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MODELLING OF THE STRUCTURE AND THE REQUIRED LEVEL OF PERFORMANCE PROPERTIES OF A POLYTETRAFLUOROETHYLENE COMPOSITES FOR SEALING

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Keywords: simulation, polytetrafluoroethylene, sealing, tensile strength
Abstract: The article describes the mathematical modelling results of the dynamics in order to determine the regularity. Further development of numerical approaches to taking into account the geometric nonlinearity of composite material on the basis of polytetrafluoroethylene with the use of the finite element method for studying the stress-strain state of the sealing elements line. Simulation were carried out under combined axial and surface radial loads. It is determined that the most "dangerous" from the point of view of the strength of the design are areas around square openings, docking zones of spherical, conical and cylindrical parts.

1 Introduction

One of the trends in the development of modern technology is the increasing use of composite materials in its production. This allows the material to be reduced in design without losing the required strength and stiffness characteristics. Promising in this regard are polymer composite materials (PCM) based on polytetrafluoroethylene (PTFE) due to its unique operational properties - the lowest coefficient of friction among polymers, high chemical inertia, thermal and cold resistance [1,2]. In the process of designing structures on the basis of fibrous composites, a preliminary calculation of deformation, strength and other structural characteristics is made. Analysis of these calculations in the future makes it possible to correct structural features by changing the mechanical properties of the composite and design parameters (size, shape, etc.).

A number of constructs of modified PCM based on PTFE, in particular by mechanical activation and/or the introduction of appropriate functional fillers, in geometric nonlinear relationships between stresses and deformations are have shown in real conditions of operation. The specified nature of deformation requires the development of conceptually new ways of its consideration [3-7]. There is a need for the development of methods for solving such problems in three-dimensional formulation, in particular the finite element method [2-4,8,9].

The aim of this work is to solve the problem of determining the stress-strain state of spatial structures of composite sealants based on the improvement of elastic constancy models and the development of effective numerical approaches to the solution of boundary-value problems of the mechanics of a deformable solid.

2 Materials and Methods

2.1 Materials

The main objective of the work is to develop antifriction composite material with high physical and mechanical properties for use in heavy wear. The main criteria laid down in the development of such materials is the ability to work without lubrication, reduced wear and tear of the part itself and the combined surface, resistance to the chemical impact of aggressive media, reliable work at low temperatures. As a polymer matrix that best satisfy the above criteria selected PTFE (Figure 1) because of its

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unique properties. The choice of fillers for the study is justified by the following considerations.

The results of research in the field of PCM based on PTFE convincingly proved the effectiveness of the use of carbon fiber (Figure 2). Established its optimal content of PTFE composites varies over a wide range (5-20) wt. % depending on the grade of the filler [3,6,10,11]. The prospects of modifying the surface of carbon fibers by mechanical activation [3,5,10,12]. Consequently, carbon fiber is selected as the main fibrous filler for a series of experiments.

Surface layer carbon fiber is characterized by microniveness with the sizes which do not exceed (0,1-0,2) microns, formed during carbonization and graphitization of hydrate cellulose tissue (Figure 2).

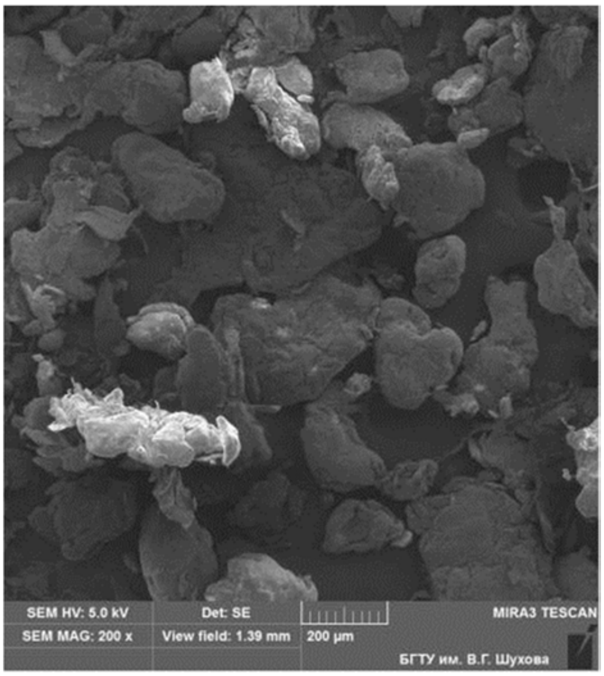


Figure 1 Microstructure of industrial PTFE

The presence of such superficial defects of different structures and geometric sizes allows us to use technological techniques based on the processes of deformation of the boundary layers on the surface of the filler as a result of their filling with particles of PTFE [14].

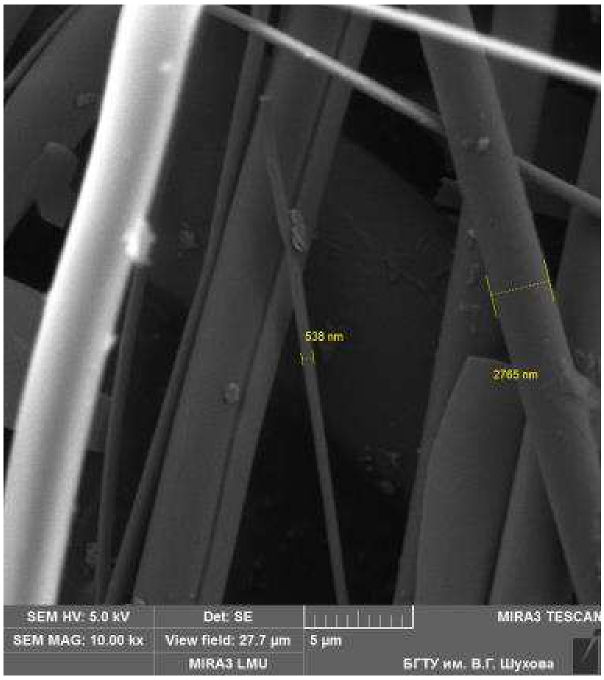


Figure 2 Microstructure of the surface of the fragment carbon fiber (x7480)

On the basis of experiments, it was found out that PTFE used for these studies is the most relevant for the requested requirements (Table 1).

Table 1 Characteristics of PTFE – unfilled [15].

Characteristic	Value of the index for the material
Mechanical Properties	
Density, g/cc	2,13 – 2,19
Tensile strength (Moulding direction), MPa Elongation at break (Moulding Direction), %	15 – 35 150 – 350
Hardness (Shore D)	57 – 64
Deformation under load, % 1 hr, 23º C, 14.2 MPa 24 hrs, 23ºC, 14.2 MPa permanent deformation 1 hr, 150°C, 5 MPa	 11,8 14,3 7,9 10,0
Compressive modulus at 0.2% off-set, 23ºC, MPa	600 – 700
Flexural modulus at 0.2% off-set, 23ºC, MPa	690

High molecular weight carbon fibers are widely sought after in the production of composite materials due to the unique combination of physical, mechanical and chemical properties (Table 2) such as high modulus of elasticity and strength, low density, high electrical conductivity, low coefficient of friction and thermal expansion, high resistance to atmospheric influences and chemical reagents [12].

Table 2 Main characteristics of carbon–fibers [13,14]

Parameter	Value
Carbon content, %	80,0 – 99,5
Diameter d·10^{-6}, m	4 – 30
Density, kg/м^3	1400 – 2000
Longitudinal strength, Pa	0,1 – 3,5
Tensile modulus, hPa	10 – 7000
Tensile elongation	0,5 – 1,3
Specific thermal capacity λ·10^3, J/(kg·K)	0,8 – 1,7
Conductivity factor, W/(m·K)	0,8 – 125,6
Electrical resistivity, Ohm·m	1·10^{-5} – 1·10^4
Thermal expansivity α·10^6, K^{-1}	2 – 20
BET surface area, m^2/g	0,3 – 1000,0
Burning duration, s	3 – 300
Resistance K to oxygen under an inert or reducing atmosphere	to 673 –723, to 3273

2.2 Mathematical simulation and optimization of composite structures based on polytetrafluoroethylene for ensuring high wear-resistance properties

Consider the two-phase composite material of random structure, which consists of a polymer continuous matrix, reinforced by the random distribution of discrete inclusions in it. The choice of two-phase material as a research object somewhat simplifies (in comparison with the three-component composite) mathematical calculations and, at the same time, contains all the hypotheses and the initial preconditions for further research. In addition, this approach allows us to consider some well-studied two-component structures - materials with spherical inclusions and materials, reinforced with short fibers. In Figure 3 shows the structure of two-component material, inclusions in which there are short fibers.

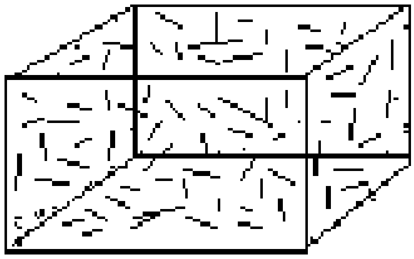


Figure 3 Structure of the two-component material based on polytetrafluoroethylene reinforced with carbon fibers

The elastic spring element creates a constant force that pushes the sealing edges for sealing along the mating surfaces of the groove.

When modelling the stress-strain state of a rubber ring, finite elements were used for which the Mooney-Rivlin model (1) was implemented [13,15]:

$$W = C_{10} \cdot (I_1^* - 3) + C_{01} \cdot (I_2^* - 3) + + \frac{1}{D_1} \cdot k(I_e^* - 1)^2 \quad (1)$$

where: C_{10}, C_{01} and D_1 are material constants, I_1^*, I_2^*, I_e^* are reduced strain invariants.

Constants of material can be used to calculate the initial shear modulus (2) as follows:

$$\mu_0 = 2 \cdot (C_{10} + C_{01}) \quad (2)$$

The initial modulus of elasticity for a material is calculated (3), (4) as follows:

$$K_0 = \frac{1}{D_1} \quad (3)$$

Use for analysis

$$D_1 = \frac{1}{500 \cdot G} \quad (4)$$

where: G is shear modulus.

To take into account the stress relaxation of the sealing element made of elastomer in the model (1), the Mooney - Rivlin constants were recalculated based on the value of the relative residual strain of 0.6; the following values were obtained [11,15-21]: C_{10} = 781178.6 Pa; C_{01} = 154173.9 Pa.

Deformations of PTFE protective rings were considered elastic, the surfaces of the cylinders and the floating piston were determined to be absolutely rigid. Used friction model [9]:

$$\tau = \mu \cdot N \quad (5)$$

where: τ is the shear stress; μ is friction coefficient; N is contact normal pressure.

The seal consists of a polymer shell, which is tightened by a metal spring after installation in the seat groove (Figure 4).

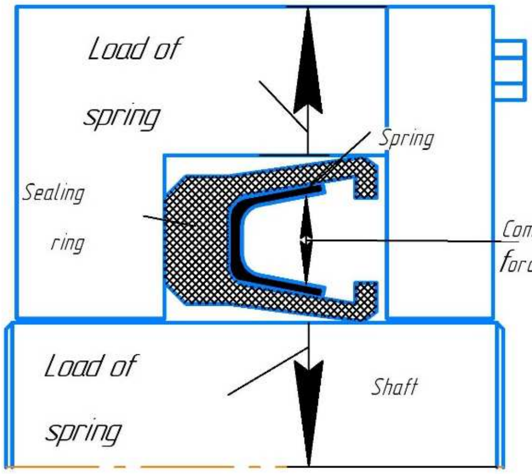


Figure 4 The principle of operation of the sealing

One of the basic calculations for designing seals is the static strength calculation. To determine the stress-strain state of the elements, apply the momentary scheme of the finite element [12].

3 The results of the simulation performance properties of a polytetrafluoroethylene composites for sealing

Conducted simulation in the software package **SimulationXpress Study.**

The following data were taken as input parameters for the simulation model:

− a geometric model of the sealing device (Figure 5);

− characteristics of physical and mechanical properties of materials;

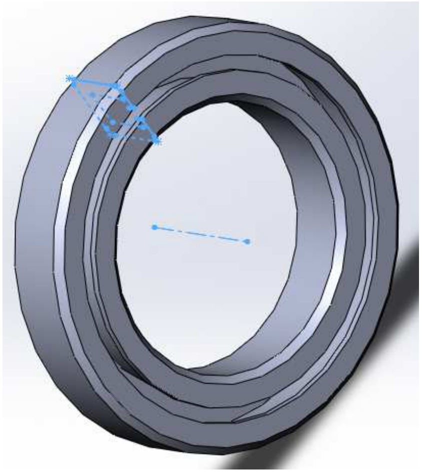
− pressure (20 MPa).

The design of the sealing ring by finite elements can be presented in the next three months by the following intermediary processes:

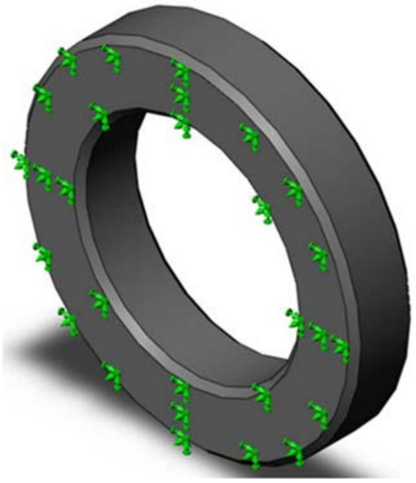
– preparation of initial data - description of the topology of the design, kinematic and force boundary conditions, physical and mechanical characteristics of the composite material, finite-element sampling of the design and others;

– numerical calculation of finite element model - calculation of coefficients of the matrix of rigidity of finite elements, formation of a global system of solving equations and its solution;

– processing of the solution results - calculation of the parameters of the stress-strain state of the design; their visual representation in the form of tables, charts, two-dimensional or three-dimensional images.



a)



b)

c)

Figure 5 The research in SimulationXpress Study Stress

a) 3D CAD model;
b) Fixed geometry;
c) Finite elements.

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For the study of the stress-strain state of structures of fibrous composites, the ratios for the stiffness matrix of a three-dimensional finite element of composite material with transistor components are proposed, taking into account the spatial reinforcement of fibers based on the momentum scheme of a finite element. The momentary scheme avoids the disadvantages inherent in the traditional scheme of the finite element, and the consideration of the spatial nature of the location of the fibers weakens the requirements for the discretization of structures.

The obtained diagrams of equivalent voltages for the sealing element of the device under consideration are shown in Figure 6. As can be seen from Figure 6, in the sealing element in a static state, the maximum equivalent voltage is 2199 Pa, which cannot lead to the destruction of the sealing element. After relaxation of the stresses in the power element, the equivalent stresses in the sealing ring decrease, as well as the decrease of the contact pressure on the sealing surface.

The diagram of equivalent stresses, shown in Fig. 4, corresponds to the development of adhesive bonds at the point of contact during a long stop of the mechanism. According to the literature data, the initial (starting) value of the friction coefficient can reach values of 0.2 and more [17]. At high values of the friction coefficient, the equivalent stresses locally increase, which exceeds the tensile strength for the applied group of polymers. The initial friction at the time of launch, as well as high values of the friction force in the process of movement or rotation of the shaft can lead not only to damage the surface of the sealing ring, but also to its twisting.

The nature of the external load and the symmetry violation, due to the presence of openings in the structure, leads to the fact that radial displacement has both a positive and a negative sign, that is, there are zones that are torn, and there are zones that bend. Although these displacements are in an order of magnitude smaller than the axial.

The values of the axial displacements in the intersections perpendicular to the axis of the design are close to the steady ones, although they are not such that due to the presence of rectangular openings and, accordingly, asymmetrical setting of the problem. The analysis of the results shows that the most vulnerable in terms of strength are areas near rectangular openings, where the intensity values of the stresses acquire the maximum values.

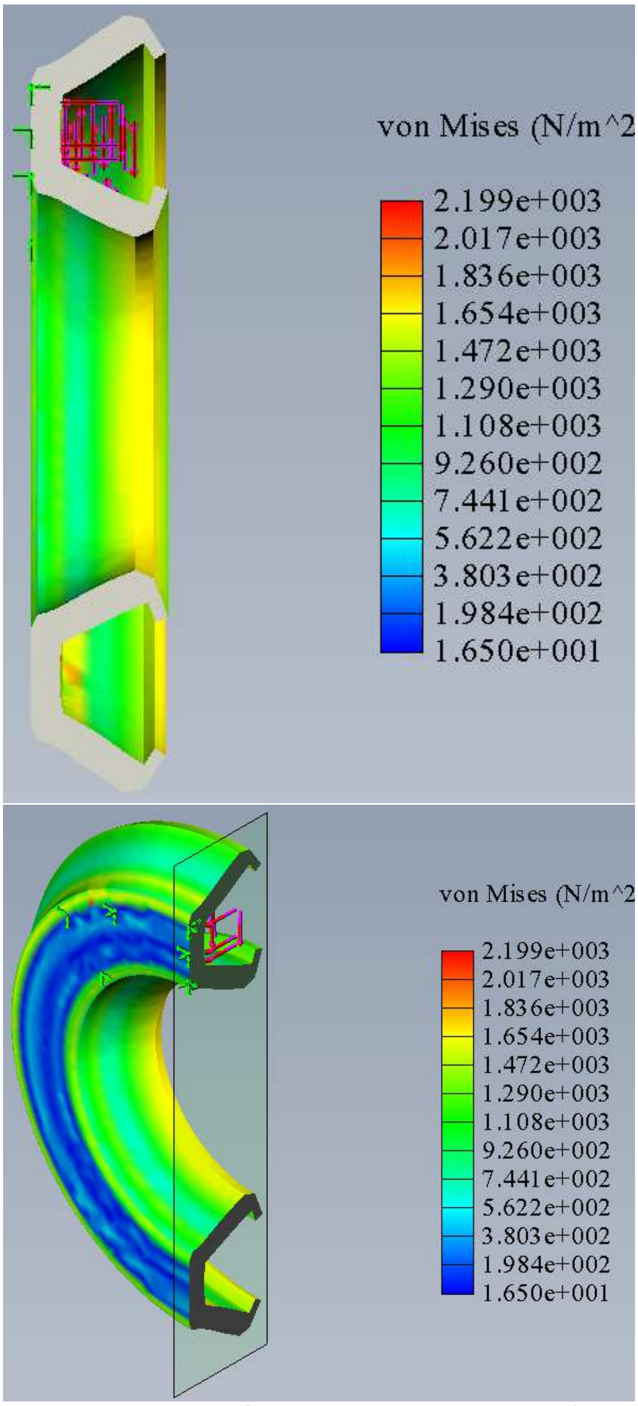

Figure 6 Diagrams of equivalent stresses in a section of a sealing ring in a static state

4 Conclusions

On the basis of established factors of mechanical activation, content and properties of fillers, the performance characteristics were obtained by antifriction material based on PTFE with increased physical and mechanical properties for use in conditions of intense wear. The developed polymer composite materials are characterized by high wear resistance and relatively low for the PTFE composites tensile modulus values (up to 197 MPa), which increase the area of actual contact of the sealing element made of PTFE-nanocomposite and sealing surface in the sealing device. This combination of properties makes it possible to recommend the developed PTFE nanocomposites for the manufacture of sealing elements of sealing devices for movable joints of machines and technological equipment.

With the help of developed approaches to determination of effective elastic stable composite, matrix of rigidity of a finite element and software complex, the stress-strain state of sealing structures is determined. On the basis of the kinematic and energy conditions of the agreement, analytical relations are proposed for determining the effective elastic characteristics of the fibrous composite material, which allow taking into account the transposition properties of the matrix and fiber. Simulation were carried out under combined axial and surface radial loads. Improving the efficiency of PCM in sealing devices is ensured by a rational choice of the geometrical parameters of the elements of sealing devices, providing the level and distribution of contact pressure on the sealing surface necessary for improving their reliability (durability) at acceptable values of wear and mechanical stresses in the sealing element.

The obtained ratios for the determination of effective characteristics of polymer composites and the developed software complex can be applied at designing and improving the designs of sealing. The maximum values of the compressive stresses at different reinforcement schemes take higher values for the case of the internal arrangement of the composite layer in comparison with the continuous arrangement (up to 30%).

Thus, the goal set in the work was achieved and the stated research objectives were solved.

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SIGNIFICANCE OF SIMULATION AS A FUTURE TREND: WORKPLACE STUDY USING SIMULATION SOFTWARE WITNESS

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Keywords: manufacturing industry, simulation model, important production factors, production research
Abstract: Globalization in manufacturing industry, aiming to reach the highest level of productivity and competitiveness oblige companies to innovate their products, technologies, processes. Using simulation and modelling to solve production problems is one of the research topics and priorities for future actions in manufacturing industry. After the simulation model is built, validated and verified, many scenarios can be tested before applying changes in a real performance, avoiding unnecessary costs if the change would have a failing effect. This article is focused on a simulation method and its application on a case study applied in manufactory.

1 Introduction

1.1 Trends in manufacturing industry

In an environment characterized by rapid social, economic and technological changes, new demands are still being placed on manufacturing research. The most common aspects of change in manufacturing research are considered following [1]: *globalization, competitiveness, high productivity, innovation, market factors, social factors, environmental factors*.

Globalization represents new ways and ways of how the individual national economies work together. National economies have become integrated through the free movement of goods and capital across borders. Standard theoretical models are to reduce trade barriers and transport costs, which will increase trade between producers in one country and consumers in another country. Such newly created international relations underline the importance of the development of manufacturing research [2].

The goal of *competitiveness* is to maintain sustainable development based on the business strategy. The strategy should be chosen in such a way that quality, productivity and innovation have a steadily increasing tendency [2]. Consequences of the implementation of the new competitiveness strategy lead to:

- the flexibility of the production process,
- reducing resource consumption,
- lower production costs,
- efficient use of transport and other components,
- applications of automated and sophisticated technologies.

High productivity - the flow of production activities is reflected in the efficiency of production systems. Growth of productivity is one of the main ways to increase competitiveness. At present, the main source of economic growth is the continual increase in labour productivity. The main types of developmental changes according to [2] can be stated:

- placing new products and services on the market compared to competitors,
- use of new materials, sources and raw materials,
- new organization of production,
- placing products and services in new market segments.

The effort of enterprises to make changes is also influenced by [3] following factors:

- *Market factors* - high competition, globalization, unstable environment, product lifecycles and production systems are diminishing; emphasis is placed on high quality at the lowest prices, customer demands are constantly evolving.
- *Social factors* - changes in the organization of working time, wage increases, emphasis on humanizing work, seeking new ways to motivate people, actively engaging employees in business changes, changing views on the job position in human life, changing the rankings of values influenced by raising the standard of living.

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2 Materials and Methods

2.1 Description of latter possible solutions that are used in production industry

Production systems with breakthrough innovations are at the stage of research and development. In the literature and in the projects, they are referred to by various terms, Factory of Future (FOF), Intelligent Manufacturing (IM), Agile Manufacturing, Sustainable Manufacturing, Breathing Factory, Excellent Production, Teaching the Learning Organization and many others [4].

General trends in system manufacturing innovation characterize productivity, flexibility, high precision and quality, environmental friendliness and investment cost acceptability (Figure 1) [5]. Other features include flexible adaptability, ergonomic standardization, cost-saving without redundancy, elimination of waste, instant availability, the ability to install and place anywhere in the world, the absence of long recovery and commissioning times, the exclusion of extra costs, optimal energy performance, the ability to rearrange and reorganize activities on a case-by-case basis to suit current products and production volumes. The general feature is the application of advanced technologies, particularly ICT (Information-communication technologies) [6].

Recently, there has been a debate about the future of production in the United States, Japan and Europe. Production is in relative decline compared to services, but the financial crisis has brought back the benefits of a stable production base into a focus. In order to assess this issue, society needs to know why production is falling and whether it really is a problem for the current economy [6].

Recently, the pace of production decline has stopped or at least slowed down. Outsourcing jobs to Asia has also slowed down. Further trends point to a better future for global production. These include new sources of demand for industrial products, with a large number of consumers in emerging economies entering the global consumer goods industry. The supply side of the supply chain is a stream of new technologies that are waiting for further use to bring new types of products to the market, to re-discover existing products and also to improve the efficiency of production processes. An example is additive production using 3D printers, robotics, nanotechnologies, and intelligent communication systems [7,8].

The future direction of European Industrial Manufacturing Research has been incorporated into the Factory of the Future project. Research activity has four core priorities:

• Sustainable production,
• Intelligent production,
• High-performance production,
• Use of new materials in production.

On the basis of analyses, information and knowledge about production research can be summarized research topics and priorities for future actions and funding [7,9]:

• Sustainable development based on the efficient use of production sources,
• Production technologies exploiting the potential of new technologies (bio and nanotechnologies),
• Using simulation and modelling to solve production problems,
• Agile, responsive production systems for customer-oriented production.

In many countries, the emphasis on production research is on high value-added industries and on their development. Experts agree that there are prerequisites that drive production research to a successful end. The assumptions are based on a multidisciplinary nature, i.e. on the interconnection of science and technology [10].

The solution suggestions of new complex tasks according to innovation of production systems can be identified as:

• network structures,
• systematic prospective studies,
• transnational forums,
• creating innovative scenarios, etc.

These recommended forms have the potential to raise awareness and relations between organizations (academia, industry, government and other innovation organizations).

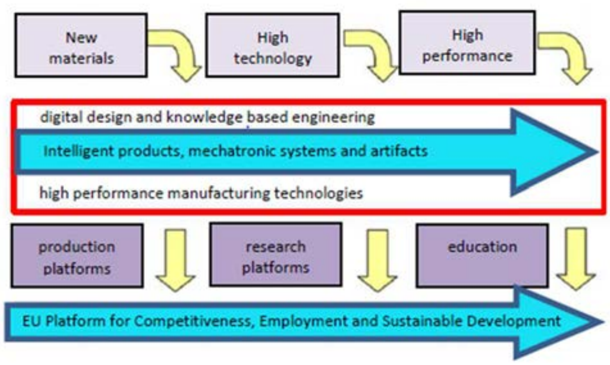

Figure 1 Industrial technology direction in the EU according to [4]

2.2 Case study description for simulation modelling

The simulation model was built in order to evaluate the value flow in the production factory of plastic and aluminium products from a window manufacturer.

First, technological process would be introduced for better understanding of a product flow in the production area. The production process starts by adding material to the cutting centre, where the material is cut to the required length. Shredded material profiles travel to the machining centres where a metal reinforcement is inserted into the

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profiles. At the same centre, holes are drilled into the profile for handles, posts, hinges, and drainage holes are milled. From the machining centres, the material loaded in the racks travels to the four-headed welding machines. There, it is split into wings and frames. Through the belt conveyor, the welded products are moved to the CNC cleaners, where the welding of the corners of the windows and the door is completely assisted by a variety of tools. After machine cleaning, it is also advisable to clean with the help of the staff for perfect cleaning around the welding site. Subsequently, the wings and frames are placed in the container. According to the plan, the worker selects from the storage container which window or door will follow. With the screws, he fixes the fittings manually on the wing, which is screwed by the screwing centre, which ensures the accurate drilling and screwing, allowing the wings to be mounted securely in the frame.

The last operation in the production process is glazing, for which an insulating double glazing or triple glazing is used. It is glazed using spacers and glazing bars that are cut to exact size [11].

2.2.1 Simulation model in Witness software

Based on input data from the production plant - cycle time; production lead time; time for machine operation and setting; logistics times: time for supply of material and quantity of production batch; simulation model was created (Figure 2, Figure 3) [11]. The operation day was set for one 8-hour working shift, according to real conditions. As working conditions, one operator performs work next to one machine, but there are operations requiring cooperation of two workers due to a weight of the piece, for example moving window frame from one position to another.

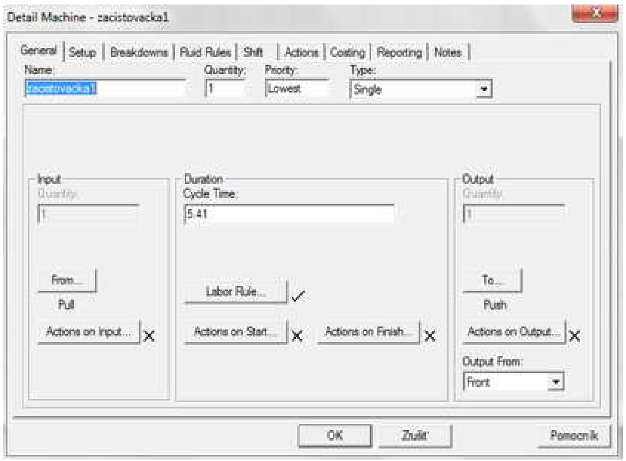

Figure 2 Detailing Workplace Weld Cleaning

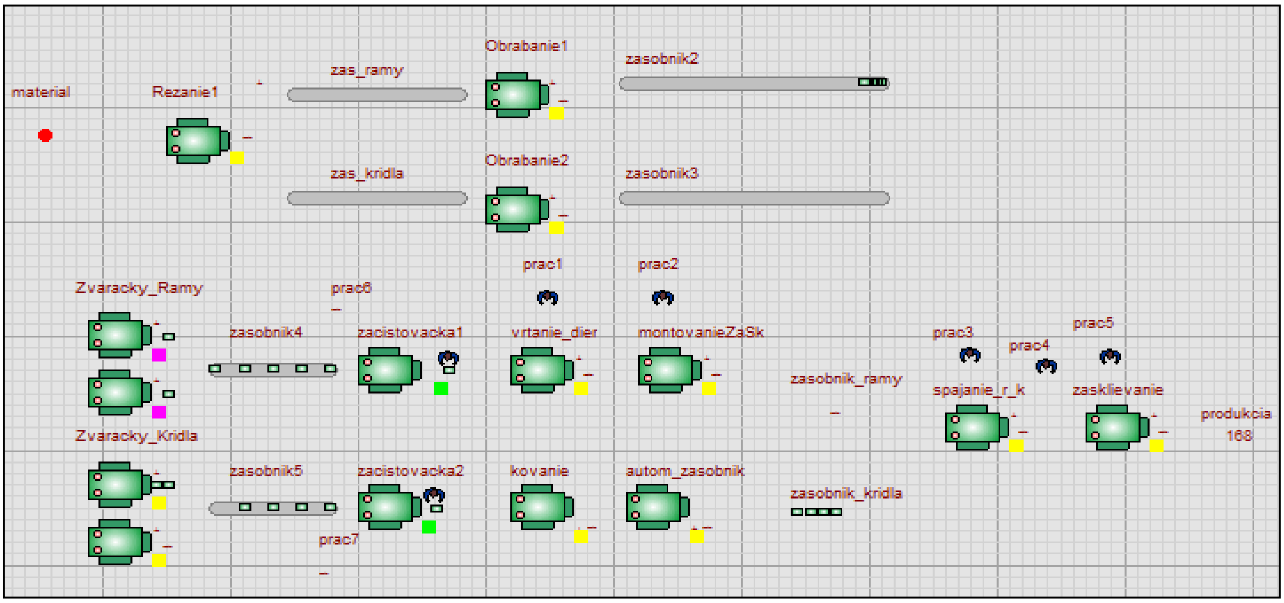

Figure 3 Simulation model of a manufacturing factory

The aim of the simulation model was to analyse the efficiency of the production plant and to propose measures due to increasing the throughput and productivity of the whole system.

After completing the simulation runs, it can be stated that the production hall is capable of producing 168 units of window units in an operation mode that can be seen in the statistics output from the model (Table 1) [11], with the actual number of machines and equipment. For a given type of production program, production output in real

operation is approximately 170 window units. Thus, can be stated, that built simulation model is validated and verified and available for experiments with a model.

The statistical outputs show that the most loaded machines are Machining and Cleaning stations, where the work is essentially continuous. On the contrary, the least loaded is the workplace for Glazing, joining frames, working station "Assembly_w" with wings, where there is a long waiting time for the semi-finished product arriving at the workplace.

The first results from simulation model indicate a possible improvement in the organisation of individual working places. Long idle times indicate speculations about efficiency and consistency of material flow on input, as well as interoperation transport.

Name	Idle [%]	Busy [%]	Blocked [%]	Setup [%]
Cutting1	53.88	19.63	25.49	1.00
Welding_	38.69	19.17	42.15	0.00
Welding_	22.53	3.11	74.35	0.00
Welding_	26.40	11.02	62.58	0.00
Welding_	26.63	11.02	62.35	0.00
Machining1	25.88	74.12	0.00	0.00
Machining2	25.88	74.12	0.00	0.00
Cleaning	3.36	95.76	0.00	0.88
Cleaning	3.36	96.19	0.00	0.46
Drilling	80.38	19.25	0.06	0.31
Forging	79.83	20.17	0.00	0.00
Assembly	80.00	17.50	0.00	2.50
AutoBuffer	96.33	3.67	0.00	0.00
Assembly_w	93.38	5.25	0.81	0.56
Glazing	97.31	1.75	0.00	0.94

Table 1 Statistics of machine productivity after simulation run

3 Conclusion

As most common scenario analysis of the results from simulation run is considered the what-if analysis. What-if analysis can be simply performed by operational manager as a part of a decision-making process. Professional operational manager can evaluate several scenarios to achieve the best operational result. Results from simulation model can be part of value stream mapping, in order to make a valuable product.

Using simulation and modelling to solve production problems is according to [7] one of research topics and priorities for future actions and funding.

The aim of the simulation model was to analyse the efficiency of the production plant and to propose measures due to increasing the throughput and productivity of the whole system. The first results from simulation model indicate a possible improvement in the organisation of individual working places. Long idle times indicate speculations about efficiency and consistency of material flow on input, as well as interoperation transport.

Such a way, experiments with valid and verified model would be further performed.

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