

# METHODOLOGY OF SYNTHESIS OF PACKING MACHINES FOR FOOD PRODUCTS BASED ON MULTICRITERIAL ANALYSIS

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## Abstract

The complex of technical means for optimization synthesis of assembling of a packing machine of separate functional modules has been developed. The method of synthesis of a packing machine, based on criterial assessment of separate functional modules (FM), combined by two main assessment groups, has been offered. FM may be selected and calculated by the program of consumption, based on the overall equipment effectiveness (OEE) criterion. An example of synthesis, based on the offered method, takes into account variants of choice of ready functional modules, based on the hierarchic structure of a module of roll packing material supply. The method takes into account the systemic approach to analysis of equipment constructions for packing fine-piece and piece food products in a consumption package. The synthesis of FM assembling as conceptual models, abstract ones, reflecting the construction structure and connections between separate elements – functional devices (FD) – has been offered.

The optimal assembling of the functional device in the structure of the functional module of roll packing material supply has been determined. As a result of solving this problem, a FM1 prototype has been created. At conducting the comparative analysis with the existent equipment, the automatic functional device has been modeled. The use of the OEE criterion with joint properties that reflects the generalized assessment of a packing machine or functional module with a maximin (minimax) criterion by the compromise principle has been substantiated. The analysis is grounded on the idea of optimality of each module or device of the machine for packing food products at adding each next functional module to its composition. The program of assessment calculation of the package equipment with the complex assessment criterion OEE for different assembling of FMi machines for packing piece and fine-piece products has been developed.

The FM of roll film material supply with using a microprocessor managing device that maintains a sinusoidal law of movement of a stretching roll of the packing machine has been developed. Optimal characteristics of the technical system have been determined. Results, obtained at processing experimental data, confirm adequacy of the offered method for assessing assembling solutions.

**Keywords:** roll film material, functional module, generalized effectiveness criterion.

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## 1. Introduction

The totality of processes in functional modules (FM) of the packing machine within an assembly line for processing food products is just a single big process. Despite the diversity of technologies of machine-apparatus formation, it is general for different machines of food products packing that the continuous technological flow, transforming initial raw materials in a packed product, is organized and functions in them. Such flow needs high-effective technological FM

divers for packing [1]. The study of FM for packing machines was realized for one of most groups – piece food products for further industrial probation. The aim of the study is structure optimization of the packing machine with separate FM, improvement of assembling algorithms of technical solution, based on the multicriterial approach [2].

## 2. Materials and Methods

The research material is an indicator of OEE (Overall Equipment Effectiveness), based on nominal capacity of the equipment and its operating time, assessed the effectiveness from different sides. The prognostication and study of FM operation were realized, based on systems of supplying packing materials in the packing machine with a linear electric drive. The methods and methodologies of mathematic modeling of technical systems, numerical methods were used. The program of OEE calculation has been synthesized, based on experimental studies, using identification methods. The author methodology of multicriterial assessment of rational FM assembling, based on the method of searching Pareto-effective solutions has been developed.

At conducting experiments, there were used the devices by Camozzi company: electric proportional pressure regulator MX-PRO (0÷10 bar); Analogue output 0–10 V DC deviation  $\leq 0.2\%$ ; analogous output 0.5–9.5 V DC [feedback].

## 3. Experimental procedures

### 3. 1. The structure of the offered optimization synthesis

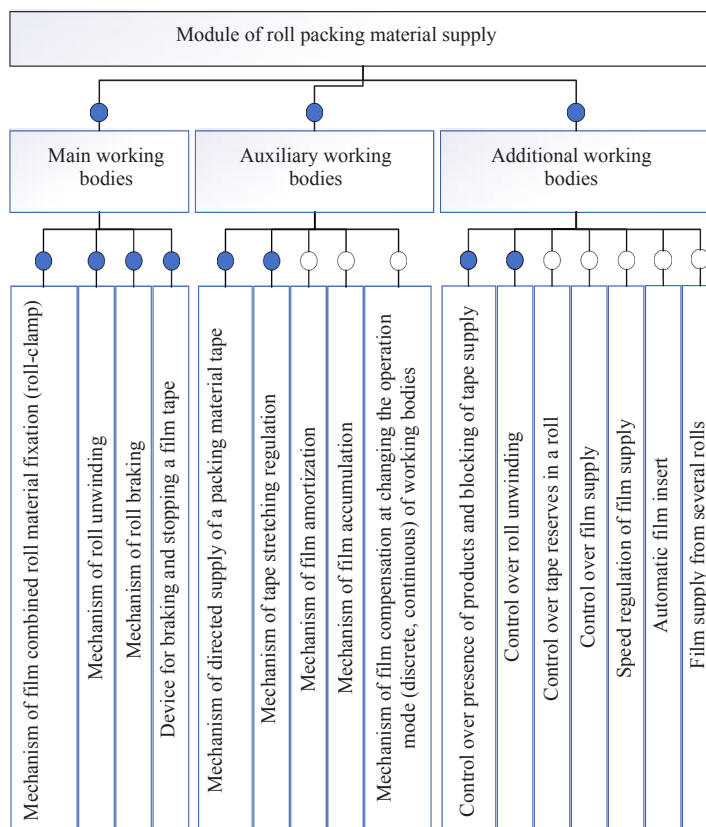
The research task is to develop the method of synthesis of the package machine, based on the criterial analysis of separate FM, combined by two main assessment groups that may be calculated by the consumption program, based on the OEE criterion.

The complex of technical means is understood as a totality of technical devices, especially: main, auxiliary and additional ones [5], interconnected for realizing the production technological packing process. The optimization synthesis of FM assembling provides the successive realization of a series of procedures. Especially: formation of an organizational system – volume of project works and methods of their realization; formation of the information environment – a totality of all types and forms of information; choice or elaboration of the complex of necessary technical means (software). Each of them is in solving a certain local problem, which results are initial data for the next one [3]. According to the results of the analysis of the hierarchic structure of the functional module subsystem for FM of packing machines for fine-piece food products (AL series by “Packing technologies” company, Ukraine), it has been established, that FM of roll packing material supply is one of first that starts operating in the technological process. That is why, based on the multicriterial approach [4, 6], we develop the program for OEE calculation with further use of the results at searching of assembling of the packing machine.

Let's present FM variants as a generalized graph of the hierarchic structure of the model of roll packing material supply ● – tops are connected by the logic function “and”, ○ – tops are connected by the logic function “or”, **Fig. 1**.

The system approach to the analysis of equipment constructions for packing fine-piece and piece food products in a consumption package provide consideration of their construction as conceptual models that are abstract ones, reflecting the construction structure and connections between their elements. Machines of this type are characterized with a diversity of components that may be distinguished by main classification signs, among which: product supply to FM; type of a dosing-packing FM; packing means supply; package hermetization type; control over main processes in the machine and so on. The analysis of constructions [5] demonstrates that each producer offers to the market both single samples and the wide spectrum of their modifications, created by using correspondent assembling methods [6]. But in the overwhelming majority of packing machines, the roll packing material supply module with the structure with an electropneumatic drive and 11 nodal devices is used.

So, taking into account the prevalence of this FM (of 11 modules), the analysis methodology was formed, based on the multicriterial approach. The graph of logic connections between the considered FM (by **Table 1** – it is the directed supply of a tape of a combined film packing material).



**Fig. 1.** Generalized graph of the hierarchic structure of FM for roll packing material supply:  
● – tops are connected by the logic function «and», ○ – tops are connected by the logic function «or»

FSS<sub>j</sub> – functional subsystems (separate joints of the technological machine with or without diver).

The formalized expression of the graph is following:

$$S: m_1(x_{1.1} \vee x_{1.2} \vee x_{1.3} \vee x_{1.4} \vee x_{1.5}) \wedge m_2(x_{2.1} \vee x_{2.2} \vee x_{2.3}) \wedge m_3(x_{3.1} \vee x_{3.2} \vee x_{3.3}) \wedge m_4(x_{4.1} \vee x_{4.2} \vee x_{4.3} \vee x_{4.4} \vee x_{4.5}) \wedge m_5(x_{5.1} \vee x_{5.2} \vee x_{5.3} \vee x_{5.4}) \wedge m_6(x_{6.1} \vee x_{6.2}) \wedge m_7(x_{7.1} \vee x_{7.2} \vee x_{7.3}) \wedge m_8(x_{8.1} \vee x_{8.2} \vee x_{8.3} \vee x_{8.4}) \wedge m_9(x_{9.1} \vee x_{9.2} \vee x_{9.3} \vee x_{9.4}) \wedge m_{10}(x_{10.1} \vee x_{10.2} \vee x_{10.3} \vee x_{10.4}) \wedge m_{11}(x_{11.1} \vee x_{11.2} \vee x_{11.3}),$$

where S – realization of the service function of FM (technological packing operation), m<sub>i</sub> – technological transfers by correspondent FM.

The description of the method, offered by the authors, is based on the study of the structural-parametric model of the FM mechanism of film roll supply to the packing machine. According to the approach of the structural-parametric modeling of the mechanism [7, 8], the composition of FM elements (1) may be determined by the set of functional subsystems FSS [10]:

$$FM = FSS_1, FSS_2, \dots, FSS_j, \tag{1}$$

where j – number of FSS<sub>j</sub> in the structure of the packing machine FM.

In this case, according to **Table 2**, the number of their types is N=42. In its turn, the studied FM of the mechanism of roll film supply to the packing machine consists of FSS<sub>j</sub> in amount N=11, by the **Table 1**:

$$FMM = (x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}). \tag{2}$$

**Table 1**

The description of FSSj to the graph of the hierarchic structure of the packing machine with FM of roll packing material supply

Name of FMM technological transfer	mi	Sign of FSSj	Cost of FSSj construction	Description of FSSj of the packing machine
Fixation of a roll of film packing material	m1	x1	x11, x12, x13, x14, x15	Device – stop cone-like shaft with fixation by a friction brake, device of roll-keeper with an electromechanical brake, bush device with external clamping fixers, bush device of a roll-keeper with a pneumatic brake, device for roll unwinding with a spindle or split fixer
Roll unwinding	m2	x2	x21, x22, x23	Electromechanical forced device, electropneumatic forced device, pneumatic forced device
Roll braking	m3	x3	x31, x32, x33	Tape, friction, electropneumatic device with a clamping roller
Braking and stop of a film tape	m4	x4	x41, x42, x43, x44 x45,	Electropneumatic device with a freely or forcedly stretched material loop, electromechanical multi-loop device with several rollers, bending clutches, self-wedging clutches, vacuum clutches
Film tension regulation	m5	x5	x51, x52 x53, x54	Device with a constant braking moment, device with a changing braking arm, device for braking by a log on the roll periphery, device with braking by a tape on the roll periphery
Film amortization	m6	x6	x61, x62	Electromechanical device for forced stretching of a loop, pneumatic device for forced stretching of a loop
Film compensation at changing the operating mode (discrete, continuous)	m7	x7	x71, x72, x73	Electromechanical device with stretching rollers; electropneumatic device, based on a rodless pneumocylinder device with a frequency-regulated electric drive
Control over products presence and blocking of tape supply	m8	x8	x8.1, x8.2, x8.3, x8.4, x8.5, x8.6	Ultrasound device with a contactless sensor, electrocontact device, capacitance sensor, photoelectric sensor, pneumatic contactless sensor
Control over a film reserve in a roll	m9	x9	x9.1, x9.2, x9.3, x9.4	Ultrasound device; couple of impulse sensors (measuring roll and tape-removing cylinder rotation frequency), tachometric device, mechanical device
Control over film supply	m10	x10	x10.1, x10.2, x10.3, x10.4	Deviation device with a contact sensor, Deviation device with a contactless sensor, optic device for flat side location regulation, reversing turning devices with parallel rollers
Automatic film insert and supply from several rolls	m11	x11	x11.1, x11.2, x11.3	Electromechanical device for changing a roll on the running machine by one-ray roll charger, electropneumatic two-roll device, electromechanical device for changing a roll on the running machine using two-rays roll charger

In their turn, these elements are also divided in components, there are mainly technical elements that must be chosen by certain operating criteria of the technological equipment of cluster libraries of producers of packing and control-measuring equipment;

$$FMM_1 = \begin{cases} FSS_1 = x_1 = \{x_{1.1}, x_{1.2}, x_{1.3}, x_{1.4}, x_{1.5}\}; \\ FSS_2 = x_2 = \{x_{2.1}, x_{2.2}, x_{2.3}\}; \\ FSS_3 = x_3 = \{x_{3.1}, x_{3.2}, x_{3.3}\}; \\ FSS_4 = x_4 = \{x_{4.1}, x_{4.2}, x_{4.3}, x_{4.4}, x_{4.5}\}; \\ FSS_5 = x_5 = \{x_{5.1}, x_{5.2}, x_{5.3}, x_{5.4}\}; \\ FSS_6 = x_6 = \{x_{6.1}, x_{6.2}\}; \\ FSS_7 = x_7 = \{x_{7.1}, x_{7.2}, x_{7.3}\}; \\ FSS_8 = x_8 = \{x_{8.1}, x_{8.2}, x_{8.3}, x_{8.4}, x_{8.5}, x_{8.6}\}; \\ FSS_9 = x_9 = \{x_{9.1}, x_{9.2}, x_{9.3}, x_{9.4}\}; \\ FSS_{10} = x_{10} = \{x_{10.1}, x_{10.2}, x_{10.3}, x_{10.4}\}; \\ FSS_{11} = x_{11} = \{x_{11.1}, x_{11.2}, x_{11.3}\}. \end{cases} \quad (3)$$

The composition of the modeled FM object, may be determined by the set of FSSj, verified by criteria (4), (5). Taking into account the fact that at the initial construction stage there is no formed solution as to the module structure, it is necessary to create a list of typical ready functional devices (FD) that may be included in the composition of FMi of the given direction (roll packing material supply). The correspondent information was given by specialists of “Packing technologies” CSC, Ukraine, according to existing technical solutions of packing machines.

### 3. 2. The substantiation of the modeling methodology of FMM within the packing machine

Optimality criteria values that may be known beforehand or determined experimentally at comparing all FDi on one mi are attributed to each FDi. The set problem was considered as an optimization one-criterion that is:

$$\begin{cases} \sum_{i=1}^n P_i x_i \geq P_{i(giv)} \rightarrow \max, \\ x_i \in FD_j; i, j = \overline{1n}; \end{cases}$$

$$\begin{cases} \sum_{i=1}^n OEE_i x_i \geq OEE_{(giv)} \rightarrow \max, \\ x_i \in FD_j; i, j = \overline{1n}; \end{cases} \quad (4)$$

$$\begin{cases} \sum_{i=1}^n C_{Ri} x_i \geq C_{R(giv)} \rightarrow \max, \\ x_i \in FD_j; i, j = \overline{1n}. \end{cases}$$

The optimization was conducted by extreme values  $P_{i(giv)}$ ,  $OEE_{(giv)}$ ,  $K_{\Gamma(giv)}$  – correspondingly extreme values of the productivity criterion, overall equipment effectiveness criterion; readiness coefficient. Then the problem of assessing the Structure of FM for the packing machine by searching Pareto-effective solutions is solved [9]. At using multicriteria optimization, the integral criterion with the extremum direction is used:

$$F(x) = \{f_1(\Pi_{\phi_i}), f_2(OEE_i), f_3(C_{Ri})\} \rightarrow \max, \quad (5)$$

That is the considered optimality criteria are combined in one integral criterion, and the extremum direction is indicated. For getting the final variant of FMi synthesis, the method of optimal structure variant search is used. It is based on the principles: separation of the set

of dominating alternatives and choosing of an optimal one and exclusion of the probability of eliminating potentially more effective variants comparing with ones, accepted for further consideration [10].

#### 4. Results

The optimization synthesis of PM assembling was realized successively, based OEE criterial assessment. Each research stage is in solving a certain local problem, which results are initial data for the next one [10]. We obtained the hierarchic structure analysis of a separate module subsystem (**Fig. 2**) as a subprogram in Excel for FM of the packing machine for fine-piece food products and **Table 2** of the description of the best variant of FM assembling.

OEE-calculating program					
Insert your data in free squares and press on the page for calculating the OEE index. Take a cursor to boxes with red angles for getting additional information					
Perion/equipment	Insert date/time period/equipment name				
Time	T3	Total operation time tact/min	22	min	
	DTL'	Planned downtime of FMMi	2	min	
	DTL''	Non-planned downtime of FMMi	1	min	
	OT	Operation time (A-B-C)	19	min	
Availability Rate=		A=OT/(T3-DTL')		95.00%	
	TP	Total production performance	200	pieces	
	IRR	Ideal time of operation/cycle	22	pieces/min	
Performance Rate=		:(TP/OT)/IRR		47.85%	
	m	Deviation/spoilage	3	pieces	
Quality Ratte		Q= (TP-m)/TP		98.50%	
result	OEE	A Availability		P Performance	
	44.77%	95.00%		47.85%	
		Q Quality		98.50%	

**Fig. 2.** Generalized methodology of OEE calculation for FM of the packing machine for fine-piece food products, based on the Excel subprogram

The software of the system is a totality of programs (program means), used in its composition for describing the process of its functioning. All software elements (means, programs) are divided in groups by their participation in one or another software function realization. As a result, functional subsystems are created. A software function is a management of concrete technical (calculating) means of the FM system for food product packing. Functional subsystems may have different importance of system functioning as a whole and correspondingly may be characterized by different requirement levels. That is why in a multifunctional system the software may participate in realization of several functions, connected with transportation of a food product, replacement of the functional device of the packing machine, maintenance of the technological operation mode of the packing process and so on. It is also taken into account, that not all programs (program means), included in the packing machine software, must participate in realizing a certain function.

It has been established, that the roll packing material supply FM is one of first that begin operating in the technological process. The FM analysis results are presented on **Fig.3**.

Taking into account recommendations [9] as to the value of satisfactory OEE for functional devices of the packing equipment, the obtained calculation results (**Fig. 3**) allow to determine the optimal assembling of the functional device in the structure of FM1 of roll packing material supply. In this solution it is the variant x72.

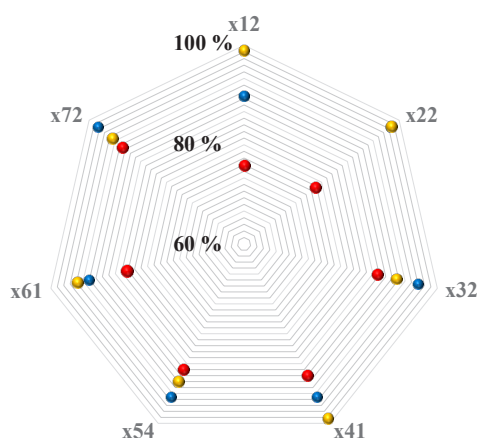
As a result of solving this problem, the FM1 prototype was created. At the comparative analysis with the existing equipment, the automatic functional device was modeled.



**Table 2**

The assessment of the FM assembling solution in the packing machine composition

FSSj	Description of the packing machine FSSj	OEE <sub>max</sub>	Cr	P
x12	Device of a roll-keeper with a digital driver for step-by-step engines with insert bluetooth and NFC systems	81.91 %	99 %	92.31 %
x22	Forced combined electropneumatic-electromechanical device (GSP 75 EVO)	83.75 %	99 %	98.36 %
x32	friction HDL-450-XSS (2 pneumatic winding friction shafts with independent friction clutches with width 25 mm)	90.74 %	94 %	97.09 %
x41	Electropneumatic device with a forcedly material loop, stretched by a roller	92.04 %	99 %	95.54 %
x54	Device with pneumatic breaking by a tape of the periphery	90.99 %	93 %	95.54 %
x61	Electromechanical device for forced stretching of a loop	88.17 %	96 %	94.04 %
x72	Electropneumatic device. based on a rodless pneumocylinder	93.46 %	96 %	98.36 %

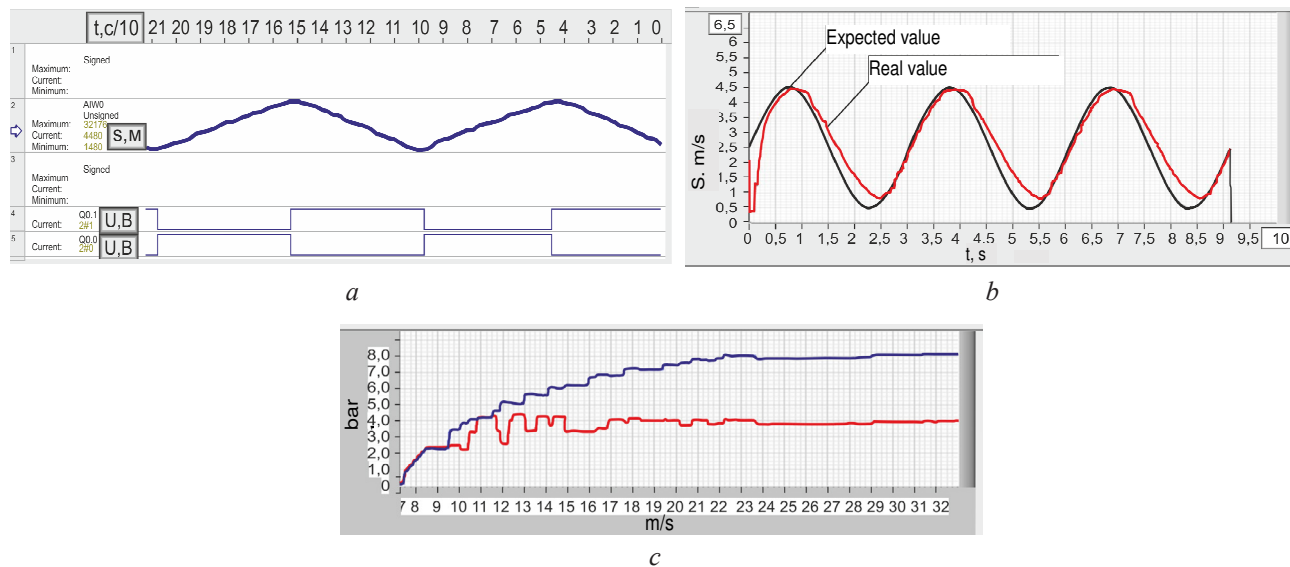


**Fig. 3.** Diagram of the criterial assessment of FD1 in FM1 of roll packing material supply by the calculation results **Table 2**

At verifying the operating quality of the FM1 prototype, a roll of packing material, the mass  $m=3\text{kg}$  was used; the friction coefficient of the material by the roller surface  $f_1=0.3$ ; roll width – 300 mm, roll diameter – 75 mm, FM planned productivity – 70pack/min. Processing parameters were reloading operation duration and roller (fixed on the pneumocylinder frame) replacement trajectory, assessed by coordinates  $x, y$  and stretching angle. The values  $T_i$  ( $i = 1, 2, 3...n$ ) were put to the calculating table in Excel (**Fig. 1**). The number of measurements was set, based on previous researches and calculations. The obtained and processed results of the experiment were compared with ones of analytic calculations, at that parameters, identical to the experimental ones, were accepted as initial data. The values of pneumocylinder friction coefficients, ones of speed renovation and constructive parameters of packages were determined by the accepted methods [1, 9]. Thus, there was verified the adequacy of the mathematical models to the real processes. The operation duration of replacing the frame with the stretched roller was calculated.  $T_i=0,65\text{s}$ . Then the relative deviation of the operation duration, obtained by theoretical studies, from the experimental ones, is:

$$\delta_1 = \frac{0,71 - 0,65}{0,71} \cdot 100 \% = 7,14 \%$$

Based on the obtained values of the assessment of the FM assembling solution in the composition of the packing machine, the experimental stand was synthesized, and a series of experiments with the correspondent load of the experimental FM, was successively realized. Its results are presented on **Fig. 4**.



**Fig. 4.** Kinematic and force parameters of the operation roll packing material supply by FM, based on a rodless pneumocylinder: *a* – dependence of the roller replacement way on time and signal of the managing system; *b* – comparative characteristic of theoretical and experimental values of roller replacement speed on time; *c* – characteristic of the pressure change on time, in the point of arterial feed with and without a booster

The maximal acceleration  $\ddot{S} = 4,5 \text{ m/s}^2$ . The report is according to the results of the planned three-factor experiment on studying FM of roll packing material supply and stretching by a roller. The equation of the mathematical-static model was obtained at the analysis:

$$t = 0,685 - 0,001 \cdot S - 0,003 \cdot m + 0,015 \cdot S^2 - 0,007 \cdot m^2 + 0,009 \cdot f_t^2 + \dots \\ \dots + 0,007 \cdot S \cdot m - 0,002 \cdot S \cdot f_t + 0,008 \cdot m \cdot f_t,$$

where  $f_t$  – friction coefficient in the roll-keeper,  $S$  – replacement coordinate of a stretching device roller,  $m$  – residual mass of a packing material roll. The obtained equation was verified for adequacy to the real studied process that is correspondence of the obtained results to the real (true) values.

Pressure  $P$  (bar) on **Fig. 4.** characterizes changes in the point of arterial feed of a roller drive. The upper graph describes the pressure characteristic with a booster (pressure intensification coefficient =2) that provides more efforts in the system of roll packing material tape stretching.

## 5. Discussion

The realization schemes and models of step-by-step multicriterial analysis are presented on the example of FM of roll packing material supply for the packing machine with different FSSj, the expedience of their use for different criteria of optimization problem is substantiated. There is substantiated the use of the OEE, criterion with joint properties that reflects the generalized assessment of FMj with a maximin (minimax) criterion by the compromise principle. The compromise principle is based on the idea of optimality of FMj for the machine for packing food products at adding the each next functional module to its composition. The experimentally obtained data confirm adequacy of the offered method for assessing assembling solutions. Especially, the total mass of a roll  $m=3 \text{ kg}$ ; the run to the stop position by the coordinate  $s=300 \text{ mm}$  (at maximal run 400 mm); the arterial air pressure  $AP=0.8 \text{ MPa}$ . The pressure fluctuation amplitude on the proportional regulator MX-PRO  $A=2.0$ ; the frequency of the given impulse  $n_j=2.5$ . The value of initial pressure on the input to a pneumatic intensifier (booster) is within 4 bar. The maximal acceleration  $\ddot{S} = 4,5 \text{ m/s}^2$ . **Fig. 4** presents the graphs of the replacement change of a film stretching roller in time, in the process of its replacements with an operating frame of a rodless cylinder. And also the graphs of the pressure change in working chambers of a pneumocylinder at operating and free



running; the graphs of the pressure change on the supplying pneumoarteria to FM with a pneumatic booster (initial pressure stabilizer with the intensification coefficient). The analysis of the graphs testifies that the type of changes of the roller movement coordinates, determined analytically, corresponds to the real reloading process. The deviation of the experimentally obtained data from the theoretical ones don't exceed ones, accepted at solving similar engineer problems (up to 10...15 %).

## 6. Conclusions

1. The realization schemes and models of step-by-step multicriterial analysis have been presented on the example of FM of roll packing material supply for the packing machine with different FSSj, the expedience of their use for different criteria of optimization problem has been substantiated. The FM prototype has been synthesized.

2. Based on the Excel subprogram, there have been offered the calculations of the assessment of the packing equipment with the complex assessment criterion OEE for different FM assembling for packing machines of piece and fine-piece products.

3. The FM of roll film material supply using the microprocessor managing device MX-PRO, maintaining the sinusoidal law of packing machine stretching roller movement has been developed. The optimal characteristics of the technical system: maximal acceleration of the initial operating chain (rod) as  $2 \text{ m/s}^2$ , fluctuation amplitude  $A=2.0$ ; frequency of the given impulse  $n_j=2.5$  have been established. There has been substantiated the use of the OEE, criterion with joint properties that reflects the generalized assessment of functional modules with a maximin (minimax) criterion by the compromise principle. The optimization synthesis of the structure of the packing machine has been conducted by the Pareto method with the own developed subprogram of PP Exel.

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