Computer System for Processing Industrial Information for Controlling the Production of Multi-Assortment Polymeric Films

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Abstract*—The results of the development of a computer system for processing big data and expert knowledge of multi-assortment production of polymeric films have been presented. The computer system is an effective tool that helps operators to make decisions on the polymeric film production control in a routine mode and in the event of a defect. It is adjusted to the characteristics of polymeric film production and allows making advices on the choice of controlling actions at the main stages of production, ensuring the specified quality of the polymeric film (in the routine mode) and entering quality indices into the regulatory restrictions (in the event of a film defect). The system integrates production data obtained from various sources (a SCADA system, a video monitoring system, a thickness gauge, etc.). The information ware of the system includes a bank of data and knowledge on polymeric film production characteristics. Mathematical models are used to calculate quality indices of intermediates (extrudate) and products (polymeric film) that are not monitored in production. Data mining methods are used to compress, cluster complete sets of measured and calculated data, and predict consumer characteristics of the film. Interfaces of managerial production staff are used to visualize the results of industrial information processing (trends in production parameters, 3D graphs of the dependencies of quality indices on controlling actions, areas for quality indices, advices on control). The results of testing the system according to the data of the productions of rigid polymeric films for pharmaceutical and food packaging on the extrusion-calendering lines of factories in Russia and Germany have confirmed the system operability. The effectiveness of the system application is due to increased efficiency of decision-making on control and ensuring resource saving in production by improving the quality of the polymeric film and reducing non-returnable waste (defective film).

Keywords*—computer system, processing industrial information, big data, expert knowledge, methods of data mining, mathematical models, product quality control, production of polymeric films

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I. Introduction

Rigid films based on polyvinyl chloride (PVC), polypropylene, polyethylene terephthalate are characterized by high resistance to shock loads, low gas and vapor permeability, thermoforming ability, environmental safety and reasonable price. Therefore, they are widely (more than 60 %) used in the pharmaceutical and food industries as packaging materials. Productions of rigid polymeric films are continuous large-capacity energy-intensive multi-assortment chemical-technological systems with recycling. Recyclables are used to return waste (shredded film edges) for recycling in order to save resources. Chemical-technological systems operate in the modes of frequent changeovers for the production of new types of films (on average 30 times a month) and are characterized by a variety of parameters of raw materials, equipment, process, products (more than 100) and complex relationships between them (about 800), big volumes of monitored data (15.8 million values of production parameters per month) obtained from various data sources. At the same time, the incompleteness of information about the state of the chemical-technological system occurs due to the limited possibilities of automatic monitoring in the production of a number of indices of the quality of intermediates and target products. Extrudate (a mixture of a film-forming polymer with additives in a viscous state) is the main intermediate product of production, regardless of the method of film production being implemented (calendering, cast extrusion). The material uniformity and the thermal state of the extrudate determine the quality of the film surface (the presence of defects, color). The subjective visual assessment of the extrudate appearance by the operator and the frequent lack of data on such important consumer characteristics of the film as the thickness difference, color coordinates, the shrinkage in machine direction orientation and transverse direction orientation, lead to the need to make control decisions based only on the operator's production experience. This causes an increase in film defects (non-returnable waste), a decrease in throughput, and an increase in the resource and energy intensity of the chemical-technological system in production with returnable waste, the

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characteristics of which (for example, color) differ from the characteristics of the produced film. A lot of possible abnormal situations describing various types of defects of the extrudate and the film, and a lot of reasons for the occurrence of abnormal situations are an important feature of the production of films. Expert knowledge about abnormal situations is accumulated in the technological regulations of production and instructions for controlling production in the event of a defect.

It is necessary to generate and process complete data on the state of the chemical-technological system for purposeful control of film production. This involves the use of mathematical modeling methods for calculating the quality indices of the extrudate and the consumer characteristics of the film [1] and methods of data mining for compressing, clustering production data and predicting production efficiency indices [2, 3]. Therefore, the development of a flexible computer system that allows processing production data of big volumes and production expert knowledge is relevant. The data sets include the values of production parameters, which are both measured and calculated using mathematical models. Expert knowledge is formalized in the form of a knowledge base. The making advices for operators on production control in a routine mode and in abnormal situations is the purpose of computer processing industrial information. The development of the computer system provides digitalization of the main stage of the life cycle of packaging films, which is the production of films with waste recycling. The use of the computer system helps to expand the range and improve the consumer characteristics of films, reduce the resource and energy intensity of the chemical-technological system, and therefore increase the profitability and competitiveness of production in the market.

II. Setting Production Control Tasks

System analysis of productions of various types films T_{film}, implementing different methods of film production M_{prod}, has allowed us to identify their main stages (s = 1 – extrudate preparation, s = 2 – forming an extrudate into a film, s = 3 – fixing the film structure by cooling).

The hardware and technological design of the stages is characterized by the flexibility necessary for processing a wide range of polymers. Flexibility means a variety of configurations of production units (extruders, forming dies, calenders, take-off and cooling multi-roll devices).

The information description of the film production as a control object is compiled based on a system analysis (Fig. 1). The following designations are adopted in Fig. 1: X, U, F, Y are vectors of input parameters, controlling and disturbing actions, output parameters; C_{line} is configuration of the production line; R_{film}, Q_{film}^0 are formulation and requirements for the quality of the film; C_{EQs}, Γ_{EQs} are configuration and geometric parameters of the s-th stage unit; N_h, N, T_{bk}, G_{ci} are speeds of the hopper and extruder screws, the temperature of the k-th heat zone of the extruder barrel, the flow rate of the i-th colorant supplied to the extruder; V_{cl}, T_{cl}, V_{tp}, T_{tp}, V_{clq}, T_{clq} are circumferential speed and temperature of the l-th roll of the calender, the p-th take-off roll and the q-th cooling roll; τ_m^{left}, τ_m^{right} are operating times of the motors moving the external calibration roll of the calender (for controlling the film thickness [4]); x, r_S are spatial skew of the internal calibration roll and the counter-bending force of the external calibration roll of the calender (for controlling the film thickness difference [4]); Ψ_{ext} is extrudate reserve in the calender feed gap; T_{air} is the air temperature in the workshop; $Y_1^{mes} = \{L_{ext}, a_{ext}, b_{ext}\}$, $Y_2^{mes} = \{\delta_f, n_{black}, n_{burn}, n_{gel}, n_{fiber}, n_{air}, n_{hol}, L_f, a_f, b_f\}$, $Y_3^{mes} = \{S_{fl}, S_{fc}\}$ are measured output parameters of the stages; $Y_1^{calc} = \{I_d, \gamma, \varphi_s, L_{ext}^c, a_{ext}^c, b_{ext}^c, \Delta E_{ext}\}$, $Y_2^{calc} = \{\delta_f^c, D_\delta, L_f^c, a_f^c, b_f^c, \Delta E_f\}$, $Y_3^{calc} = \{S_{fl}^c, S_{fc}^c\}$ are output parameters calculated using mathematical models; L_{ext}, a_{ext}, b_{ext}, L_f, a_f, b_f are the color coordinates of the extrudate and the film; n_{black}, n_{burn}, n_{gel}, n_{fiber}, n_{air}, n_{hol} are numbers of defects of various types (black points, yellow-brown stripes, inclusions of non-molten polymer, fibers, air bubbles, holes) on a given area of the film; I_d, γ, φ_s are the index of thermal destruction, the mixing degree and the volume fraction of the solid polymer in the extrudate; ΔE_{ext}, ΔE_f are deviations of the color of the extrudate and film from the standard; D_δ is film thickness difference.

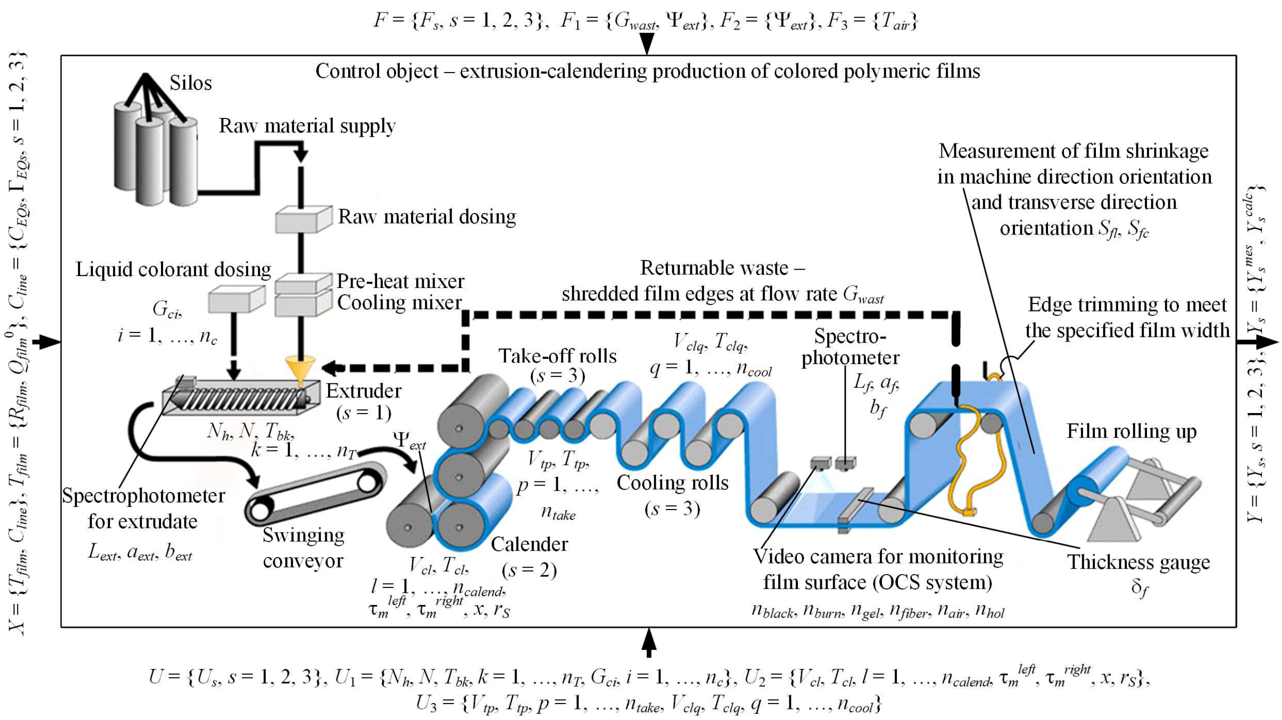

Fig. 1. Information description of film production as a control object (on the example of extrusion-calendering production)

The tasks of controlling the production of films, solved by the computer system, are set on the basis of an information description of production.

1) The task of controlling in a routine mode: it is necessary to process production data $\{U_s,\ Y_s^{mes},\ Y_s^{calc},\ s = 1, 2, 3\}$, using data mining methods, and determine the values of controlling actions $U_s \subset [U_s^{\min};\ U_s^{\max}]$, $s = 1, 2, 3$, which in the conditions of disturbances F_s ensure compliance with the requirements of the regulations for the quality indices of the extrudate and film $|Y_{s,g}^0 - Y_{s,g}| \leq \Delta_{s,g}^{\max}$, $s = 1, 2, 3$, $g = 1, \ldots, n_s$ for a given type of film T_{film}, film production method M_{prod} and production line configuration C_{line},

where $U_s^{\min}$, $U_s^{\max}$ are regulatory restrictions on controlling actions; $Y_{s,g}^0$, $\Delta_{s,g}^{\max}$ are the set value and the maximum permissible deviation from the set (or threshold) value for the g-th output parameter; n_s is the number of output parameters at the s-th stage of production;

2) The task of controlling in abnormal situations: it is necessary to perform an analysis of expert knowledge about abnormal situations St, described by deviations of the values of the extrudate and film quality indices for regulatory restrictions $Y_{s,g}^{\min} - Y_{s,g} > \Delta_{s,g}^{\max} \vee Y_{s,g} - Y_{s,g}^{\max} > \Delta_{s,g}^{\max}$, $s = 1, 2, 3$, $g = 1, \ldots, n_s$, and the reasons of abnormal situations Rs, which consist in the output of the technological parameters of the process beyond the regulatory restrictions, to determine the reason of the defect Rs^* and give the operator a tip Rc, which contains the direction and magnitude of the change in the controlling actions U_s, to enter the values of the extrudate and film quality indices into the regulatory ranges $Y_{s,g}^{\min} + \Delta_{s,g}^{\max} \leq Y_{s,g} \leq Y_{s,g}^{\max} - \Delta_{s,g}^{\max}$, $s = 1, 2, 3$, $g = 1, \ldots, n_s$ for a given type of film T_{film}, film production method M_{prod} and production line configuration C_{line},
where $Y_{s,g}^{\min}$, $Y_{s,g}^{\max}$ are threshold regulatory values of the g-th output parameter of the s-th production stage.

III. Structure and Mathematical Ware of the Computer System

The structure of the computer system for processing production data and expert knowledge for solving tasks of controlling the production of films is shown in Fig. 2. The system allows processing production data of big volumes D_{prod}, obtained from various sources: a system for forming tasks for the production of films (BDE system), a SCADA system, a MES system, a video monitoring system for the film surface (OCS system), etc.

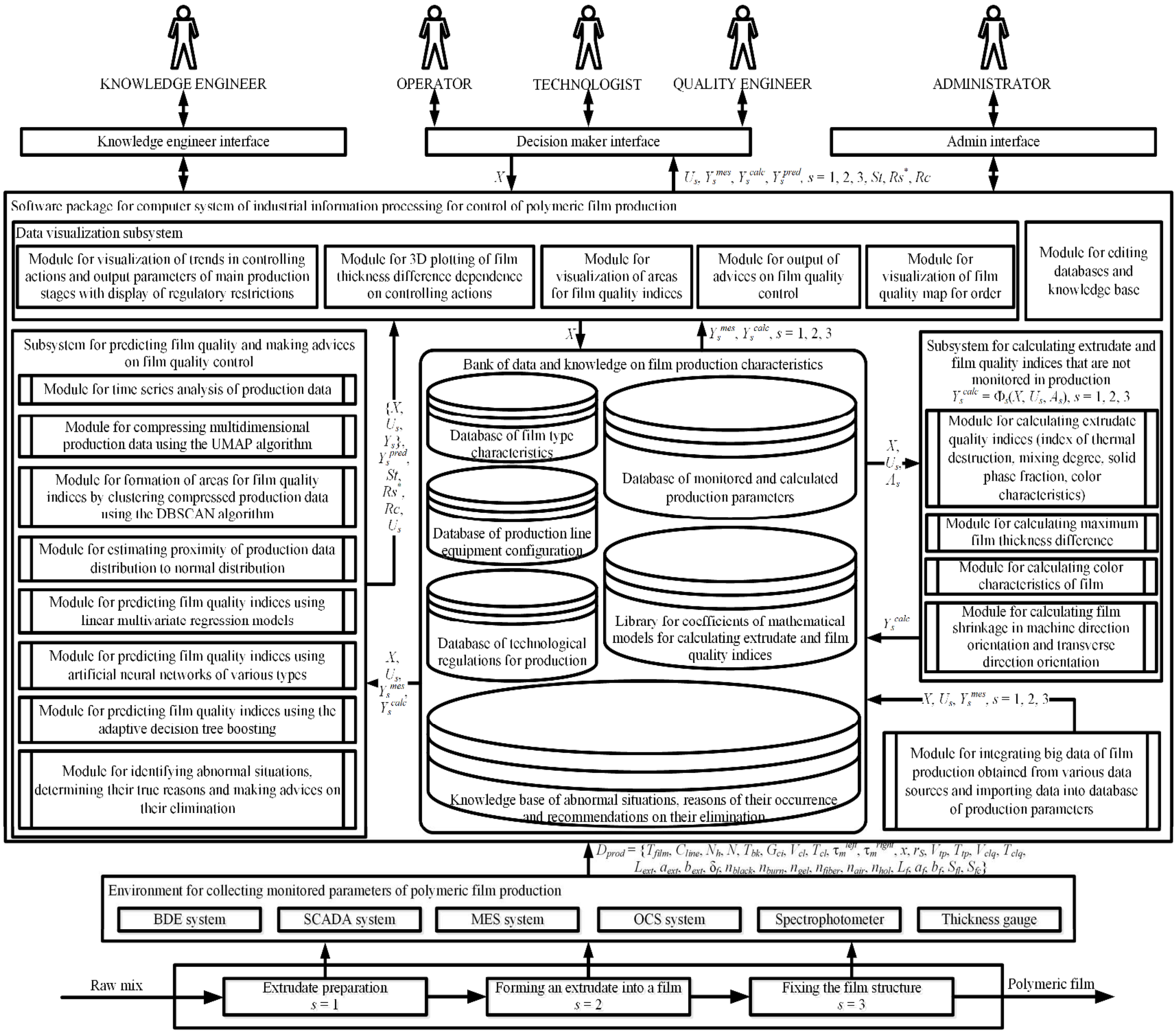

Fig. 2. Structure of the computer system for processing industrial information for controlling the production of polymeric films

The software package of the computer system includes a module for integrating production data, a bank of data and knowledge on production characteristics, deterministic mathematical models for calculating the quality indices of extrudate and film that are not monitored in production, modules for analyzing, compressing and clustering data, modules for predicting film quality using regression models and machine learning methods (Fig. 3), a module for output of recommendations for control in abnormal situations. The integration module allows us to create a single array of monitored data $\{X, U_s, Y_s^{mes}\}$, structured by types of production parameters, and import this array into the production parameters database. Monitored parameters $\{X, U_s, Y_s^{mes}\}$ and calculated parameters Y_s^{calc} are stored in this database. This ensures the completeness of the object data required for correct data processing. Mathematical models allow us to calculate the output parameters of the main stages Y_s^{calc} depending on the controlling actions U_s for different types of films T_{film} and configurations of production lines C_{line}. Adjustment of models to the variable characteristics of the object is carried out by changing the values of the coefficients A_s. The least acceptable defects of the film surface (black points, non-molten polymer inclusions, uneven coloring) occur, as a rule, due to excessive/insufficient thermal and mixing effects in the extruder. It is necessary to exclude the defect of the extrudate to prevent the defect of the film. Automatic monitoring the state of the extrudate is not performed at the production site. Therefore, the computer system calculates the current values of indices that characterize the quality of the extrudate: $I_d = (\tau_{av}/\tau_d)\exp[E_d(T_{ext} - T_d)/(RT_{ext}T_d)]100$, $\gamma = \tau_{av}(d\gamma/dt)_{av}$, where τ_{av} is average residence time in the extruder, E_d, T_d, τ_d are activation energy, absolute temperature and time of thermal destruction, T_{ext} is absolute temperature of the extrudate, R is gas constant, $(d\gamma/dt)_{av}$ is the average rate of the melt shear deformation in the extruder. Parameters T_{ext}, $(d\gamma/dt)_{av}$ and τ_{av} are calculated using mathematical models of extrusion, which are synthesized on the basis of mathematical models of motion and heat transfer in the elements of extruders, taking into account leakages and in accordance with a given type and configuration of the extruder [1]. The CIELab model is used to calculate the color deviations of the extrudate and the film. The shrinkage of the film is calculated using various mechanical models that allow describing the entire range of films.

Array of measured and calculated values of production parameters $\{X, U_s, Y_s\}$ in the specified time interval $[t_0; t_K]$ is processed using the following methods. The time series analysis method is used to evaluate the characteristics of parameters (features of time series), which include the average value, dispersion, standard deviation, kurtosis coefficient, etc. Data dimensionality reduction using the UMAP algorithm and clustering of compressed data using the DBSCAN algorithm make it possible to display areas for film quality indices (quality that meets regulatory requirements, or defects) on the flat [5]. If at the moment of time $t = t_K$ the value of the g-th output parameter $Y_{s,g}$ goes beyond the regulatory restrictions, the system identifies the abnormal situation, determines its true reason and makes the advice on elimination of the abnormal situation. The database of production parameters and the knowledge base of abnormal situations, developed on the basis of the production-frame model, are used to process the abnormal situation.

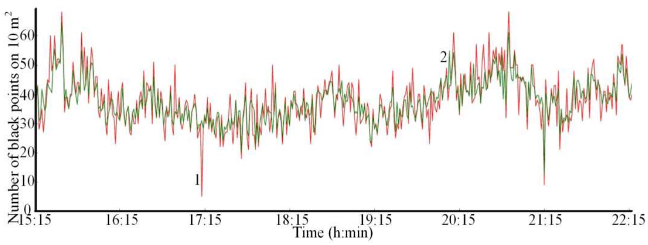

Fig. 3. Trends of measured and predicted values of black point number

To predict the consumer characteristics of the film, linear multivariate regression models (MRM) and machine learning methods (MLM) are applied [6, 7]. MRM are used if the data distribution is described by the Gauss law. MLM – artificial neural networks (recurrent, with long short-term memory, convolutional, combined) and adaptive ensemble meta-algorithm – are used if the data distribution deviates from the normal distribution. In this case, the data set is divided into three subsamples: training (for building a predictive model), validation and testing (for checking the model adequacy).

The results of testing the system according to the data of extrusion-calendering productions of rigid PVC films of a wide range at Russian and German factories have confirmed the adequacy of the mathematical models and the system's operability. Fig. 3 shows the trends of the measured (1) and predicted (2, method of adaptive tree boosting) values of the n_{black} index. A comparison of the results shows a good quality of the prediction (the error does not exceed 10 %).

IV. Conclusion

A reconfigurable system designed for processing data and knowledge of innovative industrial productions of multi-assortment polymeric films using mathematical modeling and artificial intelligence methods has been developed. The use of the system as an advisor to operators when controlling production in a routine mode and in conditions of defects allows improving the film quality and reducing non-returnable waste. This ensures resource saving in production.

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