УДОСКОНАЛЕННЯ ВЛАСТИВОСТЕЙ ТОВАРІВ

DOI: https://doi.org/10.31617/2.2025(54)07
УДК 677.07-021.465=111

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SYSTEMATIC FORECASTING OF PRODUCT QUALITY OF SPINNING PRODUCTION

Forecasting product properties and managing its quality consists in ensuring and maintaining the required level of product quality starting from its development, production and operation or consumption. These measures are carried out through systematic control and specific action on the conditions and factors that affect product quality, to forecast its

СИСТЕМНЕ ПРОГНОЗУВАННЯ ЯКОСТІ ПРОДУКЦІЇ ПРЯДИЛЬНОГО ВИРОБНИЦТВА

Прогнозування властивостей продукції та управління її якістю полягає в забезпеченні та підтриманні необхідного рівня якості продукції, починаючи з її розробки, виробництва, експлуатації або споживання. Ці заходи здійснюються шляхом систематичного контролю та визначеної дії на умови та фактори, які впливають на якість

properties and manufacture products with specified properties. Forecasting tasks are directly related to the availability of adequate mathematical models of product properties change during its production process. The hypothesis of this work is that a systems approach is the basis for creating a modern approach to obtaining a mathematical model for predicting the properties and quality of fiber products. The article defines approaches to forecasting the properties of textile threads and products during production by applying system analysis and mathematical modeling. A general process algorithm and a structural and functional model of the elementary cell of the production process of transforming product properties are proposed. To determine the state of the technological system for the production of textile threads and products, methods of system analysis and mathematical modeling of product properties during its production process are used. Modeling of product quality management and forecasting systems includes a description of the sequence of processes and operations that form the properties of finished products and semi-finished products, and are aimed at ensuring, maintaining and improving product quality. Using a mathematical model, quantitative relationships between the quality indicators of finished products and the properties of derived raw materials, semi-finished products, technological equipment and management actions by the relevant authorities are determined. The use of mathematical models for predicting product properties and managing its quality allows you to pre-determine and evaluate the results of certain measures and select those of them that are most effective for implementation. The basis of a mathematical model for predicting the properties and quality management of textile products can be a model of the production transformation of derived materials into finished products.

Keywords: mathematical modeling, forecasting, product properties, systems analysis, textile thread, product, production process.

продукції, для прогнозування її властивостей та виготовлення виробів із заданими властивостями. Безпосередньо завдання прогнозування пов'язані з наявністю адекватних математичних моделей зміни властивостей продукції в процесі її виробництва. Гіпотеза цієї роботи полягає в тому, що системний підхід є основою до створення сучасного підходу до отримання математичної моделі прогнозування властивостей та якості волокнистих продуктів. Визначено підходи до прогнозування властивостей текстильних ниток та виробів у процесі виробництва шляхом застосування системного аналізу та математичного моделювання. Запропоновано загальний алгоритм процесу та структурно-функціональну модель елементарної чарунки виробничого процесу перетворення властивостей продукції. Для визначення стану технологічної системи виробництва текстильних ниток та виробів використано методи системного аналізу та математичного моделювання властивостей продукції в процесі її виробництва. Моделювання систем управління та прогнозування якості продукції містить опис послідовності виконання процесів та операцій, які формують властивості готової продукції та напівфабрикатів, і направлені на забезпечення, підтримання та покращання якості продукції. За допомогою математичної моделі визначають кількісні зв'язки між показниками якості готової продукції та властивостями похідної сировини, напівфабрикатів, технологічного устаткування та управляючими діями з боку відповідних органів. Застосування математичних моделей для прогнозування властивостей продукції та управління її якістю дає змогу попередньо визначити та оцінити результати тих або інших заходів і вибрати для реалізації ті з них, які є найбільш ефективними. Основою математичної моделі прогнозування властивостей та управління якістю продукції текстильного виробництва може бути прийнята модель виробничого перетворення похідних матеріалів в готову продукцію.

Ключові слова: математичне моделювання, прогнозування, властивості продукції, системний аналіз, текстильна нитка, виріб, виробничий процес.

JEL Classification: O32, O33.

Introduction

Today, mathematical modeling is widely used to predict the properties of products for various purposes in many sectors of the national economy. To build adequate mathematical models of technological processes,

a detailed analysis of the technological process and its physical essence is required. Mathematical models can be obtained using theoretical and experimental approaches.

Technological processes of textile production, which are associated with the manufacture of yarn, are complex and extensive. This is due to a significant number of different factors that affect the properties of spinning products and yarn as a whole.

Laboratories use various methods and devices to determine the properties of raw materials and spinning products. The determination of the property indicators of spinning products is mostly selective in nature, which can lead to quite significant inaccuracies. Accordingly, the theoretical mathematical models obtained using such data may be incorrect. Therefore, a purely theoretical approach to building mathematical models and predicting the properties of spinning products is not appropriate. In a theoretical approach, the use of certain abstractions is permitted, which leads to the simplification of the real product of the study. Correction coefficients are also introduced into the theoretical mathematical models, which have a rather arbitrary choice of their numerical values. Such a theoretical approach to building mathematical models is mostly used for designing new processes, as well as in scientific research works.

In the experimental approach to building mathematical models of technological processes, experimental values of the properties and products of the technological process are used, which are obtained directly on operating equipment, in laboratory conditions or on a stand that simulates the physical process of obtaining yarn.

Due to the wide application of computer technology and microprocessors in textile production and research laboratories, methods of simulation mathematical modeling are used (Chuyko, 2015; Pavlenko, 2013, Grod, 2016).

Today, predicting the properties of textile materials using mathematical methods with the application of modern computing technology is promising and relevant and allows you to quickly draw preliminary conclusions about the properties of textile materials even at the design stage.

The purpose of this article is to highlight a new approach to building mathematical models using systems analysis for predicting the properties of textile threads and products, as well as managing their quality. Compared to previous studies, today there are changes in technological processes and the use of modern equipment, which makes significant adjustments to the construction of a mathematical model. To achieve this, it is necessary to have operational information about the operation of the technological system and all its elements. Timely response to changes in the production situation will provide the opportunity to influence the properties of products in a timely manner and optimize the process of its production.

The hypothesis of this work is that a systematic approach is the basis for creating a modern approach to obtaining a mathematical model for predicting the properties and quality of fibrous products.

This goal can be achieved using a systematic approach and mathematical modeling of predicting changes in the properties and quality of

textile threads and products during their production process. To do this, it is necessary to compile a general algorithm for the system and determine the main structural and functional models and blocks of product property transformation during its production.

1. Basic information

Mathematical modeling (Chattopadhyay, 2015) is a powerful tool in engineering for studying various issues related to product and process design and development, optimizing the production process, understanding phenomena, and predicting product behavior during actual use. Model development requires an understanding of the process and the use of appropriate mathematical tools. Various types of models, their development procedures, and their limitations have been considered.

Thus, (Beyreuther, 2007) considered the modeling of basic processes of fiber formation and processing in steady-state and non-steady-state regimes. The main areas include melt spinning processes, yarn spinning processes, and the description of dynamics at different process stages during fiber processing. He also examined the dynamics of the tensile force and its significance for process stability. All examples are based on industrial practice.

The publication (Velten, 2009) analyzes the most important issues in the field of modeling. Various mathematical models and their types are presented. It is determined which model is suitable for a specific problem. The issues related to modeling, parameter estimation and its verification are highlighted. The mathematical problems that arise are also considered, along with how they can be effectively solved using professional free and open-source software.

The development of manufacturing process modeling is attracting increasing attention in the textile industry (He, Xu, 2021). More and more researchers are shifting their attention from classical methods to intelligent process modeling methods, since traditional methods can hardly reflect the complex interactions of numerous process factors and characteristics. The scientific sources that study the modeling of textile production have been analyzed. The structure of this article corresponds to the procedure of textile processes from yarn to fabric, and then to clothing. Analysis and discussion of previous studies have been carried out regarding various applications in different processes. Factors and product properties that were considered during the process modeling have been collected for comparison. Input data, selection of characteristics, modeling methods, data distribution and performance evaluation have been determined by analyzing previous studies and summarized.

The complex factors of applying the technological process of textile processing and the consequences of its ozonation with color fading have been studied by process modeling (He, Tran, 2019). For this purpose, the following factors are determined: pH of the solution, temperature, water absorption, process time and the initial color of the textile, which affect the color performance of reactively dyed cotton using different reagents. It is noted that it would be more appropriate to use those reagents that have better performance prediction and lower cost in real application.

The textile manufacturing is a typical traditional industry that involves high complexity of interconnected processes with limited opportunities to apply modern technologies (He, Tran, Thomassey, 2021). When making decisions in this field, several criteria are usually taken into account, which causes difficulties. To solve this problem, this study proposes a decision support system that combines intelligent data-driven random forest (RF) models and a multi-criteria analytic hierarchy process (AHP) framework based on human knowledge, according to the objective and subjective factors of the textile manufacturing process.

It is noted (Song, 2025) that modeling predictive control (MPC) is a powerful technique for controlling complex and dynamic systems, demonstrating advantages over traditional control strategies in terms of performance and reliability. It aims to provide a comprehensive overview of the MPC theory and its application in a variety of complex dynamic systems.

In work (Beltran, 2006), a multi-layer algorithm model is presented to build a tool for predicting the efficiency of the spinning process. Different spinning mills use different raw materials, processing methods and equipment, which affects the quality of the produced yarn. Due to the large number of variables, it is difficult to develop a universal empirical/theoretical model. Sixteen input data are used to predict key yarn properties and spinning performance, including the number of fibers per cross section, unevenness (U%), thin spots, cuts, yarn strength, elongation at break, thick spots and end-down spinning. The results of the model's verification on the commercial data set of a specific enterprise indicate that the overall compliance with the target values is good.

An important aspect of the spinning process (Sette, 2000) is the ability to predict the spinnability of the yarn and its resulting strength based on the fiber quality and machine settings. Available models of fiber spinning to yarn are limited to the so-called "black box" approach, which generates an output without physically interpretable information about the process itself. This paper presents a method for predicting yarn spinnability and strength. It has been determined that the resulting prediction accuracy is good, and more importantly, it also provides additional qualitative information about the spinning process.

The paper (Lomov, 2001) considers the modeling of textile composites. To do this, it uses the advantages of the hierarchical principle of textile modeling, creating an integrated tool for modeling and designing textile composites. This allows for the rapid processing of complex calculations of the textile structure measured in minutes of computer time, rather than hours of the same nonlinear, non-conservative behavior of yarns during compression and bending. The architecture of the code implementing the model corresponds to the hierarchical structure of textile materials. The textile geometry model serves as the basis for mesomechanical and permeability models for composites, which provide modeling tools for analyzing the processing and properties of the composite.

The importance of mathematical modeling and forecasting is emphasized in the works of (Chuiko, 2015, Pavlenko, 2013, Hrod, 2016, Shcherban, 2003). Thus, (Chuiko, 2015) specifies the main methods of mathematical modeling of the input influence of parameters of raw materials

and technological equipment with different parameters, enterprises and production processes as objects, as well as methods of computer modeling of systems in different mathematical environments.

In work of (Pavlenko, 2013), a general methodology of mathematical modeling for building models and formalized description of systems and processes is defined. Significant attention is paid to the capabilities of modern information technologies for modeling, analysis, synthesis and optimization of processes and systems.

In work of (Hrod, 2016), the main principles and methodological aspects of system theory are described, as well as the features of computer modeling methods for various objects.

In work of (Slizkov, 2013), the main approaches to mathematical modeling of technological processes existing at that time are presented. Along with this, taking into account the development of textile production techniques and technologies, there has been a need in recent years to significantly adjust existing approaches to mathematical modeling of technological chains for obtaining yarn with appropriate properties and quality.

Significant attention is paid to the systemic approach and analysis of mathematical methods for modeling the properties of textile materials in the articles of (Slizcov, 2006, 2009). Methods for obtaining adequate mathematical models of the properties of textile materials for their prediction have also been determined. The solution to the tasks of the systematic approach to predicting the properties of textile materials is associated with the availability of software tools for building such mathematical models that could adapt to changes in properties during the production process. The functioning of the entire system for predicting the properties of textile materials and managing them in the process of production and operation should enable forecasting both for the entire system as a whole and for its individual components.

Thus, today the issue of mathematical modeling of the system for predicting the properties and quality of textile threads and products using a systematic approach remains relevant.

2. Results and discussion

Fibrous products of spinning production (fiber mass, ribbons, slivers, yarn) have a discrete structure, which is determined by the peculiarity of the arrangement of fibers with different characteristics (length, linear density, twist, etc.).

To obtain adequate mathematical models of spinning products, it is advisable to have a sufficient ratio between the completeness of the description and the specificity of its results, as well as the convenience of using certain statistical data of product properties. For this purpose, it is proposed to use passive experimental methods of collecting statistical information on the property indicators of fibrous products in the process of their dynamic transformation in the process of each technological transition of yarn production. This approach includes the collection of statistical information on the input and output indicators of fibrous products at each technological transition of yarn production.

To process a significant amount of statistical information, the use of computer technology with data processing software packages is required. In addition, database management software has been developed in the system for predicting the properties of spinning products.

To form the databases for the predicting system of the properties of spinning products, an analysis of the relevant statistical information at each stage of the production process has been conducted. For each fibrous product of spinning production, the following elementary complexes were determined: bundles (for fibrous mass before and after beating); fibers and their groups (for ribbon, roving and single yarn).

After calculating the statistical information, mathematical models were obtained for each fibrous product. After that, mathematical models of all complexes of fibrous products of spinning production were grouped. Thus, a general mathematical model of the entire system for predicting the properties of spinning products has been obtained.

In general, the systematic analysis for predicting the properties of fibrous products in the spinning production can be divided into the following stages: definition and clear formulation of the purpose of the system's functioning; selection of indicators of the system's operational efficiency; compilation of a list of factors affecting the system; obtaining mathematical models of indicators of material properties and creation of a general mathematical model of the system. The factors that affect the system are determined by the type of raw material, equipment, level of its maintenance, etc. In the process of spinning yarn, statistical information for each fibrous product is constantly supplemented and updated. This allows you to increase the system database, increase the accuracy of forecasting and achieve convenient and quick addition and adjustment of the mathematical model, obtaining results and making decisions for each type of raw material and yarn.

The system for predicting the properties of fibrous products of spinning production belongs to complex systems, in which the process of transforming the properties of materials from raw materials to the production of finished yarn is difficult to describe in the form of single simple system. Therefore, it is advisable to divide such a system into subsystems that can contain two or more operations of the production transformation of fibrous products. It is advisable to consider production areas for the manufacture of yarn as a system of subprocesses that occur on machines and units and form the properties of fibrous products, and not simply as a system of machines and units.

In the process of mathematical modeling of systems for predicting the properties and quality of fibrous products, all management and production areas that form and support these properties and quality are determined. The mathematical model helps to determine the relationships between the properties of the derived raw materials and the initial product. Using the possibilities of managerial influence on the parameters of the technological process, it is possible to predict changes in the properties of the initial product, which include production semi-finished products and finished products.

Using mathematical models of the system for predicting the properties and quality of fibrous products, it is necessary to analyze how much its results

coincide with the real results of experimental studies with the appropriate accuracy. In the case of significant discrepancies, such a mathematical model requires refinement and clarification.

The above-mentioned mathematical model is based on the modeling of the process of production transformation of raw material properties into semi-finished products properties at each stage of the production process and the final (finished) product. In this case, it is necessary to take into account all factors that may affect the studied production process of yarn manufacturing.

In accordance with the above, for building a mathematical model for predicting the properties and quality of textile threads and products made from them, a general algorithm of the specified system is developed at the initial stage (*Figure 1*).

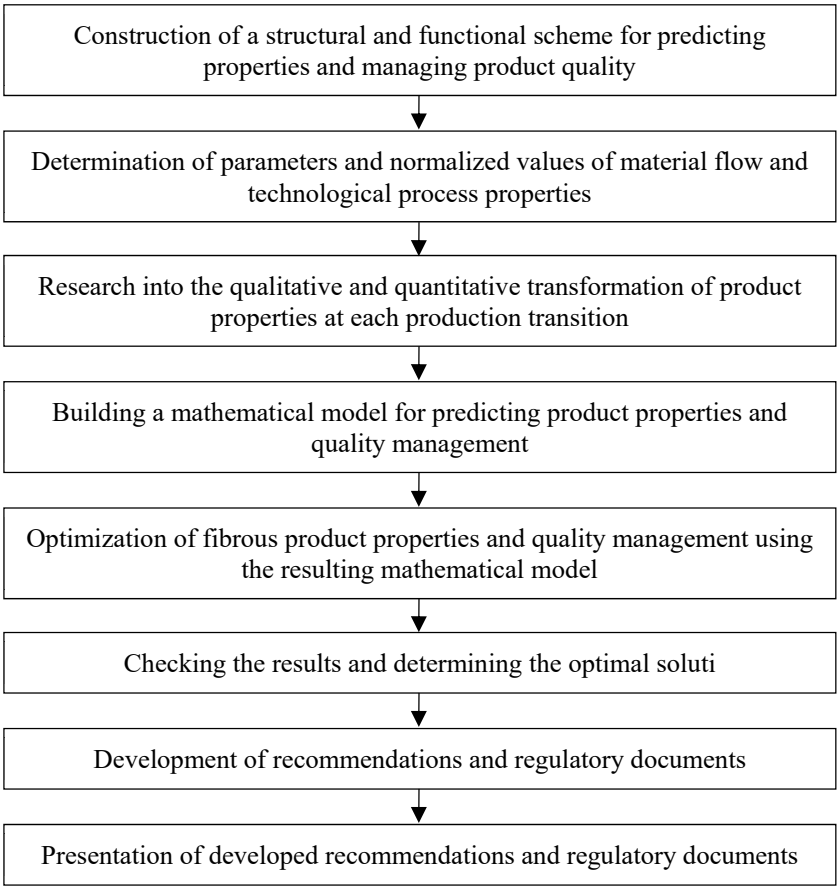


Figure 1. General algorithm for predicting
the properties of fibrous products of spinning production

Source: compiled by the authors.

The algorithm contains consecutive operations that are necessary for making decisions and actions that are required to determine the quality of the initial product.

At the initial stage of creating a mathematical model, a general structural and functional scheme for predicting properties and managing product quality is built. Subsequently, parameters and normalized values of

the material flow properties are determined, starting from raw materials, semi-finished products and ending with the initial product. The next stage includes the study of the qualitative and quantitative transformation of product properties at each production transformation of the material flow (raw materials, semi-finished products and finished products) taking into account technological and management factors. In the future, a mathematical model of the process of predicting product properties and quality is formed and the optimal or predicted parameters of the properties of spinning products are determined. At the management level, optimal decisions are made with the development of recommendations and relevant regulatory documents for the predicted functioning of the technological mode of manufacturing products based on the obtained mathematical model.

An important element in creating a mathematical forecasting model is the derivation of the initial properties of spinning products, which are determined experimentally, to their predicted values while maintaining a certain measurement accuracy. In case of significant deviations of the actual values of the properties of the material flow from the predicted ones, at each technological transition of yarn manufacturing (semi-finished products and initial products) an analysis of all factors that may cause the corresponding deviations is carried out, and the mathematical model is adjusted and refined.

The final stage of the algorithm is the creation of a mathematical model of the system for predicting the properties of fibrous products of spinning production with the presentation of recommendations and software tools.

In general, the production process of yarn manufacturing can be represented as a set of sequential operations that define a certain operator T of the transformation of the derived material flow $m_0(t)$ into the initial $m(t)$. Taking into account all production and management factors that can affect the change in the properties of the derived material flow, the mathematical model of the transformation of product properties can be defined by the following equation:

$$m(t) = T\left[m_0(t), B_T(u), k, E, S\right], \quad (1)$$

where $B_T(u)$ – parameters of the transformations of the fibrous product; u – control actions that affect the transformation parameters; k – characteristics of the working personnel; S – environmental conditions; E – parameters of energy consumption to maintain the production process.

Thus, $m(t)$ is a mathematical model of the output material flow, which includes certain properties of the output product $x_1, x_2, x_3 \ldots, x_n$, which form the level of its quality.

In the product quality forecasting system, it is advisable to introduce its quantitative quality indicator K, which is determined by the following functional:

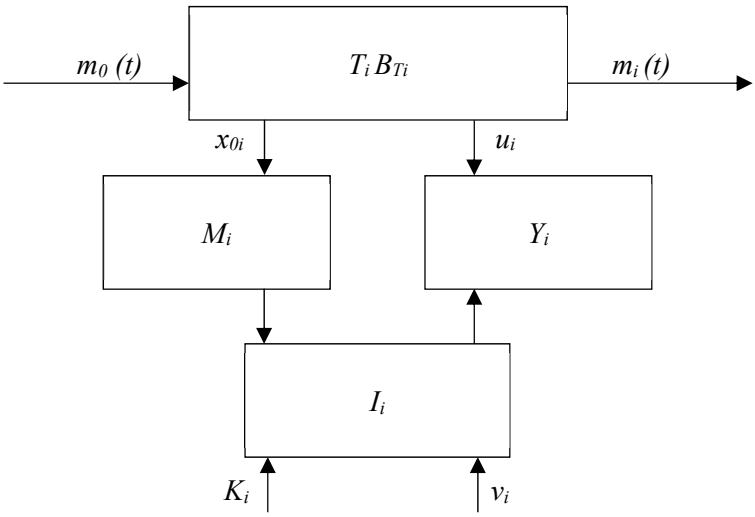
$K = T\,n\,[m(t)] = t_2 / t_1$, where t_1 and t_2 are indicators of the time interval between which the product quality is determined. The specified functional in

the forecasting system is an objective function that depends on the choice of control actions *u*, which are aimed at optimizing the quality indicators of fibrous products. At the same time, certain restrictions are introduced into the system on the parameters *k, E* and *S* of the function of the initial material flow *m(t)* while preserving the specified values of the properties of the derived material flow $m_0(t)$.

In the system for predicting the properties and quality of fibrous products, it is necessary to know what type of general operator *T* of the transformation of product properties has during its manufacture. The type of such operator is determined as a result of a detailed analysis of the production process of transforming the properties of fibrous products. Taking into account the complexity and multifactorial nature of such a production process, it is advisable to decompose it into simpler production processes that can be described by the corresponding operators T_i, which subsequently form the general operator *T*.

In accordance with the above, it is advisable to first determine simple (elementary) production cells in which a simple production (technological) process takes place. The combination of such cells as a whole form a general production (technological) system of transforming the properties of derived fibrous products into initial (finished) products.

Each simple production cell, according to a certain technological process, has its own characteristics, which are determined by different parameters of the function *m(t)*, according to equation (1). The structural-functional model of such a simple cell is presented in *Figure 2*.



where T_i – is the section of production transformation of a fibrous product; B_{TI} – parameters of the section of transformation of product properties; M_i – is the metrological section; I_i is the information-logical section of management; K_i – is the target model; Y_i – is the executive section; x_{0i} is a certain property of the fibrous flow; u_i – is the control action; v_i – is the external control actions.

Figure 2. Structural and functional model of a unit cell

Source: compiled by the authors.

According to the structural-functional model of the elementary cell in the section T_i, a production transformation is carried out in accordance with the technological mode or other material action. The section M_i is responsible for obtaining operational information about the properties of fibrous products by instrumental or visual means. The section Ii is responsible for control actions, in which the information obtained from the metrological section M_i is used and the current real situation is determined, comparing it with the target model K_i, which includes normalized or specified requirements, which allows determining the appropriate control actions.

In the executive section *Yi*, the information obtained from a certain characteristic of the fibrous product x_{0i} is converted into a control action u_i, which directly affects the change in the parameters of the properties of the fibrous product (flow) B_{Ti}, and allows for the implementation of the corresponding predicted changes in the corresponding section T_i, the production transformation of the fibrous product. Depending on the production tasks from the higher-level production management to the section I_i, external actions v_i can be implemented, which can be determined by the terms of the contract or production needs.

The change in the properties of the fibrous product in the *i-th* elementary cell can be described by the system of the following operator equations:

$$m_i(t) = T_i\left[m_{0i}(t - \Delta t),\ B_{T_i}(u_i),\ k_i, S_i, E_i\right] \quad (2)$$

$$u_i = Y_i(x_{0_i}),\quad u_i = I_i(\sum K_i, \sum v_i); \quad (3)$$

$$\sum K_i = M_i\left[m_{0i}(t), B_{T_i}\right]; \quad (4)$$

The above system of equations is a general form of the mathematical model of each elementary cell, which determines the change in the properties of the fibrous product at each technological transition. Depending on the characteristics of the operator T_i, the equations presented above may have a certain physical meaning.

For each moment of time, the production transformation of the properties of the fibrous product will be determined by its corresponding values, as well as the parameters of the corresponding factors that characterize the system. The number of factors that can affect the production system of the transformation of the properties of the fibrous product is quite significant, therefore, to simplify the forecasting task, it is advisable to determine a small number of independent parameters (factors) that sufficiently fully characterize the system in order to achieve the specified forecasting goal.

The production cycle of yarn production is a complex system that combines certain production subsystems (sections, workshops, etc.), where the transformation of the properties of the fibrous product (raw materials, semi-finished products) is carried out. Such subsystems are in fact blocks of

the production process, which include certain elementary cells of the transformation of a fibrous product into semi-finished products and yarn. Such blocks, when combined with each other, respectively, constitute a system for predicting the properties and quality of fibrous products of spinning production.

Conclusions

The hypothesis regarding the importance of a systems approach in obtaining a mathematical model for predicting the properties and quality of fibrous products is confirmed.

For mathematical modeling of the system for predicting the properties and quality of fibrous products of spinning production, it is advisable to adopt a mathematical model of the production change in the properties of derivative materials into yarn. This allows you to set the specified parameters of the product that will determine its quality.

The creation of a mathematical model of forecasting is based on the developed general algorithm for predicting the properties of fibrous products of spinning production, which includes sequential operations that are necessary for making decisions and actions that are required to determine the predicted quality of the initial product.

The production cycle of yarn production combines certain production areas (production plants, workshops, etc.), where the properties of the fibrous product (raw materials, semi-finished products) are transformed, which are actually subsystems of the general yarn production system. Such subsystems form blocks of the production process, which include certain elementary cells for converting the fibrous product into semi-finished products and yarn. Such blocks, when combined with each other, respectively, form a system for predicting the properties and quality of fibrous products of spinning production.

In general, the application of a systemic approach to predicting the properties and quality of fibrous products of spinning production by analyzing subsystems (production process blocks) of the technological process with elementary cells make it possible to specify a general algorithm, which can be the basis for creating mathematical models for predicting product properties, which can be used for tasks of predicting the properties and quality of various fibrous products.

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Conflict of interest. The authors declare that have no financial or non-financial conflicts of interest with respect to this publication; they have no relationships with government agencies, commercial or non-profit organizations that might have an interest in presenting this point of view. Given that the authors work for the institution that is the publisher of the journal, which could lead to a potential conflict or suspicion of bias, the final decision to publish this article (including the selection of reviewers and editors) was made by those members of the editorial board who are not affiliated with this institution..

The authors received no direct funding for this study.

Slizkov A., Krasnitskiy S., & Mykhailova H. (2025). Systematic forecasting of product quality of spinning production. *The international scientific-practical journal "Commodities and markets", 2*(54), 106–119. https://doi.org/10.31617/2.2025(54)07

Received by the editorial office 06.03.2025.
Accepted for publication 28.04.2025.
Online publication 11.06.2025.