Decision support system for resource-saving control of extruders at multi-assortment productions of polymeric films

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Annotation. A decision support system (DSS) is described, which helps operators to solve the problem of resource-saving control of extruders of various types used in the production of multi-assortment packaging polymer films (PF). It includes an industrial data mining subsystem for predicting the state of extruders and film quality, a subsystem for evaluating the performance of extruders, an information subsystem, and a data visualization subsystem for building trends of controlled and calculated parameters, interfaces for the extruder operator, administrator and knowledge engineer. The results of testing according to the data of extruders produced by PF at factories in Russia and Germany confirmed the efficiency of the DSS. The use of DSS allows you to save the resource of extrusion equipment, increase the time periods between its stops, and reduce the repair time.

Introduction

The intense competition in the global market for packaging products for the pharmaceutical and food industries and the tightening of environmental requirements for them stimulate companies that produce rigid and flexible packaging PFs to actively develop and introduce high-tech innovative technological solutions into production. Technological innovations consist primarily in improving the structure and consumer-oriented (dimensional, barrier, strength, optical) characteristics of PF, modernizing technologies and equipment for the production, primary and secondary processing of PF, improving control systems for key production stages in order to ensure resource saving and high quality products.

Modern control systems for technological processes, including resource-saving control systems, solve the control problem mainly on the basis of information about the parameters of the state of the technological process and indicators of product quality. However, in production systems that use structurally complex, expensive and often reconfigurable technological equipment, the condition of this equipment plays a key role, which largely determines the productivity of the process and the quality of the products. Solving the problem of resource-saving control of extrusion equipment is significantly complicated for the following reasons. Reconfiguration of production lines for various types of PFs, differing in the number and types of materials of barrier and structural layers, requirements for consumer-oriented quality indicators, and productivity occurs on average 30 times a month (the range of lead times for production orders, depending on their volume, ranges from several hours to several days). A wide range of PFs (for example, 10 types of rigid pharmaceutical PFs based on polyvinyl chloride) and different requirements for line productivity determine the need to use
various types of extruders for processing polymer compositions. To prepare the extrudate from which PF is made, single-screw, oscillating and twin-screw (with different directions of screw rotation) extruders are used [1, 2]. During operation, the extrusion equipment is naturally worn out, which requires periodic cleaning and preventive maintenance to maintain the extruders in working order. However, an early shutdown of the line for cleaning or repairs leads to a decrease in the volume of PF produced and, as a consequence, to non-fulfillment of orders for PF manufacturing on time. This is especially critical for the production of multilayer PF’s, in which it takes 2 to 12 hours to reach the mode after stopping the extrusion equipment. On the other hand, overdue cleaning or repair of extruders leads to substandard PF due to rejects (for example, to the appearance on the PF surface of helices, inclusions of unmelted polymer, yellow-brown destructive stripes, black dots, uneven PF coloration). Therefore, timely diagnostics of the condition and maintenance of extruders can reduce the downtime of lines (one day of downtime of one line brings about 3 million rubles of losses due to non-produced PF with a mass of ~24000 kg with a productivity of ~0.278 kg/s), reduce the cost of production and prevent the appearance of more serious malfunctions. For example, failure of the extruder screw drive gearbox due to breakage of the toothed gears or the block of thrust bearings (perceiving the axial pressure of the screw) due to the formation of cracks in them require long and expensive repairs. Many possible emergency situations (ES) associated with faults in extruders, the reasons for their occurrence and at the same time incomplete information about the actual state of the elements of extruders lead to the fact that in practice they rely on expert knowledge about ES, their causes and recommendations for elimination formalized in the form of an appropriate knowledge base (KB). Thus, to build an effective PF production management system, it is relevant to develop a computer decision support tool for operators on resource-saving control of extruders and control in ES, which is based on processing big data and knowledge of experts (management production personnel). Big production data includes both monitored parameters of equipment condition, process and PF quality indicators, as well as calculated indicators of extruder reliability and extrudate quality.

The aim of the work is to develop a flexible (adjusted to the characteristics of PF production) problem-oriented DSS, which allows, based on methods of processing large production data, mathematical models (MM) for calculating parameters uncontrolled in production and knowledge base of experts about ES associated with equipment malfunctions, to solve problems of resource-saving control and management in the ES for various types of extruders. The proposed DSS is a development of the computer systems for monitoring and controlling the quality of PF used in extrusion and extrusion-calender production of PF [3–4]. These systems are based on the technologies of systematic multi-method mining of big production data, mathematical modeling, and presentation of expert knowledge and visualization of production characteristics [5, 6]. DSS allows you to reduce the time for making management decisions, increase the time periods between equipment stops, increase productivity and reduce irrecoverable waste (PF rejects).

1. Formulating the problem of resource and energy saving control of extruders. DSS architecture

The information description of the extrusion process as a control object is shown in Figure 1. The information description includes vectors of input parameters $X(t)$, variable parameters $U(t)$ and output parameters $Y(t)$. Here $t$ is time.

Input parameters vector $X(t) = \{ T_{film}(t) – PF type; M_{ext}(t) – the brand of the $j$-th extruder, determined by the type of extruder, the diameter and relative length of its screw, $j = 1, \ldots, n_{ext}(t)$; $n_{ext}(t) – the number of extruders used at the stage of extrudate preparation (determined by the number of layers of the PF produced); U_{0j}(t), U_j(t) – nominal and current voltage on the electric motor of the screw drive of the $j$-th extruder, V; S_{0j}(t), S_{j}(t) – rated slip and synchronous speed of the electric motor rotor, min$^{-1}$; k_j(t) – motor load factor; $\tau_0(t) – service life of electric motor insulation at rated
voltage and load, h; \( n_{j}(t) \) – number of \( j \)-th extruder failures; \( \tau_{j}(t) \) – the time of normal operation of the \( j \)-th extruder between \((l-1)\)-th and \( l \)-th failures (time between failures), h;.

\[
X(t) = \{ T_{\text{film}}(t), M_{\text{ext}}(t), U_{\text{eq}}(t), T_{\text{eq}}(t), \}
\]
\[
\{ S_{k}(t), N_{j}(t), k_{j}(t), \tau_{j}(t), U_{j}(t), n_{j}(t), \tau_{j}(t) \}
\]
\[
l = 1...n_{j}, j = 1...n_{\text{ext}}
\]

\[
Y(t) = \{ G_{j}(t), T_{\text{eq}}(t), Q_{\text{film}}(t), P_{j}(t), \tau_{j}(t), V_{\text{mdj}}(t), j = 1...n_{\text{ext}} \}
\]

\[
U(t) = \{ N_{j}(t), T_{\text{eq}}(t), T_{\text{eq}}(t),
\]
\[
k = 1...n_{j},
\]
\[
q = 1...n_{\text{eq}}, j = 1...n_{\text{ext}}
\]

Fig. 1. Information description of the extrusion process as a control object.

Variable parameters vector \( U(t) = \{ N_{j}(t) \) – screw speed of the \( j \)-th extruder, min\(^{-1}\); \( T_{\text{eq}}(t) \) – barrel temperature in the \( k \)-th heating zone, °C; \( n_{eq}(t) \) – number of heating zone of the barrel; \( T_{\text{eq}}(t) \) – temperature of the extruder die in the \( q \)-th heating zone, °C; \( n_{eq}(t) \) – number of heat zones of the die \}.

Output parameters vector \( Y(t) = \{ G_{j}(t) \) – throughput of the \( j \)-th extruder, kg/h; \( T_{\text{eq}}(t) \) – extrudate temperature, °C; \( Q_{\text{film}}(t) \) – vector of quality indicators (consumer characteristics) of PF (the number of black dots, destruction bands, inclusions of unmelted polymer, helices on a given area of the PF web); \( P_{j}(t) \) – probability of uptime operation of the \( j \)-th extruder; \( \tau_{j}(t) \) – service life of motor insulation at current voltage and load, h; \( v_{\text{mdj}}(t) \) – extruder drive vibration speed, mm/s \}.

Based on the informational description, the task of resource-saving control of extrusion equipment is formulated, which consists in the following:

1) for the given input parameters \( X(t) \), by varying the control actions in the regulatory ranges \( U(t) \in [U_{\text{min}}(t); U_{\text{max}}(t)] \), determine their values \( U^{*}(t) \) that ensure the maximum throughput of the extrusion line and the specified quality of the PF surface

\[
G(X(t), U^{*}(t)) = \max_{\text{var} U(t) \in [U_{\text{min}}(t); U_{\text{max}}(t)]} G(X(t), U(t)),
\]
\[
Q_{\text{film}}(X(t), U^{*}(t)) \leq Q_{\text{film}}^{\text{max}} (t)
\]

provided that the required parameters of the extruders performance

\[
P_{j}(t) \geq P_{\text{min}}(t), \quad \tau_{j}(t) \geq \tau_{0}(t),
\]

where: \( G(t) = \sum_{j=1}^{n_{\text{ext}}} G_{j}(t) \); \( Q_{\text{film}}^{\text{max}} (t) \) – vector of maximum permissible values (for a given type of PF) for the number of surface defects of various types of PF; \( P_{\text{min}}(t) \) – minimum acceptable probability of uptime operation of extruders.
2) control problem in the ES is as follows: for a given method of production $M_P$, PF type $T_{film}$ and equipment configuration of the stage of extrudate preparation based on the description of ES $St$, associated with faults in extruders and characterized by deviations of the current values of the parameters of the state of extruder elements beyond the regulatory threshold limits, and the reasons for their occurrence $R_S$, determine the true cause of the extruder fault $R_{S^*}$ and generate an $R_c$ advice containing a sequence of actions for the extruder operator to correct the fault.

To solve this problem, a DSS was developed, the structure of which is shown in Fig. 2. It includes the following components: a subsystem for industrial data mining; a subsystem for evaluating the performance of extrusion equipment; an information subsystem; a data visualization subsystem for building trends of controlled and calculated parameters and displaying management tips; interfaces for the extruder operator, administrator, and knowledge engineer.

The intellectual analysis subsystem allows predicting the throughput of extruders, extrudate temperature and PF quality indicators, as well as the parameters of the extrusion equipment condition. To process large production data in order to predict the controlled output parameters of the extrudate preparation stage, the principal component method (PCA) and multiple regression analysis are used. PCA allows you to reduce the dimension of big data, while losing the least amount of information. When constructing a PCA model, the number of principal components is determined, which provides a fairly accurate description of the structure of production data. The first principal component determines the direction in the space of the initial data, along which the set of objects has the maximum variance. The second principal component is constructed in such a way that its direction is orthogonal to the direction determined by the first principal component, and it explains as much of the residual variance as possible, etc. [7]. After determining the principal components, a structurally parametric synthesis of linear multifactorial regression models is carried out, describing the dependences of the output parameters $y$ on the corresponding control actions $u_p, p = 1, \ldots, n_U$ and their double interactions and allowing the prediction of output parameters for new values of the control actions:

$$y = a_0 + \sum_{p=1}^{n_U} a_{p} u_p + \sum_{p=1}^{n_U-1} \sum_{s=2}^{n_U} a_{ps} u_p u_s \quad (s > p). \quad (3)$$

To find estimates of the coefficients of the regression model (3), the least squares method is implemented. The procedure for checking the adequacy of the synthesized models includes the use of the Fisher criterion and the coefficient of determination [8].

The subsystem for calculating the reliability characteristics of extrusion equipment contains a MM library for calculating the service life of the motor insulation, the probability of uptime and failure of the extruder. To estimate the margin of performance of each extruder, the DSS calculates the probability of failure-free operation $P_j(t)$ and failure $Q_j(t)$ of the extruder:

$$P_j(t) = \exp(-\lambda_j t), \quad Q_j(t) = 1 - P_j(t),$$

where $\lambda_j$ is the failure rate ($c^{-1}$), which is assumed to be constant (independent of the operating time of the extruders) for the period of normal operation of the extrusion equipment preceding the wear period, and calculated from statistics on the number of sudden failures $n_{fj}$ and the time of normal operation between failures $\tau_{jl}$.

The service life of the insulation of the electric motor of the $j$-th extruder at the current voltage and load, which characterizes the service life of the insulation, is determined as follows:

$$\tau_j = \tau_{0j}/R_{\Delta U_{j}}$$

where $R_{\Delta U_{j}}$ - coefficient depending on the relative voltage deviation on the electric motor of the screw drive of the $j$-th extruder $\Delta U_{MDj} = [U_{MDj}(t) - U_{0j}]/U_{0j}$ and the load factor of the electric motor $k_{MDj}$ and calculated as follows:
If the current voltage on the electric motor is not measured, then it can be calculated depending on the current rotor speed of the electric motor \( N_{MRj}(t) = f[N_{j}(t)] \) according to the following formula:

\[
U_{MDj}(t) = \sqrt{k_{MDj}^2 S_{0j} N_{sj}/N_{MRj}(t) - N_{MRj}(t)} U_{0j}.
\]

The information subsystem allows you to customize the DSS for various production methods of PF \( M_p \), types of PF \( T_{film} \), brands of extruders \( M_{Ej} \). The information subsystem contains a database of characteristics of PF production methods, types of PF and brands of extruders, DBs of equipment and process state parameters monitored and calculated by MM, parameters of extruder reliability, extrudate and PF quality, a database of statistics on extruder failures databases are built on the basis of a relational data description model.

![Fig. 2. Functional structure of DSS for extruder control](image)
example frames obtained on the basis of a prototype frame. Figure 3 shows a frame example of an unrecoverable ES associated with increased vibration of the equipment, which requires stopping the extruder to eliminate it.

Fig. 3. Information structure of the frame-example \( Fr_1 \) “Emergency situation “Increased vibration in the extruder screw drive”

The control knowledge needed to identify faults in extruder elements, determine their true causes (which in the current production environment lead to faults) and generate tips for troubleshooting are represented in the form of production rules: \( Pr := IF (condition), THEN (consequence) \). An example of a focusing rule is: IF (there is an ES "Increased vibration in the drive of the extruder screw") ∧ (the reason "Mechanical defects (cracks) in thrust bearings" is the true cause of the occurrence of an ES), THEN (the recommendation to eliminate the ES has the form "Stop the extruder, check and replace defective thrust bearing ")\[9-10\].

The DSS data visualization subsystem allows you to build trends in technological parameters of the extrudate preparation stage, parameters of the state of extrusion equipment, indicators of the quality of extrudate and PF for a given time interval, display the values of extruder reliability indicators, display the generated advice on resource-saving management and control in the ES.

DSS software is implemented on the .NET Framework platform using the object-oriented programming language C#. DSS information support was developed in the relational database management system SQL Server.

2. Results and discussion

DSS was tested according to the data on the stages of extrudate preparation of industrial production of packaging PF at factories in Russia and Germany. Data for testing was collected on extrusion-calender production of rigid single-layer flat PF based on PVC for packaging pharmaceuticals in two days of production and on extrusion production of flexible multilayer tube PF based on low density polyethylene for packaging meat and meat products for a week of production. The production data is large. The data array of the stage of extrudate preparation in an oscillating extruder of extrusion-
calendering production equipped with a die contains more than 126 thousand numerical values for 10 monitored parameters of the state of equipment, process and PF quality indicators. The extrusion production data set contains over 637 thousand values for 107 controlled technological parameters of the coextrusion process on 11 single-screw extruders connected to an annular die. Heat-shrinkable PF, manufactured by blown coextrusion, contains 11 barrier and structural layers, has a reduced thickness (40-60 microns for packing meat without bones with a thickness of each layer of 3-5 microns), is characterized by a reduced oxygen permeability, which initiates the oxidation of fats contained in meat products. This allows not only preservation of the original quality of meat products during transportation over long distances and storage in various environmental conditions, but also increases the period of its sale. To obtain a PF with the specified unique characteristics and the required performance, it is necessary to ensure the uninterrupted operation of the extrusion equipment for a long time and the preparation of an extrudate suitable in terms of material homogeneity and thermal state for further molding into a sleeve PF. A computer tool that helps operators to solve these problems is a DSS with an ergonomic graphical user interface. DSS allows visualizing large production data received from the control object in the form of trends in technological parameters of the process (Fig. 4) and parameters of the state of extrusion equipment (Fig. 5) with the display of threshold regulatory values of these parameters on the operator interface.

Fig. 4. Trends of monitored technological parameters of the process in the extruder $j = 3$ of the packing multilayer blown PF production
DSS allows synthesizing linear multivariate regression models to predict the output parameters of the extrudate preparation stage (throughput, extrudate temperature) depending on the control actions on the process. Figure 6 shows the trends of the measured (1) and predicted (2) temperature of the extrudate at the exit from the extruder $j = 2$ for the production of packaging multilayer tubular PF. The root-mean-square deviation of the calculated values from the measured ones is 3%.

To assess the operability margin of the equipment, the DSS based on statistical data on extruder failures during normal operation and on the basis of the exponential law of the distribution of uptime, calculates the dependence of the probability of uptime for each extruder on its operating time (Fig. 7).
Conclusions
A reconfigurable DSS has been developed for resource-saving control of extrusion equipment in multi-assortment PF production, the core of which is a subsystem for data mining and a subsystem for calculating the reliability of extruders. The DSS allows you to build trends in the parameters of the state of processes and equipment at the stage of extrudate preparation, predict the throughput of extruders and the temperature of extrudate using synthesized regression models, evaluate the reliability (reliability, durability) of extruders and the quality of extrudate, and form tips for eliminating ES associated with extruder failures.

The DSS has been successfully tested on modern high-tech industrial production of multi-assortment packaging PF in Russia and Germany. The use of DSS helps to increase the productivity of lines, reduce the scrap of PF and increase the profitability of production in general.

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