and the formation of research results. The technology process performance evaluation subsystem uses methods and algorithms to analyze accuracy evaluations, a technological process indicator, and a probable share of defective products based on a predefined indicator. The results of the information processing system operation regarding the resulting quality of PET-packaging are the value of the quality of polymeric bottles (Q) and the use of preventive and corrective measures for providing the required quality of PET-packaging according to the formulation selected by an operator (Q_r).

4. 2. An algorithm to monitor the quality of PET-packaging shape formation based on the application of modern control methods

To ensure resource-saving in the PET-packaging shape formation process, we suggest using modern methods of quality monitoring, rather than managing the factors, which, in most cases, may cause a negative impact. Therefore, it is necessary to take into consideration secondary factors (the type, size, and configuration of preforms), which can lead to the emergence of irregularities in bottles under certain conditions. This generally would ensure the collection, classification, storage, processing, and analysis of dissimilar statistical data for a further substantiated decision on quality improvement.

The use of statistical methods of control based on the Shewhart control charts (SCC) [18, 19] would ensure the development of authentic algorithms of quality monitoring aimed at tracking the violations of technological parameters and compiling recommendations for improving the quality of the process.

The proposed quality monitoring algorithm includes the organization of work on the assessment of the status of a PET-packaging shape formation process, as well as the finished products, with further corrective actions of types 1 and 2, respectively. The first action is aimed at identifying and eliminating the negative impact of causes and consequences affecting the investigated object and reconfiguring technological equipment. The second action is aimed at defining recommendations for changing the general requirements for the process, documentation, as well as making decisions on the execution of equipment repair.

We validated the results experimentally applying the preliminary chosen study parameter, namely, the wall thickness of a PET-bottle (0.28 mm, near the neck of a bottle) with permissible deviations ± 0.015 mm. We found that $K_T=1.04$ (coefficient of accuracy) exceeds the norm of 0.98 [14] at an average share of defective products: $P=3.36\%$. Analysis of the control chart $\bar{X}-R$ (average values and spread) for the thickness of a bottle wall in line with experimental data (Fig. 2) has made it possible to assert the following: the process is stable only at an R spread with the following process indicators: C_p, P_p, P_{pk} , which were calculated on the basis of its own variability σ_1 and complete variability σ_T . The statement about the points leaving the control limits, and in our study – three (leaving the 3σ normal distribution) and two (leaving beyond c points), testifies to the onset of the process dismantling [19]. The resulting location of points based on the \bar{X} chart indicates the use of a new batch of preforms (a change in formulation), thereby providing for a sign of the “warning” about the application of corrective actions.

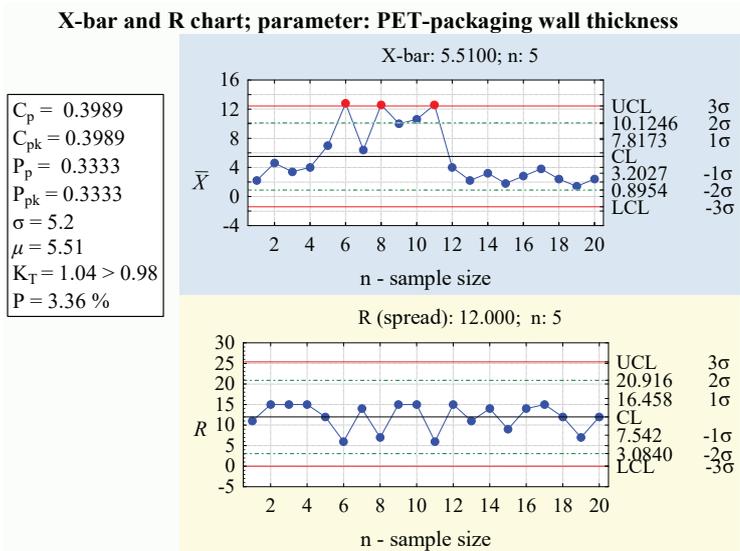


Fig. 2. A control chart of $\bar{X}-R$ values for the technological dimension: a bottle wall thickness

Four out of five points in a row ranging from 1 of the normal distribution to -2 of the normal distribution, or beyond, signal an “early warning” of the possible dismantling of the process with 2% of mistakenly accepted decisions from their total number in the management process.

The results obtained from the implementation of the quality monitoring algorithm of PET-packaging shape formation make it possible to carry out the following:

- a statistical data analysis involving the estimation of technological process effectiveness (determining the statistical characteristics: μ and σ ; the probability of a proportion of defective products (P). Including the estimation of indices of the indicators: capacity (C_p), reproducibility (C_{pk}), applicability (P_p, P_{pk}) and accuracy of the technological process (K_T) with the possibility to implement the process in a statistically managed state;
- the systematic implementation of corrective and preventive actions aimed at the implementation of a technological process based on the Shewhart control charts with the dynamic identification of parameters to simplify the actions directed to change them.

The data obtained confirm the stability of the process in terms of spread, however, the PET-packaging shape formation process is unstable by default, as $C_p=0.3989$, at the bottle quality level noncompliance about 27 % [17] of the batch volume. To reduce the percentage of noncompliance with PET-bottles quality, it is necessary to perform corrective actions aimed at eliminating the influence of negative phenomena and improving the quality of the management process as a whole.

4. 3. Implementation of the proposed technique to estimate the quality of finished PET bottles based on the thickness of their walls

Practical implementation of the proposed technique to estimate the quality of finished PET bottles when studying the resulting thickness of a wall of the finished product is based on the analysis and estimation of the impact of the causes of potential inconsistencies on the target factors of their production. Taking into account the correspondence of the degree of their criticality, a fuzzy cognitive chart (FCC) was constructed to develop preventive and corrective actions aimed at eliminating the main possible causes of the defect.

Building a fuzzy directed graph of NNC of TP of PET-bottle shape formation in order to justify and identify the main causes and consequences of all possible irregularities in containers involved the participation of an evaluation group of operators (five experts). The result of FCC research was that the experts determined and grouped the possible causes of PET-packaging defects while determining the arcs that are responsible for a relation of the cause-effect connections among the obtained factors. Basic concepts have been defined, specifically: a set of destabilizing factors (the causes of a defect) belonging to the group: “material”, “operator”, “process”, “equipment”, a set of target factors (the consequence of discrepancy). As well as controlling factors (preventive corrective actions), the power of relations among them is set in an expert way. The study result in determining the fragments of selections for the analysis of quality concepts of PET-packaging is given in Table 1.

The next stage of our research established the cause-effect relations among the factors indicating, for each of them, a link to its character in the form of a cognitive chart (Fig. 3). The weights of the arcs were set on the basis of expert assessments using the terms of linguistic variables (“weak”, “moderately”, “strong”) along the $[-1,0]$ scale: it does not affect (0.0); it affects weakly (-0.1 to -0.4), it affects moderately (-0.5 to -0.6), it influences strongly (-0.7 to -1.0). The linguistic variables such as “very weak influence” and “very strong influence” are disregarded. The results of the experts are summarized in Table 2. For example, the consequence of improper loading of the preforms (C_8^R) is the “weak” influence exerted by the concept “Low-quality preform” (C_4^U) and “strong” influence exerted by the concepts “Improperly installed preform” (C_4^D), “Jamming preforms” (C_{20}^G), and “Improper coupling installation” (C_{21}^G) (Table 2). This makes it possible to quantify the assessment of the impact of the main causes aimed at the occurrence of a defect and represent an effective decision-making mechanism to ensure the quality of PET-packaging shape formation. The use of FCC makes it possible to visually identify the negative effects of factors for the formation of defective bottles and to indicate the

ways of their weakening by introducing preventive corrective-correction actions (C^K) to reduce the level of defects.

Table 1

List of factors affecting the quality of PET-packaging

Factor description					
Material		Failure (defect) in a technological process		Preventive-corrective actions	
Designation	Principal cause	Designation	Failure consequence	Designation	Action description
C_1^U	Dirty air of primary pressure (P1)	C_1^R	Porosity (orange skin effect)	C_1^K	Check the primary pressure air quality (P1)
C_2^U	Impurities in PET			C_2^K	Check the preform's quality
C_3^U	Damaged neck of a preform	C_2^R	White coating on individual bottles	C_3^K	Check the neck of the preforms. Remove corrupted preforms.
C_4^U	Low quality preforms
		C_8^R	Preform filling	C_2^K	Check the preform quality
...
Process					
C_{23}^B	Overheated bottle bottom	C_{25}^R	Insufficient thickness of bottles in bottoms area	C_4^K	Increase or decrease the temperature of the profile in the required area
...
Operators					
C_4^D	Preform is improperly installed	C_8^R	Preform filling	C_8^K	Check the filling operation
...
Equipment					
C_{19}^G	Faulty pull cylinder	C_{25}^R	Insufficient thickness of bottles in bottoms area	C_{52}^K	Repair or replace the pull cylinder
C_{20}^G	Preforms jamming	C_8^R	Preform filling	C_{53}^K	Remove the preform
C_{21}^G	Improperly installed coupling			C_{54}^K	Adjust or replace the coupling
...

Thus, if the cause of the “Insufficient bottle thickness in the area of the bottom” (C_{25}^B) is the “Overheated bottom bottle” (C_{23}^B) and “Defective pull cylinder” (C_{19}^G), then, to eliminate the impact of these causes of defects, one must introduce corrective actions from “Increase or decrease the temperature profile in the required area” (C_4^K) and “Repair or replace a pull cylinder” (C_{52}^K).

Analyzing the represented data on a fuzzy cognitive chart allows us to conclude about the interconnectedness of the factors influencing the quality of PET bottles and to predict the consequences of change in them.

Table 2

Assessment of the degree of influence of the causes of the defect on the target factors

Defect cause	The impact of the cause of a PET-bottle defect on a target factor											
	C_1^R	C_2^R	C_3^R	C_4^R	C_5^R	C_6^R	C_7^R	C_8^R	...	C_{10}^R	C_{11}^R	...
C_1^U	weakly	no influence	...	no influence	no influence	...						
C_2^U	strongly	no influence	...	no influence	no influence	...						
C_3^U	no influence	strongly	no influence	...	no influence	no influence	...					
C_4^U	no influence	strongly	strongly	strongly	strongly	strongly	strongly	weakly	...	no influence	no influence	...
C_4^D	no influence	no influence	no influence	no influence	no influence	no influence	no influence	strongly	...	no influence	no influence	...
C_5^D	no influence	no influence	no influence	no influence	no influence	no influence	no influence	no influence	...	no influence	no influence	...
...
C_{20}^G	no influence	no influence	no influence	no influence	no influence	no influence	no influence	strongly	...	no influence	no influence	...
C_{21}^G	no influence	no influence	no influence	no influence	no influence	no influence	no influence	strongly	...	no influence	no influence	...
...

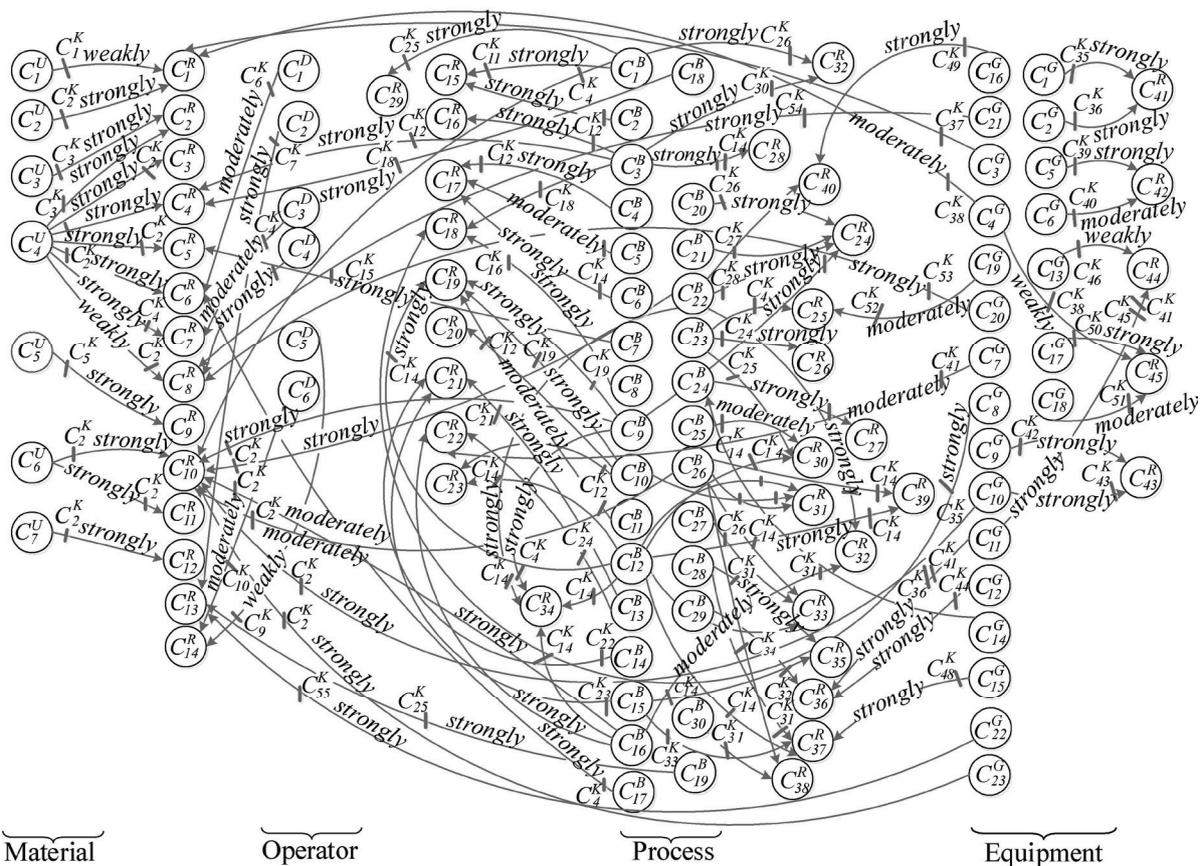


Fig. 3. A fuzzy cognitive chart for assessing the impact of the causes of a defect on the target factors of PET-packaging production

6. Discussion of results of studying the improvement of the quality of a technological process of packaging shape formation

The use of the information structure of the automated quality monitoring system for PET-bottles shape formation

would help to identify the unpredictable factors in the parameters of a PET-material that result in the change of the technological-hardware component of the process of polymeric container manufacturing. This, in turn, would ensure less responsibility from the operator of technological equipment and the minimization of obtaining defective products

while detecting and preventing latent negative factors for the occurrence of defects.

Experimental and practical application of the algorithm for monitoring the quality of PET-packaging shape formation (Fig. 1) makes it possible to obtain a statistical estimation of the cause-effect relations among the main technological parameters and indexes of product quality. This ensures the possibility of statistical control over the technological processes of PET-packaging shape formation to provide for their further qualitative improvement at a minimum level of bottle defects when applying the devised SCC (Fig. 2).

We analyzed the Shewhart control chart using a zone analysis method in accordance with the ISO 7870-2:2013 standard [20] and the rules of their interpretation regarding the technological process of PET-packaging shape formation. The formalized rules for the SCC interpretation were used in the construction of a PET-packaging shape formation quality monitoring algorithm based on the statistical data for the Type 1 corrective action unit, which helps the operator track deviations in the process of bottle manufacturing. A given algorithm makes it possible to track the pre-defined set of criteria and, once detected, initiates practical recommendations for improving the quality of the manufacture of containers. Experimental and practical studies have established an increase in the accuracy coefficient ($K_T=1.04$) compared to the norm, 0.98 [18], at the average proportion of defective products $P=3.36\%$ when the wall thickness of a PET bottle near its neck is 0.28 ± 0.015 mm. When one or more values leave the control borders of the control chart, that signals a violation of the parameters of the process of the examined sample (Fig. 2).

To set the initial values of factors and loadings on the arcs of the developed cognitive chart (Fig. 3), we used direct methods of polling five experts considering the subjectivity of the derived cognitive model and the calculation approximations. One should note that the evaluation of the values of factors is more difficult because they can consist of different indicators. For example, the inconsistency of the improper loading of preforms (C_8^R) is the “weak” influence exerted by the concept “Low-quality preform” (C_4^U) and the “strong” influence exerted by the concepts: “Improperly established preform” (C_4^D) “Preform jamming” (C_{20}^G) and “Improper coupling installation” (C_{21}^G) (Table 2). That makes it possible to quantify the impact of major causes aimed at the occurrence of a defect and to represent the mechanism of decision-making regarding the quality of PET-packaging shape formation. The formation of a causative defect – “Insufficient bottle thickness in the area of the bottom” (C_{25}^R) is a consequence of “Overheated bottle bottom” (C_{23}^B) and “Faulty pull cylinder” (C_{19}^G). Eliminating these shortcomings is achieved by the introduction of corrective actions aimed at “Increasing or decreasing the temperature of the profile in the required area” (C_4^K) and “Repair or replacement of a pull cylinder” (C_{32}^K). Building a fuzzy cognitive chart makes it possible to construct the matrices of interconnected concepts with the further application and introduction of the required corrective-preventive actions by the criterion of conformity and strength of influence. The limitations of the current study are in the properties of the methodology for building a fuzzy cognitive chart, which includes not all subjective factors that can affect the change of qualitative characteristics of the object of study.

Today, further scientific and practical research is underway into the kinematics of shape formation in order

to substantially improve the resource-efficient properties, specifically the cost of materials. The methodology proposed on the basis of the information structure of the automated system to monitor the quality of PET-packaging shape formation, using the statistical methods of control on the basis of control charts, is being further advanced by the developed software AMPET [21]. The software developed makes it possible to track the mode settings of technological parameters and, once they deviate, gives an operator the practical recommendations on their optimization and, consequently, saving of raw materials.

7. Conclusions

1. The improved model of the automated system to monitor the quality of PET-bottle shape formation combines the functions of managing the PET-bottles technological process and processing of the acquired information on their quality while maintaining the permissible restrictive technological parameters. The use of formulation methods of processing and the data from laboratory measurements, given in the DB of an information processing system, makes it possible to investigate the required quality indicators of PET-packaging, which cannot be measured during the technological process. That would ensure control over the technological process in non-standard cases, as well as prompt control over the preliminary derived estimates, specifically, on the heating of PET-packaging, thereby taking into consideration the recommendations on the initial bottle blowing speed according to the properties of polyethylene terephthalate. In addition, the proposed model provides for the additional determination and consideration of recommendations regarding ways to eliminate possible defects to improve the quality of the technological process of polymeric container (Q_T) shape formation.

2. We have constructed an algorithm to monitor the quality of PET-packaging shape formation using the statistical methods of control based on the Shewhart control charts by estimating the cause-effect relations among main technological parameters and indexes of quality of received products. The accuracy factor has been determined in the shape formation of a wall thickness of the PET bottle (0.28 ± 0.015 mm, near the neck of the bottle), at the level $K_T=1.04$, which characterizes a deviation from the norm ($K_T=0.98$), predetermining the need for corrective action. This confirms the feasibility of applying, in the developed algorithm, the analysis of the average values and $\bar{X}-R$ control chart spreads and the detection of preventive corrective actions aimed at improving the quality of products obtained and the resource efficiency of the process.

3. The results of estimating the developed fuzzy cognitive chart by the group of experts are aimed at overcoming and eliminating the main possible causes of defects in PET-packaging shape formation, specifically, the thickness of the wall of the finished product. Additional determining and construction of arcs, which are responsible for the cause-effect relations among the received factors, confirm the effectiveness of actions aimed at overcoming and eliminating the basic possible causes of defects at shape formation. For example, the result of the improper loading of preforms (C_8^R) is the “weak” influence exerted by the concept “Low-quality preform” (C_4^U) and the “strong” influence exerted by the concepts: “Improperly installed preform” (C_4^D) “Preform

jamming” (C_{20}^G) and “Improper coupling installation” (C_{21}^G). In case the cause of the defect is “Insufficient thickness of a bottle at the bottom” (C_{21}^G) “Overheated bottle bottom” (C_{23}^B) and “Faulty pull cylinder” (C_{19}^G) one of the solutions to eliminate their impact is the introduction of corrective actions from “Increasing or decreasing the temperature of the profile in the required area” (C_4^K) and “Repair or replacement of a pull cylinder” (C_{52}^K).

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