Optimal Planning Software Package for Use in the Control System of Flexible Extrusion Production of Polymer Materials

Tamara B. Chistyakova
St. Petersburg State Institute of Technology (Technical University)
St. Petersburg, Russia
chistb@mail.ru

Ol'ga E. Shashikhina
St. Petersburg State Institute of Technology (Technical University)
St. Petersburg, Russia
shashikhina@mail.ru

Ivan G. Kornienko
St. Petersburg State Institute of Technology (Technical University)
St. Petersburg, Russia
naiv_89@mail.ru

Aleksandr A. Plekhanov
St. Petersburg State Institute of Technology (Technical University)
St. Petersburg, Russia
plehalex09@gmail.com

2021 IV International Conference on Control in Technical Systems (CTS) | 978-1-6654-2454-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/CTS53513.2021.9562893

***Abstract*—A software package has been developed that allows solving the problem of optimal planning of the distribution of a package of orders over time for execution on extrusion lines of various configurations in conditions of limited resources and taking into account deliveries. The complex allows you to automate the planning task for geographically distributed industrial enterprises and corporations that manufacture products on production lines that are reconfigured to a different assortment and face the problem of efficient use of their production resources. The production director interface allows the user to select the planning period, the target function (time or cost of production), orders and production lines. The database administrator interface supports the information support of the software package and allows you to import data for planning. The knowledge engineer interface allows you to configure the system for various hardware configurations and the rules for its reconfiguration. The basis of the software package is a customizable library of optimization methods, which allows you to choose an optimization method depending on the dimension of the task and the characteristics of the planning object. After building the production plan, the software package presents the planning result to the user, presented in the form of a Gantt chart and a tree of solutions to the optimization problem. Testing of the developed system was carried out on the production data provided by companies producing polymer films in Russia and Germany, and confirmed its operability and efficiency of application due to a reduction in the expected time and cost of production, as well as by reducing the time for making managerial decisions in the production planning process.**

Keywords*—software package, production planning, schedule theory, genetic algorithms, expert knowledge, mathematical models, extrusion and calendering production, polymer films

I. Introduction

The most important task in the management of a modern polymer enterprise is to optimize the production planning process. Geographically distributed industrial polymer companies and corporations that manufacture a large range of products on extrusion-calendering equipment of various configurations face the problem of effective management of their production resources [1, 2].

The problem of scheduling the production of polymer films belongs to the class of discrete problems of the theory of schedules and is an extremely complex, multidimensional problem with a large number of limitations due to the peculiarities of production [3]. In the course of solving the planning problem, it is necessary to take into account various characteristics of the production process: a large number of different orders (from 5 to 100 orders per month for one production line, the number of film formulations ~200); the number and configuration of production lines (from 1 to 20 lines, ~10 types of equipment reconfigurations).

Since the production of polymer films is multi-assortment (various types of pharmaceutical single-layer and multi-layer (up to 11 layers) rigid polyvinyl chloride films and packaging films for food products), it is characterized by frequent transitions to new tasks by film type and / or performance (on average 40 times a month per line); hardware flexibility (30 types of technological units); the variety and complexity of the relationships between the consumer characteristics of the film, the quality indicators of intermediates and the parameters of raw materials, equipment, technological regime (~800 relationships between more than 100 parameters).

In the control system of extrusion production of polymer materials, calendar planning is one of the most important stages of production. In practice, it takes a lot of time to draw up a calendar production plan manually, while it is possible to draw up a production schedule that is not optimal in terms of execution time, cost and resources consumed. Therefore, the development of automated systems for calendar production planning is extremely relevant.

This paper describes the development of a specialized software package that allows you to automate the planning process and form an optimal production schedule for tasks of various dimensions in an acceptable time. The complex includes a module for presenting knowledge about the planning object, a database of orders, production lines, types and recipes of polymer materials, various optimization methods and an algorithm for displaying the optimal solution in the form of a Gantt chart and a decision tree for the

The research was carried out at the expense of a grant from the Russian Science Foundation, the project №21-79-30029

978-1-6654-2454-7/21/$31.00 ©2021 IEEE

optimization problem. The complex allows you to solve the planning problem for various optimization criteria (production time, production cost). The flexibility of the software package is achieved thanks to a special interface of the knowledge engineer, and allows the management staff to configure the complex for various configurations of production lines and the rules for their reconfiguration using the knowledge representation in the form of tables. Optimization of the production plan allows you to reduce the time and cost of manufacturing products and ensure maximum utilization of the enterprise's equipment.

II. INFORMATIONAL DESCRIPTION OF THE PRODUCTION OF POLYMER FILMS AS A PLANNING OBJECT

At the first stage of the development of the software package, a system analysis and an information description of the production of polymer films as an object of planning were carried out. To clearly reflect the hierarchical relationships between various characteristics of production, equipment and orders, intelligence maps were developed as a form of representing knowledge about the planning object [4]. In the future, the intelligence maps of knowledge made it possible to effectively form databases that are the basis of the information support of the software complex.

When solving the planning problem, the input data vector is $X = \{\tilde{O}, \tilde{E}, \overline{Pd}, Cp\}$. The vector of variable variables is $U = \{\tilde{Q}, \widetilde{A_o}\}$. The output data vector is $Y = \{Q^{opt}\}$. Q^{opt} – vector describing the optimal distribution of orders across production lines, including, among other things, the start date, time and cost of manufacturing each order.

$\tilde{O} = \{\overline{O_\iota}: \bar{O} = (K_o, W_o, Qrm, Fg, W, O_t, \bar{R}, Cu, D_o, Po), i = \overline{1, N}\}$ – a vector that characterizes the order, where K_o – order code; W_o – order width, cm; Qrm – the amount of material in linear meters, m; Fg – the amount of material in the finished form, kg; W – material losses, kg; $\tilde{R}$ – vector that characterizes the recipe of a polymer material; $\tilde{F}$ – vector that characterizes the type of polymer material; C_u– customer; D_o – the desired delivery date of the order; i – order sequence number; N – number of orders.

$\tilde{E} = \{\overline{E_j}: \bar{E} = (N, K_e, V, \bar{M}, \bar{C}), j = \overline{1, Me}\}$ – vector that characterizes production lines, where *N* is the name of the line; K_e – line code; V – maximum speed, m/s; $\bar{M}$ – vector that characterizes the restrictions on the mother roll, $\bar{C} = \begin{pmatrix} T^{Th}, C^{Th}, T^{Wd}, C^{Wd}, Ff, Ft, T^{Rf}, C^{Rf}, Nz, T^{Nz}, C^{Nz}, \\ Cb, T^{Cb}, C^{Cb}, Cl, T^{Cl}, C^{Cl} \end{pmatrix}$ – vector describing the reconfigurations, where T^{Th} – time to reconfigure the thickness of the material, s; C^{Th} – material consumption for reconfiguration by material thickness, kg/s; T^{Wd} – time to reconfigure the width, s; C^{Wd} – material consumption for reconfiguration in width, kg/s; Ff – the original type of film; Ft – the final type of film; T^{Rf} – the time of reconfiguration according to the film recipe, s; C^{Rf} – material consumption for reconfiguration according to the recipe, kg/s; Nz – the final diameter of the nozzle, *DN*; T^{Nz} – time of reconfiguration of the nozzle diameter, s; C^{Nz} – material consumption for reconfiguring the nozzle diameter, kg/s; Cb – the final diameter of the calibration (forming) gap of the co-extrusion head:, *DN*; T^{Cb} – time of reconfiguration of the diameter of the calibration (forming) gap of the co-extrusion head, s; C^{Cb} – material consumption for reconfiguring the diameter of the calibration (forming) gap of the extrusion head, kg/s; Cl – final setting of the cooling ring, DN; T^{Cl} – the time of reconfiguration of the diameter of the cooling ring, s; C^{Cl}– material consumption for reconfiguring the diameter of the cooling ring, kg/s, j – serial number of the production line; Me – number of production lines. $\widehat{Pd} = (\tau_o, Y_{cr})$ – vector that characterizes the planning parameters, where $\tau_o = [\tau_b, \tau_e]$ – parameter that defines the planning period, τ_b – start date of the planning period; τ_e – end date of the planning period; Y_{cr} – parameter that determines the optimization criterion (reconfiguration time, cost). $Cp = \{Cp_r, r = \overline{1, R}\}$ – available amount of resources, where Cp_r – *r* resource quantity, kg, *r* – number of the resource type.

$\tilde{Q} = \{\overline{Q_\iota}: \bar{Q} = (j, \tau_{oi}, k, \tau_i, K_i^{film}), i = \overline{1, N}\}$ – vector describing the distribution of orders across production lines, $j \in [1, Me]$ – the number of the line on which the *i*-th order is executed; $\tau_{oi} \in [\tau_b, \tau_e]$ – the start date of the *i*-th order (includes the date and time of the start of the production order), $k = \overline{1, L}, L \in N$ – the sequential number of the execution of the *i*-th order on the *j*-th line in the current schedule $\bar{Q}$, L – the number of orders executed on the *j*-th line in the schedule $\bar{Q}$, τ_i – the time of execution of the *i*-th order, s, K_i^{film}– the cost of raw materials required for the production of a polymer film of the *i*-th order, c.u.

$\widetilde{A_o}$ – vector that characterizes the parameters of the optimization algorithm.

The key factor in optimizing the production schedule is the time of equipment reconfiguration from one order to another. Therefore, for efficient operation and ensuring the flexibility of production, a template was compiled for presenting knowledge about reconfigurations and technological regulations of equipment operation in the form of tables that are filled in by a knowledge engineer.

III. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

The formulation of the problem of optimal planning of the production of polymer materials can be formulated as follows: for a given vector of input parameters $X = (\tilde{O}, \tilde{E}, \overline{Pd}, Cp)$, it is required to find such an optimal placement of Q^{opt} for *N* orders on *Me* production lines within the planning period $[\tau_b, \tau_e]$, which will provide the extremum of the objective function: $F \to min$, subject to all restrictions.

The total production time and the total cost of production are used as optimization criteria. These criteria are the most frequently used target functions in similar tasks of production scheduling and the most important key performance indicators for users of the software package-specialists in production management of enterprises [5, 6].

A. Order completion time as an optimization criterion

The total time for completing orders and reconfiguring equipment is minimized:

$$F\big(\tau(Q^{opt})\big) = max_{j=1}^{Me}\big(\textstyle\sum_{k=2}^{L} \tau\big(O_{j,k-1}, O_{j,k}\big)\big) + \big(\textstyle\sum_{i=1}^{L} \tau_i\big) \to min,$$

where $\tau\big(O_{j,k-1}, O_{j,k}\big)$ – time of equipment reconfiguration from the previous order to the current one, s:

$$\tau(O_{j,k-1}, O_{j,k}) = T^{Th}{}_{j,k} + T^{Wd}{}_{j,k} + T^{Rf}{}_{j,k}\left(F_{f_{k-1}}, F_{t_k}\right) + T^{Nz}{}_{j,k}(Nz_k) + T^{Cb}{}_{j,k}(Cb_k) + T^{Cl}{}_{j,k}(Cl_k);$$

τ_i – completion time of the *i*-th order, s:

$$\tau_i = \frac{Qrm_i}{V_j(O_i)};$$

$V_j(O_i)$ – the production speed of the *j*-th production line when fulfilling the *i*-th order (depends on the type and thickness of the film being manufactured), m/s.

B. The cost of completing orders as an optimization criterion

The cost of executing the production plan is minimized:

$$F(K(Q^{opt})) = K^m(Q^{opt}) + K^l(Q^{opt}) \to min,$$

The cost of polymer materials spent on production: $K^m(Q^{opt}) = \sum_{i=1}^{N} K^{Mchng}{}_i + K_i^{film}$, where $K^{Mchng}{}_i$ – the cost of raw materials consumed during the reconfiguration of the production line to fulfill the *i*-th order:

$$K^{Mchng}{}_i = = Mc_{i,r}\begin{pmatrix} C^{Th}{}_i T^{Th}{}_i + C^{Wd}{}_i T^{Wd} + \\ +C^{Rf}{}_i\left(F_{f_{i-1}}, F_{t_i}\right) T^{Rf}{}_i\left(F_{f_{i-1}}, F_{t_i}\right) + \\ +C^{Nz}{}_i(Nz_i) T^{Nz}{}_i(Nz_i) + \\ +C^{Cb}{}_i(Cb_i) T^{Cb}{}_i(Cb_i) + C^{Cl}{}_i(Cl\,_i) T^{Cl}{}_i(Cl_i) \end{pmatrix},$$

$K_i^{film} = Mc_{i,r} Fg_i$, – the cost of raw materials required for the production of polymer film of the first order, c.u., $K^l(Q^{opt}) = \sum_{i=1}^{N} \tau_i k_j^l$, – the cost of equipment operation during the implementation of the plan, c.u.: where $Mc_{i,r}$– the cost of a resource of the type *r*, required for the production of the *i*-th order, c.u.; ready-made material, kg; Fg – the amount of material in the finished form, kg; k_j^l – the cost of the equipment operation, c.u./s.

C. Constraints in the optimal planning problem

When solving the problem of optimizing production planning, a number of restrictions are taken into account:

- Each order is executed within the specified planning interval$\tau_b \le T(Q_i) \le \tau_e$, $T(Q_i)$ – date of completion of the *i*-th order;
- Each order is made no later than the required date $T(Q_i) < Do_i$, Do_i– the desired delivery date of the order;
- Each order is allocated to the type of production line on which the required type of products can be manufactured: $\forall i = \{1, N\}: \bar{F}_i \in \tilde{F}$, $\bar{F}$– vector that characterizes the type of film, $\tilde{F}$ – vector that characterizes the production lines;
- On each *j*-th production line, only one order can be made at a given time at a given time $T(Q)$;
- In the optimal production plan, the production of all orders from a given order package is planned: $Q^{opt} \ni \bar{O}_i,\ i = \{1, N\}$.

Also, one of the main indicators of the efficiency of production planning is the resource efficiency of production [7, 8]. In the optimal planning task, it is necessary to evaluate whether it is possible to complete a package of orders in full: $Rs(Q^{opt}) \ge 0$, $Rs(Q^{opt})$ – deviation of the required volumes of resources from their available volumes, kg: $Rs(Q^{opt}) = \sum_{i=1}^{N}\sum_{r=1}^{R}(Cp_r - a_{i,r}(Fg_i + W_i))$, where $a_{i,r}$ – the rate of resource costs of the type r for the production of the film of the *i*-th order.

If the number of available resources is not enough to fulfill the *i*-th order, the planning task is solved anew without taking into account this order.

IV. COMPUTER SYSTEM ARCHITECTURE

The developed structure ensures the interaction of users with the software package through graphical user interfaces:

- the production director (the decision-maker) selects the planning period, the target function (production time or cost), orders for execution and production lines for loading, starts the optimal planning process, sees the planning result presented on the Gantt chart and the progress of solving the optimization problem;
- the database administrator keeps the information support (structure and content of databases) up to date;
- the knowledge engineer sets up data on the rules for reconfiguring production lines using tables representing knowledge about the technological regulations of the equipment.

A separate module has developed a form for visualizing the results of order planning and the progress of solving the optimization problem (the process of searching for an extremum) [10]. The subsystem for solving the optimization problem includes mathematical models of the objective functions and constraints of the optimization problem, as well as mathematical models and software implementations of optimal planning methods. For tasks of small dimension (1 production line and 1–25 orders), a software implementation of the full search method (the brute force method) is used. Finding the optimal production plan for problems of large dimensions (from 2 lines and up to 100 orders) is based on a genetic algorithm [9–11]. The following modern technologies are used as software development tools: SQLite DBMS, DB Browser, Entity Framework Core, Visual Studio 2019 environment, programming language C#.

V. CONCLUSION

The paper describes a software package for optimal planning of the production of polymer films. The complex is designed for geographically distributed industrial polymer production facilities that produce a large range of products on extrusion-calendering equipment of various configurations.

The development of an information description of the process of forming a production plan as an object of optimization is considered, the main characteristics of optimal planning are described, the formulation of the optimization problem, the formulas for calculating target functions (the time of execution of the production plan and the cost of its implementation) and limitations in the optimization problem are described, possible scenarios for working with the software package are described.

Successful testing of the software package based on real industrial data of polymer film manufacturers in Russia and Germany allows us to conclude that the complex can be offered as an effective system for automating the production planning process, since the use of the software package can significantly save time spent on drawing up a plan and production resources, reduce the time and cost of making orders.

REFERENCES

[1] Shashikhina O.E., Chistyakova T.B., Kohlert Ch. Computer system for optimal planning of multi-assortment polymer films industrial production. Proceedings of the 2020 2nd International Conference on Control Systems, Mathematical Modeling, Automation and Energy Efficiency (SUMMA 2020), Institute of Electrical and Electronics Engineers, 2020, pp. 561-565

[2] Chistyakova T.B., Polosin A.N. Mathematical models and software for extrusion process control in flexible multi-assortment production of polymer materials. *Vestnik Juzhno-Ural'skogo gosudarstvennogo universiteta. Serija «Matematicheskoe modelirovanie i programmirovanie»* [Vestnik YuUrGU. Ser. Mat. Model. Progr.], 2019, V. 12, I. 4, pp. 5–25. (in Russian)

[3] Lazarev A.A., Gafarov E.R. *Teorija raspisanij. Zadachi i algoritmy.* [Schedule theory. Tasks and algorithms]. Moscow, Lomonosov Moscow State University, 2011, 222 p. (in Russian)

[4] Gavrilova T.A., Strakhovich E.V. Visual-analytical thinking and mind maps in ontological engineering. *Ontologija proektirovanija* [Ontology of desig], 2020, V. 10, no. 1, pp. 87-99. (in Russian)

[5] Logunova O.S., Arkulis M.B. Automated system of operational scheduling of multistage production: mathematical model and software implementation. *Vestnik Cherepoveckogo gosudarstvennogo universiteta* [Bulletin of the Cherepovets State University], 2021, no. 3 (102), pp. 18–37. (in Russian)

[6] Danilov A.D., Lomakin V.A. Intelligent planning system for flexible automated production. *Vestnik voronezhskogo gosudarstvennogo tehnicheskogo universiteta* [Bulletin of the Voronezh State Technical University], 2019, V. 15, no. 1,pp. 7-11. (in Russian)

[7] Sevastyanov S.V. Resource constraints in scheduling problems and scheduling theory. Development of a general approach. *Trudy VI Mezhdunarodnoj konferencii "Problemy optimizacii i jekonomicheskie prilozhenija"* [Proc. of the VI International Conference "Optimization Problems and Economic Applications"], 2015, pp. 69–73. (in Russian)

[8] Meshalkin V.P., Bogomolov B.B., Boldyrev V.S., Zubarev A.M., Menshikov V.V. Intelligent logic-informational algorithm for choosing energy-resource-efficient chemical technology. *Teoreticheskie osnovy himicheskoj tehnologii.* [Theoretical foundations of chemical technology], 2019, V. 53, no. 5, pp. 483-492. (in Russian)

[9] Arkhipov I.V. Application of a genetic algorithm for a multicriteria scheduling problem. *Nauchno-tehnicheskij vestnik informacionnyh tehnologij, mehaniki i optiki* [Scientific and technical bulletin of information technologies, mechanics and optics], 2015, V. 15, no. 3, pp. 525–531. (in Russian)

[10] Mishchenko V.Ya., Gorbaneva E.P, Manukovsky A.Yu., Safonov A.O. Genetic algorithms in solving multicriteria problems of optimization of resource allocation when planning energy-saving measures. *Nauchnyj vestnik Voronezhskogo GASU. Stroitel'stvo i arhitektura.* [Scientific Herald of the Voronezh State University of Architecture and Civil Engineering. Construction and Architecture], 2014, No. 3 (35), pp. 77–82. (in Russian)

[11] Karpenko A.P. *Sovremennye algoritmy poiskovoj optimizacii. Algoritimy vdohnovlennye prirodoj* [Modern search optimization algorithms. Algorithms inspired by nature]. Moscow, Bauman MSTU, 2021.448 p. (in Russian)