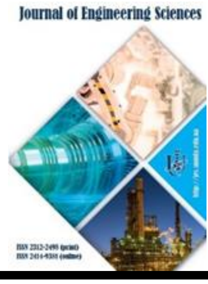
JOURNAL OF ENGINEERING SCIENCES

Volume 10, Issue 2 (2023)

Berladir K., Mitalova Z., Pavlenko I., Trojanowska J., Ivanov V., Rudenko P. (2023). Design and manufacturing of polymer composite materials using quality management methods. Journal of Engineering Sciences (Ukraine), Vol. 10(2), pp. B16–B29. DOI: 10.21272/jes.2023.10(2).b3



Design and Manufacturing of Polymer Composite Materials Using Quality Management Methods

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Article info:
Submitted: May 30, 2023
Received in revised form: September 4, 2023
Accepted for publication: September 26, 2023
Available online: September 29, 2023

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Abstract. Many factors influence the design and manufacturing of products from polymer composite materials. The expert assessment method was applied in the article for the corresponding analysis. A cause-and-effect diagram was built as a result of a preliminary analysis of the influence of factors on the primary indicator of product quality indicators (e.g., wear resistance). Based on the expert assessment results and quality function deployment analysis, the most critical factors affecting wear resistance were obtained: polymer brand, filler shape and size, technological parameters of mixing, pressing, sintering, and mechanical processing. Their impact was studied to establish quantitative dependencies. A stable value of the wear resistance of the product in the manufacturing process can be ensured by timely adjustment of the mixing, pressing, and sintering modes. As a result of the structural analysis of the process of developing materials with predetermined properties at the enterprise according to the IDEF0 methodology, the importance of assessing the risks associated with the process of multi-criteria optimization of their main quality indicators was confirmed.

Keywords: industrial growth, polymer composite material, cause-and-effect diagram, process innovation, Pareto diagram, quality function deployment, product innovation, small enterprise.

1 Introduction

The global polymer composite materials (PCMs) market faces up-to-date challenges due to various technological, environmental, economic, and regulatory aspects [1]. Their most challenging concerns are raw material cost, environmental sustainability, quality control and consistency, and competition with traditional materials [2].

Moreover, technological advancements, regulatory compliance, global supply chain management, market volatility, and uncertainty also complicate the design and manufacturing processes of PCMs [3].

Therefore, the above-mentioned modern challenges in the global market for producing and selling PCMs are substantiated by the following facts. Firstly, PCMs require a combination of polymers, reinforcing fibers, and additives [4]. Fluctuating costs of raw materials (e.g., resins, carbon fibers, and additives) impact production costs and profitability [5]. A limited availability of certain fibers challenges manufacturers in maintaining competitive pricing.

Secondly, the rapidly increasing focus on environmental sustainability is because composite materials often rely on non-renewable resources and may have limited end-of-life options [6]. This leads to the need to solve waste management issues. Therefore, manufacturers find more sustainable alternatives, including bio-based polymers and recyclable or biodegradable composites. Also, PCMs face competition with traditional materials (e.g., steel and alloys, wood). As a result, PCM manufacturers should permanently demonstrate their products' better performance, cost-effectiveness, and durability over traditional alternatives [7].

Moreover, variations in raw materials, manufacturing processes, and curing conditions can lead to inconsistencies in mechanical properties and product performance. Therefore, implementing robust quality control measures and optimizing production techniques are essential to meet customer expectations.

It should also be noted that PCMs are subject to various regulations and standards related to safety, performance, and environmental impact [8]. Manufacturers should ensure compliance with international regulations, such as REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) and RoHS (Restriction of Hazardous Substances) [9]. Adhering to these standards can involve additional costs and stringent testing requirements.

Overall, the global market of PCMs is highly influenced by technological advancements in materials, processing techniques, and design capabilities. Keeping up with emerging technologies and investing in research and development can be demanding, especially for smaller manufacturers. These challenges require a combination of innovation, sustainability practices, strategic planning, and continuous improvement in manufacturing processes.

2 Literature Review

The PCM industry relies on a complex global supply chain [10] involving multiple suppliers and partners. Managing these issues effectively, ensuring a consistent supply of raw materials, minimizing lead times, and navigating potential geopolitical or trade-related challenges is vital for uninterrupted production and customer satisfaction. Global market dynamics, uncertainty in trade policies, and other global factors impact the demand and pricing of PCMs [11]. Therefore, adapting to changing conditions and diversifying the customer base and product portfolio can help mitigate risks for manufacturing enterprises.

Answering the question "What is the place and role of Ukrainian enterprises in the global market of PCMs?" it can be stated that machine-building products produced by domestic enterprises are not always competitive on the global market in terms of price-quality ratio [12]. Therefore, the technologies of manufacturing parts from PCMs have been intensively developed to ensure the high competitiveness of products.

Despite all these challenges, Ukrainian enterprises can play a significant role in the global market of PCMs, contributing to both production and sales due to the following reasons: market potential, manufacturing capabilities, cost-competitiveness, and increased international collaboration. Firstly, Ukrainian enterprises possess manufacturing capabilities for producing PCMs [13]. These capabilities include the formulation and processing of polymer matrices and the incorporation of reinforcing fibers or fillers. Enterprises offer various PCMs for automotive, aerospace, marine, and other engineering fields. They supply composite components, semi-finished products, and raw materials to customers worldwide.

Remarkably, collaborations with academic institutions and research organizations help drive innovation in materials, processing techniques, and composite design [14]. This focus on R&D enables Ukrainian companies to introduce advanced PCMs with improved properties and performance.

Secondly, enterprises often benefit from lower labor and production costs than some Western counterparts. This cost-competitiveness can be an advantage in the global market, attracting customers looking for cost-effective solutions without compromising quality. Moreover, enterprises actively seek partnerships and collaborations with global manufacturers, distributors, and research institutions. Such collaborations facilitate technology transfer, market expansion, and knowledge sharing.

Thus, the global market for PCMs is growing, driven by increasing demand for lightweight and high-performance materials across multiple industries. Ukrainian enterprises can tap into this market potential by capitalizing on their strengths, including technical expertise, cost-competitiveness, and adaptability. Ukrainian companies can expand their market share by continuously improving their products, investing in research and development, and effectively marketing their capabilities.

The application of Quality Management Systems (QMS) in engineering industries is reflected in the following state-of-the-art systems, particularly in [15], where prospects in developing new sustainable metal composite materials were highlighted. As a result, ways for environmental preservation, cost reduction, and sustaining the metal waste management system were proposed. Also, in [16], prospecting fiber-reinforced composite materials for sustainable remediation of emerging contaminants were developed. Moreover, in [17], the comprehensive energy management problem at metallurgical enterprises was solved by implementing energy-saving projects. As a result, ways for their multiple application in engineering, wastewater decontamination, and energy storage were proposed.

A critical comparison of various fiber-reinforced plastics and their recycling approaches was carried out in [18] based on the multi-criteria decision-making analysis. Also, an automated decision-making process for optimizing polymer composites was successfully implemented in [19]. Moreover, a comprehensive approach to intelligent warping detection was proposed in [20] for fused filament fabrication of metal-polymer composites.

Prospective ways to implement nanocomposites as building materials for modern architectural design practices were analyzed in [21]. Additionally, a practical approach to enhance the performance of carbon nanotube array composites by chemical-thermal treatment was developed [22]. Finally, ways for structuring modified composite materials were developed in [23].

An improvement of machine-building enterprises took place in three main directions. The first concerns integrating structural materials technology with lean production [24] and the just-in-time concept [25]. The second direction includes the implementation of QMS according to the ISO 9000 requirements. Moreover, the Six Sigma method is widely used for QMS development [26].

Thus, a modern approach to QMS development for products from composite materials involves unifying all the above-mentioned organizational improvement issues into a comprehensive system. Their application includes both the use of traditional quality control tools and the active development of improved QMS for ensuring the improvement of innovative projects. The design of composite materials and quality management in this area is based on the use of up-to-date and reliable QMS.

This work aims to conduct a statistical analysis of factors affecting the quality of polymer composite materials and develop a methodology for designing and manufacturing PCMs based on quality management methods. The novelty of this study is an application and combination of management tools to solve the problem of increasing the quality of the used materials during their manufacturing and the new materials during the design stages.

This case study paper is helpful for scientists and producers in manufacturing, materials, and mechanical engineering to understand the concept and applications of traditional quality management tools and have an opportunity to use them.

3 Research Methodology

The study of PCM quality management methods was conducted based on the Research and Development Enterprise "Sumy Plast Polymer" LLC (Sumy, Ukraine), which produces PCMs based on polytetrafluoroethylene (PTFE) with various fillers by pressing the appropriate compositions with subsequent sintering.

The blanks are intended for further production from them by mechanical processing of various antifriction products, including sliding bearings, sealing rings of movable supports, and other friction units operating in air and liquid media, wet and dry gases, and in a vacuum in the temperature range from –120 °C to 260 °C (Table 1).

Table 1 – Nomenclature of antifriction PTFE products

Nomenclature of blanks	Type of filler	The recommended scope of application
FC 01	PTFE and modified carbon fiber	Production of sealing and support elements of friction units operating in general-purpose compressors with limited lubrication and without lubrication.
FC 02	PTFE and a mixture of fibers (carbon and others)	Production of sealing and support elements of friction units of compressors without lubrication, operating in an air environment and wet gases.
FC 03	PTFE, carbon fiber, and dispersed powders	Production of sealing and support elements of friction units operating in harsh working conditions, including an environment of oxygen and dry inert gases
FC 04	PTFE, a mixture of fibers (carbon and others) and dispersed powders	Production of sealing and support elements of friction nodes with increased wear resistance and corrosion resistance, which allows working with oxygen or oxygen-containing gases
FC 05	PTFE and a mixture of polymers	Production of sealing and support elements and friction units for work in cryogenic and high-temperature operating conditions

Thus, PTFE materials with high physical and mechanical properties for work in conditions of intensive wear are considered in this article.

The main criteria in developing such materials are the ability to work without lubrication, reduced wear of the part itself and the connecting surface, resistance to the chemical influence of aggressive environments, and reliable operation at low temperatures.

The primary data about the developed material for designers, technologists, and operators, wear resistance, strength, relative elongation, and friction coefficient can be highlighted.

The coefficients of friction of unfilled PTFE and compositions based on it on a steel counter body under normal conditions differ insignificantly; that is, the coefficient of friction is not a sensitive characteristic of the filling.

The wear resistance of products made of composite material is an important characteristic that determines the service life of PCM parts in metal-polymer tribological connections.

Statistical methods of product quality control are now widely used in industry. Their main task is to ensure the production of usable products and the provision of helpful services at the lowest costs. Seven quality control tools are most common among the statistical methods of quality control: Pareto Diagram, Cause and Effect Diagram, Control Chart, Histogram, Scatter Diagram, Stratification, and Control Sheets. They can be used in any sequence, in any combination, and in various analytical situations; they can be considered both a complete system and separate analysis tools.

This work used the Pareto and cause-and-effect diagrams as the statistical methods of quality control of PCMs.

To built a Pareto diagram, the raw data are presented as a table, the first column of which indicates the analyzed factors, the second column shows the absolute data characterizing the number of cases of detection of the analyzed factors in the current period, the third column shows the total number of factors by species, and the fourth column shows their percentage ratio, in the fifth is cumulative (accumulated) percentage of cases of detection of factors. The defining advantage of the Pareto diagram is that it makes it possible to divide factors into significant and minor factors.

A cause-and-effect diagram (Ishikawa diagram) is a graphical arrangement of factors affecting the object of analysis. Its main advantage is a visual representation of factors that affect the object under study and the cause-and-effect relationships of these factors. When structuring the diagram at the level of the primary arrows of the factors, the 5M rule (materials, machines, methods, measuring, men) proposed by Ishikawa can be used. This rule consists of the fact that, in the general case, there are five possible causes of specific results related to causal factors.

One of the most effective methods of directly translating consumer requirements into the production characteristics of new products is the Quality Function Deployment (QFD) methodology. It helps an organization focus on the critical characteristics of new or existing products or services from an individual customer, market segment, company, or technology development perspective.

Application of the methodology in clear diagrams and matrices that can be reused for future goods or services. The QFD is an expert method that uses a tabular way of presenting data with a specific form of tables called the "house of quality". It is based on several key elements (Figure 1).

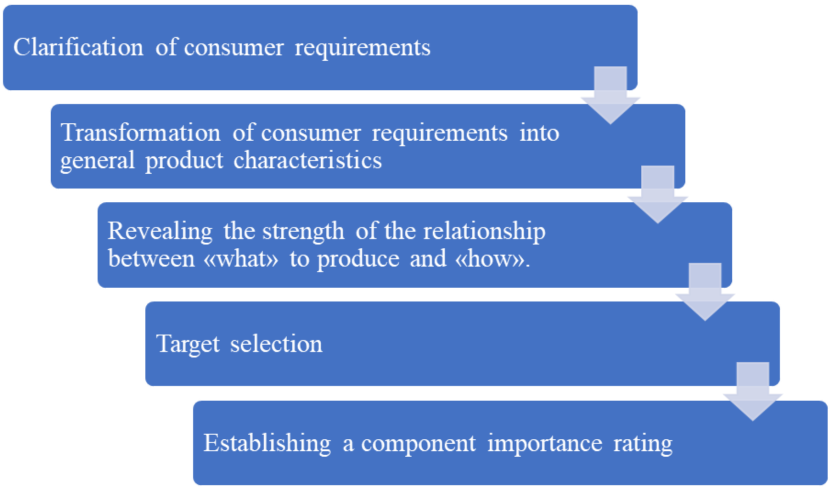


Figure 1 – Five key elements of QFD methodology

The QFD methodology transforms consumer requirements into designing the quality of the finished product. The method covers development goals and fundamental quality assurance issues, which are key points and milestones in achieving sales levels, preventing the repetition of existing and potential emergence of new problems during product development. When applying the QFD method to the analysis of already manufactured products, it is possible to identify which technical characteristics play the most significant role in consumer satisfaction with the quality of the product.

The IDEF0 methodology used in the work is one of the most progressive models used in business projects and projects based on modeling all administrative and organizational processes. Its feature emphasizes the hierarchical representation of objects, which significantly facilitates understanding the subject area; logical connections between works are considered, not the sequence of their execution in time.

Thus, summarizing the methods used to solve the set goal of the work, Figure 2 presents a graphic scheme of the proposed research methodology.

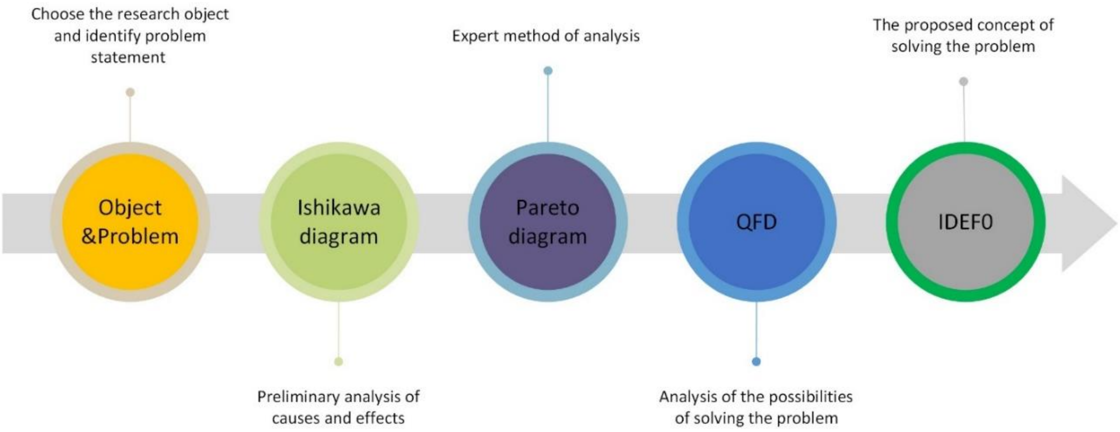


Figure 2 – The proposed methodology of design and manufacturing of PCMs based on quality management methods

4 Results

4.1 Quality control of PCMs using the statistical method

The process of creation and production of PCM products is influenced by many factors, for the analysis of which the expert evaluation method was applied. Five qualified specialists from manufacturing enterprises were invited as experts. They are practitioners and occupy leading technologist positions according to specialization – materials science, powder metallurgy, composite materials, and mechanical engineering.

A cause-and-effect diagram was constructed as a result of a preliminary analysis of the influence of factors on the primary indicator of product quality indicators – wear resistance (Figure 3).

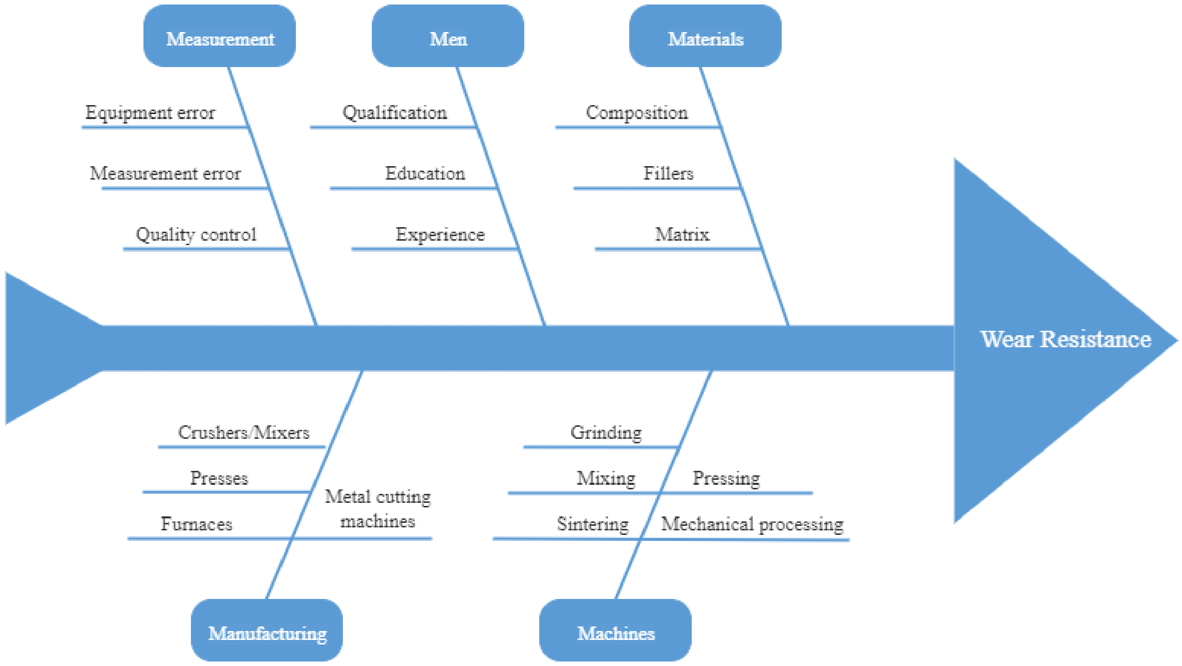


Figure 3 – Cause-and-effect diagram of the influence of factors on the wear resistance of PTFE products

Based on production experience, the 5M rule, and previous research, the most critical factors affecting the indicated indicators and their possible limit values were established. Such factors include the following:

1) material (composition, ratio, and properties of the matrix and fillers);

2) manufacturing technology (grinding, mixing, pressing, sintering, mechanical processing);

3) machines and equipment;

4) methods and means of measurement, control of regulated parameters, and product quality indicators

A questionnaire was drawn to determine each essential factor during the experts' survey(Table 2).

Based on the questionnaire results, tables of the quantitative influence of factors on the primary indicator of product quality (Tables 3–5) and Pareto charts for two levels (Figures 4–6) were compiled.

Thus, it turned out that at the first level, the influence of material and technology on the quality of PCMs is the main one and amounts to 75 %.

At the second level, it was established that for the initial characteristics of the matrix and the filler material, the influence is 72 %; for technology – mixing, pressing, and sintering – 72 %. These numbers are close to the classic Pareto ratio of 80:20.

The QFD analysis methodology was used to analyze the influence of factors further. The transformation of customer requirements by deploying quality functions allows for determining the relationship between requirements and characteristics [27].

Table 2 – The developed form for expert assessments of the influence of factors on the wear resistance of PTFE products

First-level factors	Second-level factors	Third-level factors
Raw materials	Matrix	Polymer brand
		Powder particle size
	Fillers	Chemical nature
		Size and shape of inclusions
Manufacturing technology	Grinding	Grinding time and speed
	Mixing	Mixing time and speed
	Pressing	Pressing modes (pressure, exposure)
	Sintering	Heating, exposure, and cooling of pressing
	Mechanical processing	Cutting speed, cooling medium, presence of shavings

First-level factors	Second-level factors	Third-level factors
Machines and equipment	Crushers and mixers	Grinding conditions (heat sink, vacuum), knives, revolutions
	Presses	Geometry and roughness of press forms
	Furnaces	Sintering modes (heating/cooling rate), furnace atmosphere
	Metal cutting machines	Material and hardness of the cutting tool, turning conditions, dimensional accuracy
Control	Measurement error	Equipment error
		Measurement technique error
	Quality control	Visual control
		Testing
Staff	Qualification	Education
		Certification training
		Experience

Table 3 – Expert assessments of the importance of influencing factors according to the 5M rule, %

First-level factors	Expert assessment					Average value	Accumulated percentage
	1	2	3	4	5		
Raw materials	50	60	40	30	55	47	47
Manufacturing technology	30	15	30	40	25	28	75
Machines and equipment	10	5	20	15	10	12	87
Control	5	15	5	10	5	8	95
Staff	4	3	2	4	2	3	98
Other	1	2	3	1	3	2	100

Table 4 – Pareto diagram showing the influence of first-level factors on the wear resistance of PTFE products, %

Raw materials	Expert assessment					Average value	Accumulated percentage
	1	2	3	4	5		
Polymer brand	50	45	60	35	55	49	49
Chemical nature of fillers	30	25	15	30	15	23	72
Size and shape of inclusions	5	25	15	20	25	18	90
The particle size of polymer powder	15	5	10	15	5	10	100

Table 5 – Expert analysis of the influence of second-level factors (manufacturing technology) on the wear resistance of PTFE products, %

Manufacturing technology	Expert assessment					Average value	Accumulated percentage
	1	2	3	4	5		
Pressing modes	30	20	15	25	35	25	25
Heating, exposure, and cooling of pressing	30	15	25	20	30	24	49
Mixing time and speed	25	30	20	25	15	23	72
Grinding time and speed	5	20	20	15	15	15	87
Cutting speed, cooling medium, presence of shavings	10	15	20	15	5	13	100

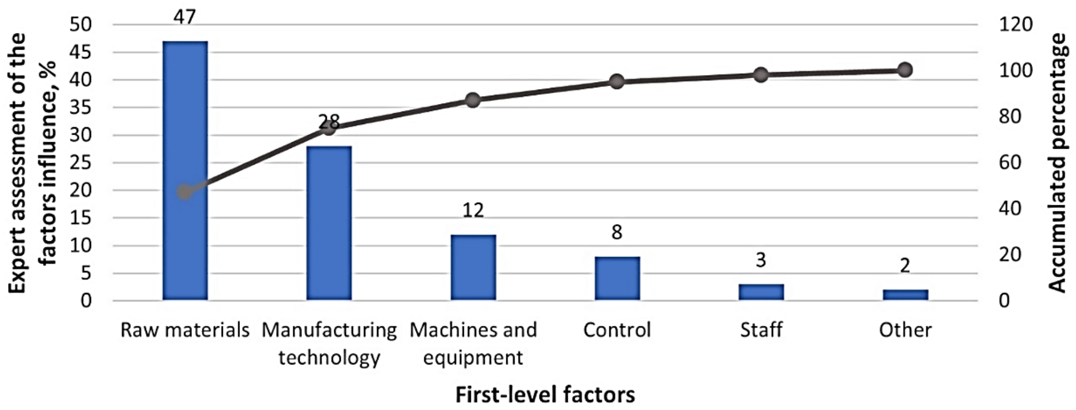


Figure 4 – Pareto diagram showing the influence of first-level factors on the wear resistance of PTFE products

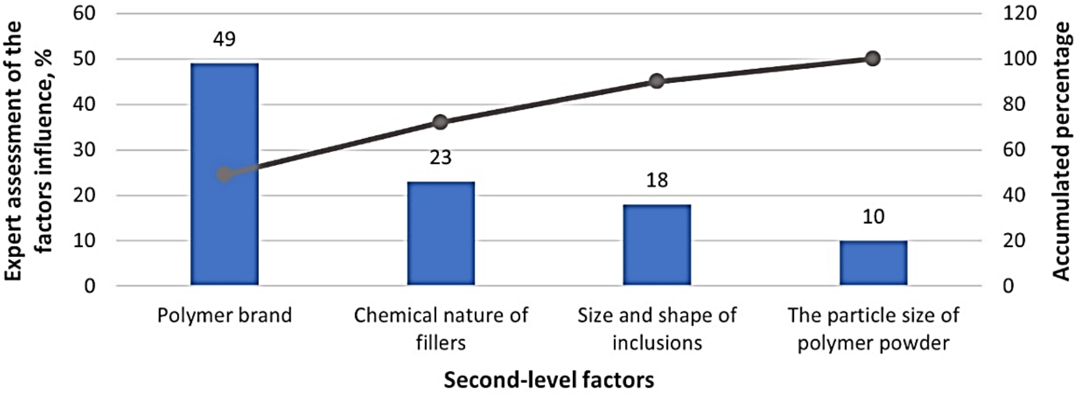


Figure 5 – Pareto diagram showing the influence of second-level factors (raw materials) on the wear resistance of PTFE products

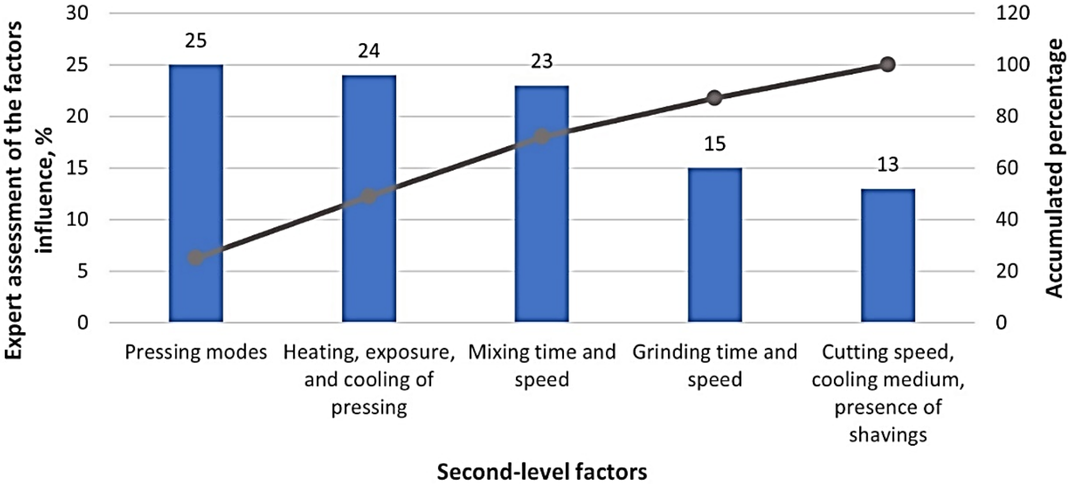


Figure 6 – Pareto diagram showing the influence of second-level factors (manufacturing technology) on the wear resistance of PTFE products

4.2 Quality control of PCMs using the statistical method

The manufacturing of polymer products is carried out based on regulatory documents, and at the same time, the level of quality is not evaluated. The requirements of consumers, which are necessary when planning the production of competitive products, are not considered. A product cannot be considered competitive if consumers, i.e., do not demand it, have no demand. Demand is determined by consumer preferences, where objective characteristics are decisive, and subjective perception of product properties – purchase value consists of several components. Therefore, it is essential to establish the criteria by which the buyer evaluates PTFE products with the desired combination of properties.

The questions asked to the respondents reflect the most critical aspects of the product – technical and economic requirements.

The most essential first-level factors, established according to Pareto diagrams, are raw materials (47 %), manufacturing technology (28 %), and machines and equipment (12 %). Therefore, we must rely on these factors when performing QFD analysis.

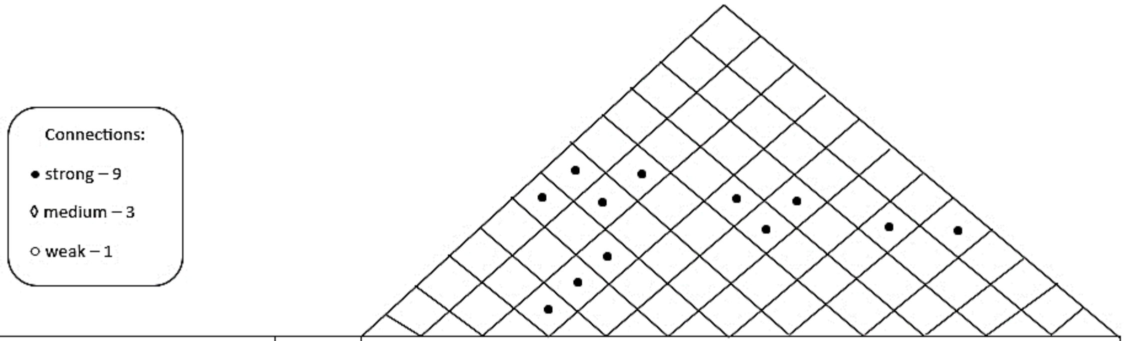
A ranking of consumer requirements was carried out in terms of the degree of importance of each requirement (Table 6).

Table 6 – The importance of consumer requirements

Consumer Requirements	Consumer Assessment
Ability to Operate Without Lubrication	5
Corrosion Resistance	4
Operating Temperature Range	5
Durability	5
Dimensional Accuracy	3
Surface Quality	3
Lower Price	4

A five-point scale was used for this: 1 – not important; 2 – not very important; 3 – less important, but desirable; 4 – important; 5 – very important.

The deployment of the quality function is implemented using the construction of the house of quality matrix diagram (Figure 7) for the most critical performance of PTFE products, where the relationships between requirements (what) and characteristics (how) are shown.



Consumer Requirements (what)	Value	Technical Characteristics (how)											
		Raw Materials			Manufacturing Technology					Equipment			
		Polymer Brand	Chemical Nature of Filler	Size And Shape of Filler	Grinding Mode	Mixing Mode	Pressing Mode	Sintering Mode	Mechanical Processing	Crusher/Mixer	Press	Furnace	Metal Cutting Machines
Ability to Operate Without Lubrication	5	•	•	◊	○	•	•	•	○	◊	•	•	○
Corrosion Resistance	4	•	◊	○	○	○	○	◊	○	○	○	○	○
Operating Temperature Range	5	•	•	◊	◊	◊	◊	•	○	◊	○	•	○
Durability	5	◊	◊	•	◊	◊	◊	◊	◊	◊	◊	◊	◊
Dimensional Accuracy	3	○	○	◊	○	○	◊	○	•	○	◊	◊	•
Surface Quality	3	○	○	◊	○	○	○	◊	•	○	○	◊	•
Lower Price	4	•	•	◊	◊	◊	○	○	○	◊	○	○	○
Absolute Value		183	159	97	57	97	95	133	87	67	85	131	87
Relative Value, %		14,3	12,4	7,5	4,5	7,5	7,4	10,4	6,8	5,2	6,6	10,2	6,8
Unit of Measurement				μm	rpm	rpm	MPa	°C	m/min	rpm	MPa	°C	HB

Figure 7 – House of quality for products made of PTFE composites

The performed QFD analysis made it possible to identify factors whose influence should be investigated to establish quantitative dependencies: polymer brand (14.3 %), chemical nature of filler (12.4 %), size and shape of filler (7.5 %), mixing mode (7.5 %), pressing mode (7.4 %), and sintering mode (10.4 %).

PTFE and fillers are purchased materials. Therefore, their predominant properties cannot be regulated during the production process. The size and shape of the filler are obtained at the previous stages of the production process. Their parameters must be subjected to input control. Thus, three significant factors have been identified by adjusting, which makes it possible to ensure the stability of the values of wear resistance within the established limits: modes of mixing, pressing, and sintering.

Thus, the developed QFD methodology made it possible to analyze the quality of PCMs based on PTFE. As a result, the most priority influencing factors were identified for further research and developing recommendations for quality improvement.

4.3 Designing PCMs with predetermined properties in production

The design of products with predetermined operational characteristics involves selecting processing methods and modes to ensure the monolithicity of the material, the required orientation, and the uniform tension of the reinforcing filler.

Figure 8 shows a generalized scheme of the production technology of PTFE composites.

Fillers have several general and special requirements for which PCMs are given the necessary properties. The general requirements include high wettability by the polymer material, high chemical and thermal resistance, polymer dispersion, non-toxicity, and low cost. Special requirements are determined by tasks that are solved with the help of fillers: increasing electrical conductivity and heat resistance, creating non-combustible materials and reducing their density, improving manufacturability, and others. Therefore, the characteristics of filled PCMs are determined by the properties of the polymer matrix, the dispersed filler, and their joint action at the interface.

The analysis of designing a new PCM uses the IDEF0 methodology; the result is presented in the context diagram (Figure 9).

The input information is the technical task and information about previous projects. Controlling influences include regulatory documentation of the enterprise, policy in the quality field, and a database of polymer materials, fillers, and additives that can be used.

Certified employees of the department and the organizational and technical system (computers and organizational equipment of the enterprise, certified software) act as mechanisms. As a result, we received new PCMs with predetermined properties that meet the requirements of the technical task.

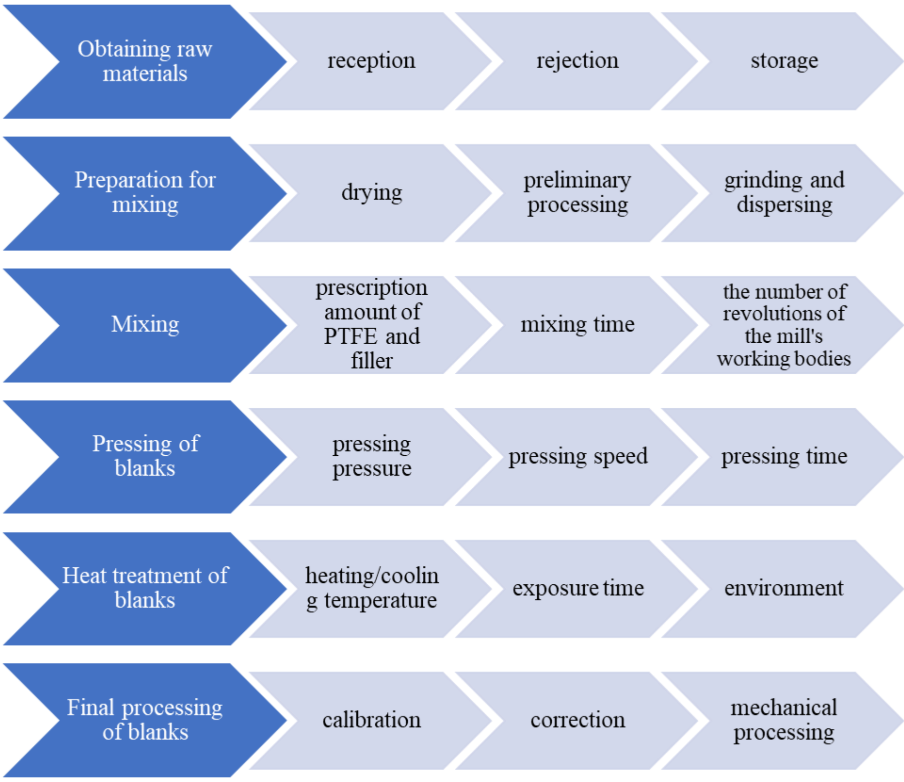


Figure 8 – The scheme of the technology for obtaining PCMs based on PTFE

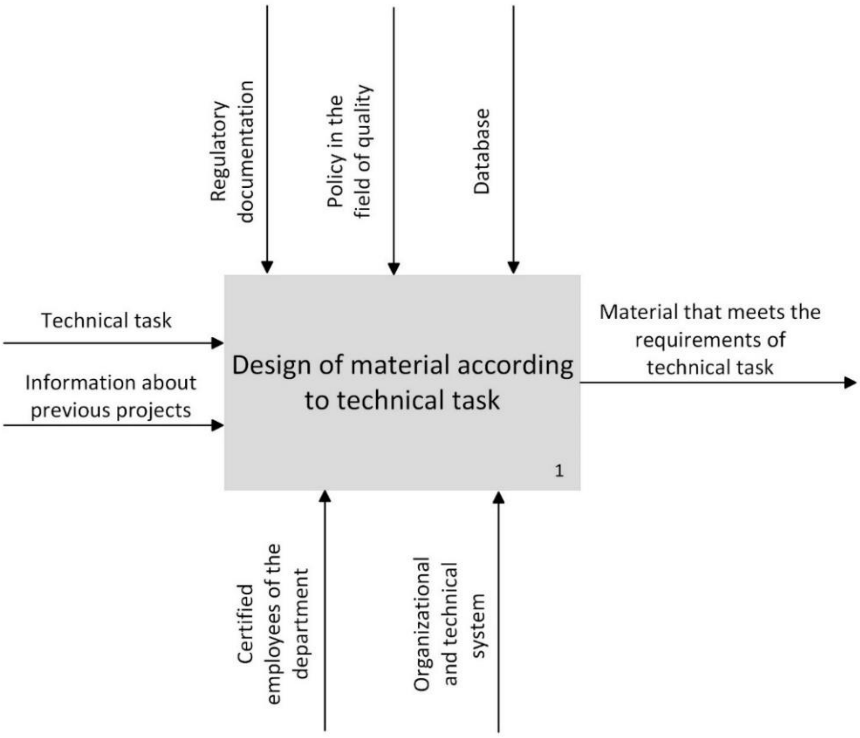


Figure 9 – IDEF0 methodology context diagram

When obtaining PCMs with predetermined properties, it is necessary to solve the task of selecting polymer matrices with optimal initial characteristics and a sufficient level of adhesive combination with fillers, which are responsible for ensuring the main functional characteristics (wear resistance, strength in the required temperature ranges, and hardness).

Thus, when performing the work, the implementation of the following main stages is required:

– selection and testing of polymer matrices, among which matrices based on thermoplastic or reactive polymers should be considered;

– selection and testing of fillers of different chemical nature with distinctly different characteristics;

– development and research of material compositions based on selected polymer matrices and fillers based on the principle of mutual compatibility of constituent parts, determination of qualitative and quantitative ratios of components, including step-by-step measurement of the main parameters for prompt adjustment of compositions.

When obtaining PCMs with predetermined properties, the following tasks arise. Firstly, there is minimal information about what material properties will be obtained when combining specific values of manufacturing technological modes.

Secondly, the specificity of the materials is that the end-user produces them before use by mixing the mixture's components (e.g., polymer, filler, modifier, and additive). No technique allows for predicting the most valuable properties of PCMs depending on the percentage ratio of components and technological modes of production.

An option for solving these tasks is the development of a decision-making support tool based on the values of the parameters of manufacturing technological modes and the composition of composites, which ensure the production of materials with the optimal level of predetermined properties of the obtained materials. A graphic interpretation of the decision support system concept is shown in Figure 10.

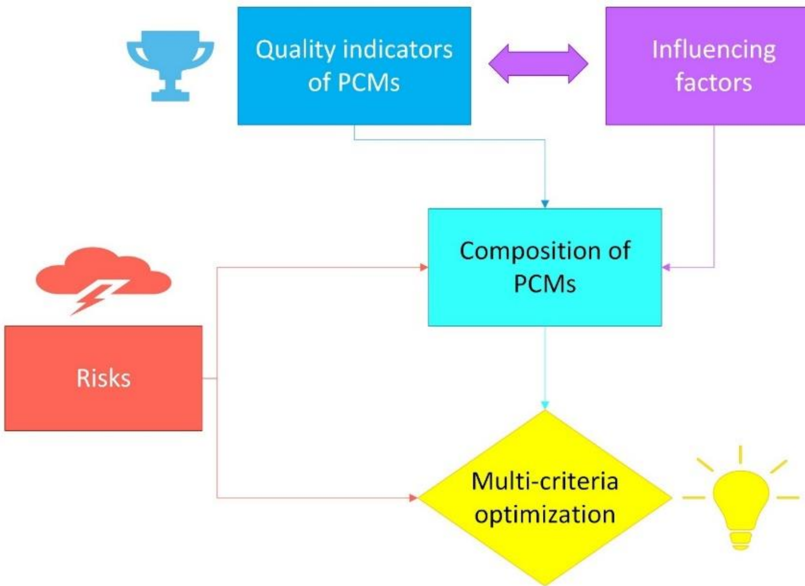


Figure 10 – The concept of a decision support system in the development of PCMs with predefined properties

In the first stage, it is necessary to highlight the most important quality indicators for consumers of such materials. Next, the relationship between the operating characteristics of PCMs and the influencing factors (e.g., raw materials, material composition, and technological modes of production) should be determined and presented in the form of mathematical models, which allows further optimization of the properties of the received PCMs [28]. This involves using multi-criteria optimization methods (obtaining a functional considering the risks) of the set of physical and mechanical characteristics of PCMs [29].

Introducing risk-oriented thinking into the concept being developed is mandatory in implementing ISO 9001:2015. Risk-oriented thinking is an integral part of the process approach and includes the concept of preventive actions. By using risk-based thinking, the researcher can identify the factors that can cause deviations from the planned results of the processes and minimize the negative consequences through preventive measures.

With the help of structural analysis tools from the IDEF0 methodology, a context diagram (Figure 11) and its first-level decomposition (Figure 12) of creating PCMs with predetermined properties were developed.

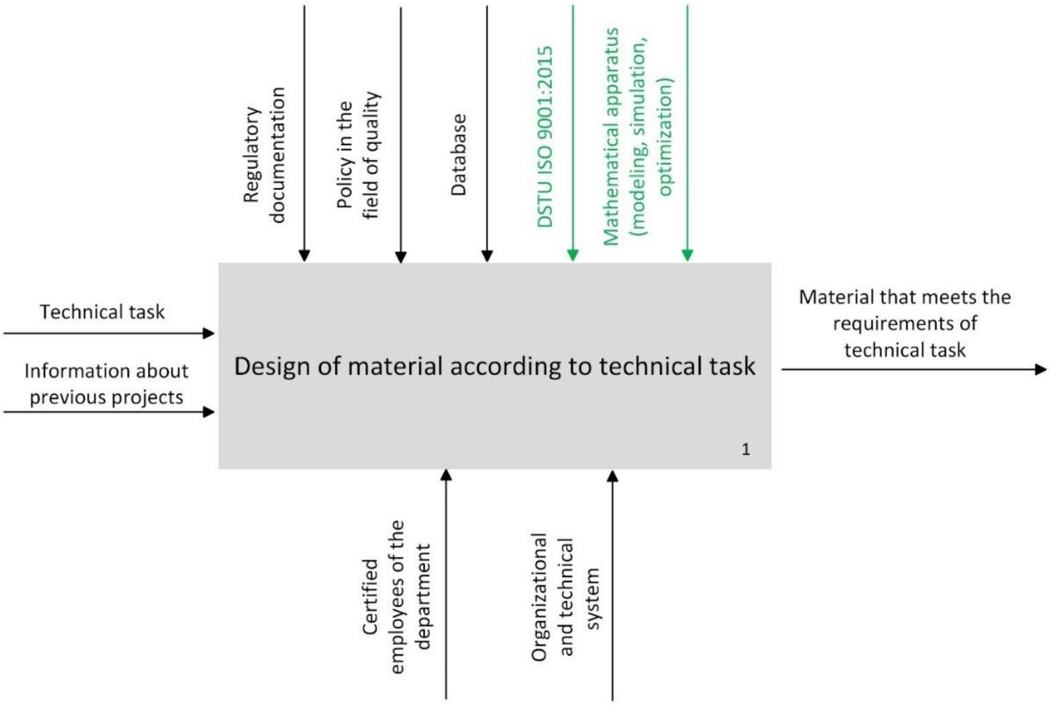


Figure 11 – Context diagram of the IDEF0 methodology in the development of PCMs with predetermined properties

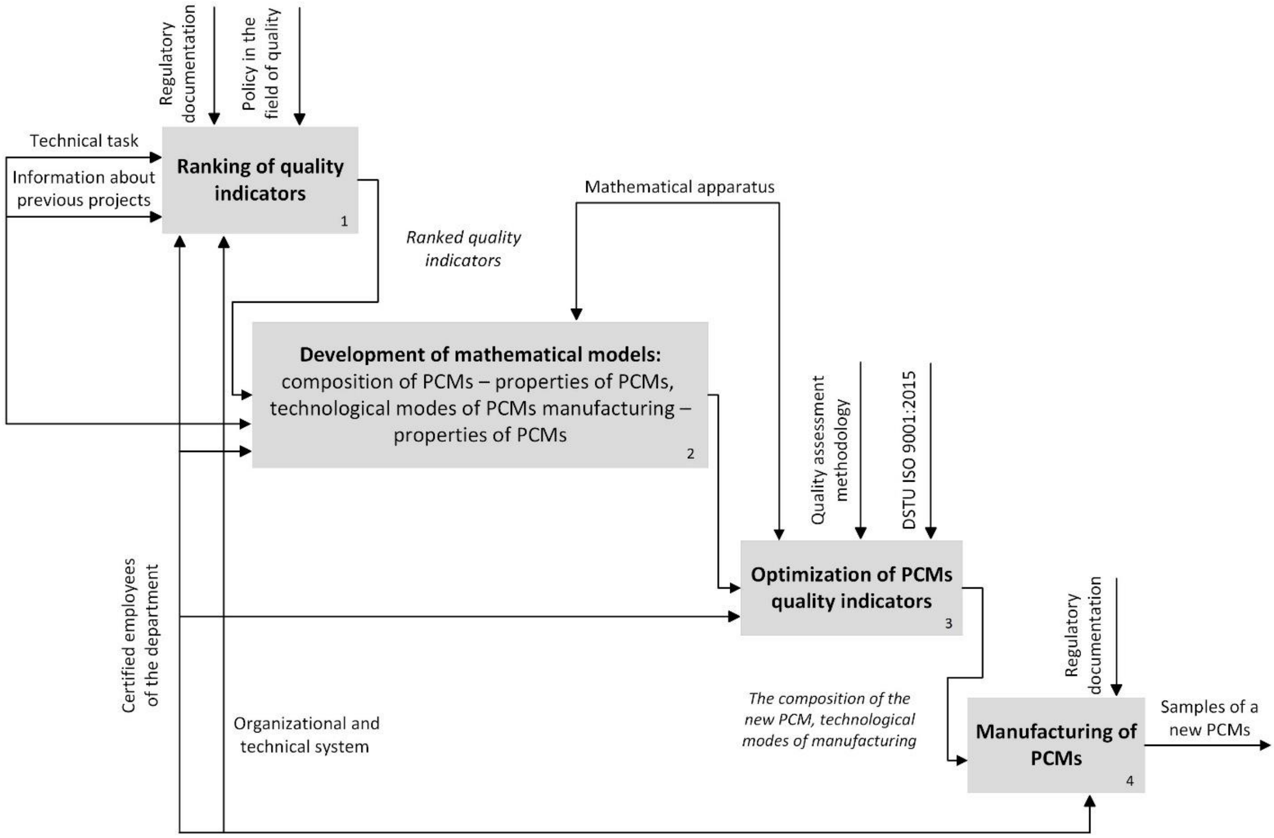


Figure 12 – Decomposition of the first level of the context diagram of the IDEF0 methodology when developing PCMs with predefined properties

ISO 9001:2015, which defines risk-based thinking, is added to the governing influences. Also, the mathematical apparatus for modeling material properties and risk assessments is added to the controlling influences.

To obtain the material, according to the requirements of the technical task, at the first stage, it is necessary to arrange the quality indicators of the material in descending order. For ranked quality indicators, develop mathematical models of two types: composition of PCMs – properties of PCMs, and technological modes of PCMs manufacturing – properties of PCMs. It is necessary to develop special software to implement the corresponding mathematical models. Optimizing quality indicators is solved in the next stage by considering possible risks. As a result, a new material is designed that meets the requirements of the technical task.

5 Discussion

European enterprises face challenges in the global market for PCMs. These challenges include competition from established international enterprises, access to advanced materials and technologies, market awareness and visibility, and navigating complex international regulations. Overcoming these challenges requires strategic planning, investment in technology and infrastructure, participation in international trade events, and building strong relationships with customers and reliable partners [30, 31]. In this regard, manufacturing enterprises should play a significant role in the global market of PCMs. They contribute to manufacturing capabilities and R&D product diversification. By leveraging their strengths, focusing on innovation, and seeking international collaborations, enterprises have the potential to expand their presence and competitiveness in the global market of PCMs.

The properties of the matrix largely determine the properties of products made of PCMs, the composition of the mixture, and the modes of manufacturing processes. The material's wear resistance is the main parameter that characterizes the necessary properties of the products under study.

Based on the results of expert assessment and QFD analysis, the most critical factors affecting wear resistance are polymer brand, filler shape and size, and technological parameters of mixing, pressing sintering, and mechanical processing, the influence of which should be investigated to establish quantitative dependencies. A stable value of the wear resistance of the product in the manufacturing process can be ensured by timely adjustment of the mixing, pressing, and sintering modes. This confirms the experimental and computational research results [32, 33].

The used in this research quality management methods can help create products that meet or exceed customer expectations and preferences, eliminate unnecessary or redundant functions and processes, involve cross-functional groups in the process, stimulate brainstorming and problem-solving, and optimize the design and development process.

6 Conclusions

The developed methodology for deploying the quality function made it possible to analyze the quality of PCMs based on PTFE. As a result, the most priority technical characteristics were identified for further research and development of recommendations for quality improvement.

As a result of the structural analysis of the process of developing PCMs with predefined properties at the enterprise using the IDEF0 methodology, the importance of conducting a risk assessment related to the process of multi-criteria optimization of their primary quality indicators was confirmed. Based on the analysis, the following results were obtained:

− the necessity of optimizing the ranked indicators of PCMs quality and determining the composition of the material and technological modes of production has been established;

− it was established that a small enterprise that deals with the creation of antifriction PCMs for the machine-building industry should have at its disposal mathematical models: composition of PCMs – properties of PCMs and technological modes of PCMs manufacturing – properties of PCMs, as well as an algorithm for assessing risks when creating materials according to the requirements of the international standard ISO 9001:2015.

In the future, the authors plan to analyze and implement the technologies of mathematical analysis and machine learning in quality management to solve the problem of improving the quality of engineering materials.

Acknowledgment

The results have been obtained within the research project "Fulfillment of tasks of the perspective plan of development of a scientific direction "Technical sciences" Sumy State University" funded by the Ministry of Education and Science of Ukraine (State reg. no. 0121U112684).

The authors appreciate the support of the Research and Educational Center for Industrial Engineering (Sumy State University), the International Association for Technological Development and Innovations, and the International Innovation Foundation.

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