Determination of maximum productivity the technological system of multi-product chemical plant

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Abstract. The mathematical formulation of the problem to determining the maximum productivity of a fixed hardware design for a technological system of multi-product chemical plant for a specific product is proposed. The algorithm for solving this problem involves checking and ensuring that the conditions for the suitability of the apparatus stages of the system for processing batches of the specified product are met. An example of the problem solution for a specific multi-product chemical plant is given.

1. Introduction
The problems of choosing and modifying the hardware design of multi-product chemical plants (MCP) are actively discussed in the scientific periodicals, see [1-5]. In the publication [6], the problems of choosing equipment of existing MCP are considered. The problem of the organization of the release of a new product in the planned volume by the specified date using the equipment of the existing production is formulated as a two-level hierarchy of problems. The mathematical formulation of the upper level's task involves the search for the batch size of the product and parameters of the production schedule, and the tasks of the lower level – the choice of equipment for the implementation of each stage of batch processing. The algorithms for solving problems, including the algorithmic scheme for their joint solution, are considered.

In this paper, we consider the problem of determining the maximum productivity of a fixed set of equipment at the stages of a technological system (TS) for a specific product. The need to solve such problems quite often arises in the practice of operating MCP, for example, if you urgently need to increase the output of a product, compensate for TS downtime due to lack of raw materials or equipment failures. At the same time, the requirements for filling capacitive apparatuses can be adjusted, the values of the specific capacities of filters and dryers can be clarified.

2. Problem formulation
In this case, the sizes and number of the main units of the stages of TS \((x_j, n_j, j = 1, J)\) are given and it is necessary to solve the problem of finding the maximum value of the size of the batch of the product \((w)\), indicators of the regime of processing the batches of products by the parallel main apparatuses of the stages and changing the sizes of the batches of the stage \((p_j, r_j, j = 1, J)\), which ensure the release of a given quantity product \((Q)\) for a minimum period, i.e. minimum value of sum.
\[
\max_{y=1,Y} \left\{ \sum_{e=1}^{E_y} \theta_{\mu_{ye}} \right\} + \left( \frac{Q \min \{r_j\}}{w} - 1 \right) \max_{j=1,J} \left\{ \theta_j \right\},
\]

where \(Y\) – number of batch processing routes, see[6],
\(E_y\) – number of stages of \(y\) route,
\(\mu_{ye} = j\) (sequential number of the stage), if the stage \(N\) of \(y\) route of processing batches of products is implemented in the apparatuses of stage \(j\),

\[
\theta_j = \begin{cases} 
\frac{K_j}{n_j} \tau_j, & \text{if } n_j > 1, p_j = 0 \\
\tau_j, & \text{otherwise} 
\end{cases}
\]

the duration of the cycle of operation of the apparatuses of stage \(j\) TS (the minimum possible time interval between the moments of the beginning of the first operation of the first cycle and the end of the last operation of the last cycle of operation of the stage apparatuses),
\(K_j = r_j / \min \{r_j\}\) – number of cycles of operation of the main apparatuses of stage \(j\) for one cycle of the system,
\(\tau_j\) – the sum of the durations of the operations of processing the batch of the product by the apparatuses of the stage \(j\) TS, or release of the maximum number of batches of a product for a given period \((T_o)\), i.e. maximum fraction value

\[
T_o = \max_{y=1,Y} \left\{ \sum_{e=1}^{E_y} \theta_{\mu_{ye}} \right\} / \max_{j=1,J} \left\{ \theta_j \right\},
\]

and satisfying restrictions:

\[
\frac{x_j \Phi^*}{v_j u_j} \leq w \leq \frac{x_j \Phi^*}{v_j u_j}, j \in \Sigma_b,
\]

where \(\Sigma_b\) – set of numbers of stages of processing batches of product, where the main ones are capacitive apparatuses;
\(\Phi_\rho, \Phi^*_\rho\) – minimum and maximum permissible degree of filling of the apparatuses of stage \(j\) TS with the processed mass;
\(u_j = (p_j + (1 - p_j)n_j) / (n_j r_j)\) – coefficient of change in batch size at the stage \(j\) TS;
\(v_j^* = \min_{k=1,L_{j,k};j=1,L_{j,k}} \{v_{jk}\}\), \(v^*_j = \max_{k=1,L_{j,k};j=1,L_{j,k}} \{v_{jk}\}\);

\(L_{jk}\) – number of batch processing operations during \(k\) operation cycle of the main apparatus of stage \(j\);
\(v_{jk}\) – volume material indices of operations implemented at stage \(j\) in the course of product release (volume of materials that must be processed to obtain 1 ton of product);
\(w \leq \frac{x_j \delta_j}{v_j u_j}, j \in \Sigma_f,\)

where \(\Sigma_f\) – set of numbers of filtration stages, equipped with frame or chamber filter presses, which are designed to isolate the solid phase of the suspension;
\(\delta_j\) – precipitate layer thickness when processing a batch of the product at the stage \(j\) (half the depth of the frame or chamber of the filter press of the selected type);
\(w \leq \min_{j=1,Y} \left\{ \frac{x_j \Phi^* \delta_j}{v_j u_j \mu_j}, j \in \Sigma_d, \right\},
\]

where \(\Sigma_d\) – set of drying stages equipped with conducted batch dryers;
\(x^1_j, x^2_j\) – working volume and working surface of the dryer, respectively;
\[m^*_j = \max_{k=1}^{\Sigma_j} \{m_{jkl}\};\]
\[m_{jkl} \quad \text{mass material indices of operations implemented at the stage } j \in \Sigma_d \text{ in the course of product release (mass of materials that need to be processed to obtain 1 ton of product);}\]
\[w \leq x_j \tau_j a_j / (g^*_j u_j), \quad j \in \Sigma_s / (\Sigma_t \cup \Sigma_d), \quad (6)\]
where \(\Sigma_s\) – set of stages of filtering and drying, equipped with other main apparatuses;
\(a_j\) – specific productivity of the devices of stage \(j\) in terms of the processed mass (kg/(m^2-s), m^3/(m^2-s), kg/(m^3-s), m^3/(m^3-s));
\[g^*_j = \max_{k=1}^{\Sigma_j} \{g_{jkl}\};\]
\(g_{jkl}\) – main material indices of operations implemented at the stage \(j \in \Sigma_s\) during the release of the product (\(v_{jkl}\) or \(m_{jkl}\) depending on the size \(a_j\));
\[p_j = \begin{cases} 0, & \text{if } n_j = 1 \\ 0 \text{ or 1, if } n_j > 1 \end{cases}; \quad (7)\]
\[r_j = \begin{cases} 1, & \text{if } \gamma > 1, \text{whole - separating a batch on } \gamma \text{ portions.} \\ 1/\gamma, & \text{if } \gamma > 1, \text{whole - joining } \gamma \text{ batches} \end{cases}; \quad (8)\]

3. Algorithm for problem solving
The algorithm for solving this problem provides the following procedures.

Determination of the minimum and maximum values of the batch size of the product \(w^*_j, w^*_j\), corresponding to fixed values \(p_j, r_j, j = 1, J\) (initially it is set \(p_j = 0, r_j = 1, j = 1, J\) ) and satisfying the restrictions from (3) - (6), which correspond to the types of the main apparatuses stages, defining the values \(w^*_{j1} = \max\{w^*_{j1}\}, w^*_{j1} = \min\{w^*_{j1}\},\) and, for \(w^* \leq w^*_j\), we select \(w^*\) as the value of the batch size of product \(w^*\), see figure 1.

![Figure 1](image-url)

Figure 1. Illustration for determination of value of product batch size.
The appearance of the situation $w^* > w^*$ indicates that the selected set of equipment for TS stages at fixed values $p_j, r_j, j = 1,J$ is not suitable for the implementation of all stages of the product release. Its suitability can be ensured by changing the values of $r_j, p_j, j = 1,J$. Dividing a batch of product into parts and their parallel ($p_j = 1$) or sequential ($r_j > 1$) processing, combining several batches and their sequential processing ($r_j < 1$), as a rule, leads to an increase in the duration of the processing period of the batch of the product (increase in the fraction (2)) and to fall in the quality of the product. Therefore, changes in values $p_j = 0, r_j = 1, j = 1,J$ must be agreed with an expert (experienced technologist) and, in any case, strive for the minimum possible changes in the batch of the product during its processing.

In the case of $w^* \leq w^*$ for a fixed value of $w = w^*$, the values of the moments of the beginning and end of operations of the cycles of processing batches of product at the stages of TS $t^n_{k_l}, t^n_{k_l}, j = 1,J, k = 1,K, l = 1,L_{k_l}$ are determined, see [6], which ensure a minimum of the sum (1) or a maximum of the fraction (2).

4. Illustrative example

As an example of the problem’s determination of the maximum productivity of TSMCP, we consider the problem of determining the minimum production period of 1.3 phenylenediamine (an intermediate product for the production of dispersed colorants), which was solved by the order of Design and Development Department of PJSC “Pigment”, Tambov. The planned production volume is 170 tons, the planned production period is 2400 hours (100 days with round-the-clock operation).

The data of the technological regulations of the process for the production of technical 1.3 phenylenediamine (stages, types of main apparatuses, material indices, regime norms) are presented in Fig. 2. The value $h_3 = 0.45$ in Fig. 2 shows the fraction of the actual filtering of the total time occupied by the filter press set in stage 3, and $z_2 = z_4 = 1$ shows that during the filtering period, in addition to the filter press, the batch processing is occupied by the apparatus of stage 2 (feeding the suspension to the filter) and the apparatus of the stage 4 (intake of filtrate).
Product release route: \( M = (1,2,3,4,5,6,7) \) (TS flow structure is linear). The sets of stage numbers are: \( \Sigma_0 = \{1,2,3,5,6,7\} \), \( \Sigma_4 = \{4\} \), and \( \Sigma_7 = \emptyset \) (cleaning filtration).

Among the main equipment of the workshop, where it was planned to place the production of 1.3 phenylenediamine, the apparatuses capable of realizing the stages of its production were selected. Their sizes: \( x_1 = 2.166 \text{ m}^3 \), \( x_2 = 6.3 \text{ m}^3 \), \( x_3 = 6.3 \text{ m}^3 \), \( x_4 = 57.8 \text{ m}^2 \), \( x_5 = 5.1 \text{ m}^3 \), \( x_6 = 3.7 \text{ m}^3 \).

For all stages, except for stage 6, there is only one suitable apparatus; two identical devices can be installed in stage 6. First, we take \( r_j = 1, j = 1,7 \), therefore \( p_j = 0, j = 1,7 \). According to the algorithm for problem solving, we initially take \( r_j = 1, j = 1,7 \), therefore \( u_j = 1, j = 1,7 \).

According to (3), we have:

\[
0.322t \leq w_1 \leq 1.288t,
0.141t \leq w_2 \leq 0.376t,
0.118t \leq w_3 \leq 0.4t,
0.151t \leq w_4 \leq 0.376t,
0.149t \leq w_5 \leq 0.678t,
1.005t \leq w_7 \leq 2.68t.
\]

The filtering stage is not considered yet, because the value of \( \tau_4 \) is not specified for it. As can be seen, \( w^* = 1.005 \text{ t} > w^* = 0.376 \text{ t} \), i.e. the proposed set of equipment with \( r_j = 1, j = 1,7 \) cannot provide processing of batches of 1.3 phenylenediamine.

In order to overcome this situation, in agreement with the technologist, an additional stage was introduced in TS before stage 7. This new stage equipped with a tank without a mixing device, where seven batches of one steamed product will be combined. This will lead to the following changes in the initial data: stage 7 will receive the number 8, with \( r_7 = r_8 = 1/7 \), respectively, \( u_7 = u_8 = 7; x_7 = 6.3 \text{ m}^3 \), \( v_7 = 1.104 \text{ m}^3/t \), \( \tau_7 = 1.0 \text{ h} \), \( \phi_7^* = 0.2 \text{ }, \phi_7^* = 0.9 \).

Then, according to (3), we receive:

\[
0.163t \leq w_7 \leq 0.734t,
0.144t \leq w_8 \leq 0.383t,
\]

i.e. \( w^* = 0.322 < w^* = 0.376 \), i.e. the changes in the operating conditions of the apparatuses of stages 7 and 8 led to the fulfillment of the conditions for processing of product batches for all stages of TS equipped with capacitive apparatuses. At \( w = w^* = 0.376t \tau_4 = \frac{G_4u_4w}{x_4a_4} = 4.1 \text{ h} \), see. [6], i.e. the restriction (6) will be fulfilled automatically.

The duration of the operation cycles of the apparatuses for this example \( \theta_j = \tau_j, j = 1,8 \), however, it should be remembered that the apparatus of stage 7 accumulates 7 sequentially processed batches of the product, and the apparatus of stage 8 processes all 7 batches at the same time, i.e. the sum (1) is converted to the form

\[
\sum_{j=1}^{6} \tau_j + 6 \max \{\theta_j\} + \tau_7 + \tau_8 + \left( \frac{Q \min \{r_j\}}{w} - 1 \right) \max \{\theta_j\},
\]

And its meaning: 23.18 + 66 + 1 + 36 + (170/7/0.376 – 1)·36 = 2415.4 h exceeds the planned product release period.

In order to reduce the product release period, it is proposed to use the possibility of installing at stage 6 two identical devices, each of which receives and processes the entire product batch, i.e. \( n_6 = 2, p_6 = 0, \theta_6 = \tau_6/n_6 = 5.5 \text{ h} \). Then the production period of 170 tons of 1.3 phenylenediamine will be 23.18 + 33 + 1 + 36 + (170/7/0.376 – 1)·36 = 2385.4 h. As can be seen, in this case, TS will have a reserve of working time of ~ 15 hours, which can be used to compensate for unexpected downtime.

Figure 3 shows the formed TS of the production of 1.3 phenylenediamine, which includes 8 apparatuses stages, one of which is equipped with two identical devices that process incoming batches of the product in turn.
Figure 3. TS production of 1.3 technical phenylenediamine

We note that as a result of the problems solving of equipment design of TS of the current MCP, see [6], the same option of TS was produced for the production of 1.3 technical phenylenediamine, however, the duration of its operation cycle was reduced due to the application of the algorithm for optimizing the functioning of the devices of TS stages (Alg algorithm, see [7]) and, as a result, minimizing the durations of “filled downtimes” at stage 7, see Fig. 4.

Figure 4. Diagram of one cycle operation of TS production of 1.3 phenylenediamine (70 of 93.18 h are shown: the operation cycle of the apparatus of stage 8 is shorten)

5. Conclusions
The mathematical formulation of the problem determination of the maximum productivity of a fixed equipment design for TS MCP for a specific product is proposed.

An algorithm is proposed for this problemsolving, which provides for checking and ensuring that the conditions for the suitability of the equipment design stages of TS for processing batches of the specified product are fulfilled.
As a result of problem solving, the maximum volume of product release by a specified date or the minimum duration of a given volume of product is determined.

The resulted reserve of TS performance can be used both to compensate for unforeseen downtime, and for additional product release.

References

[1] Cavin L, Fischer U and Hungerbühler K 2004 A method for identifying the optimal design of a single chemical process to be implemented in an existing multipurpose batch plant *AIChE Journal* **50** 1134

[2] Nemtinov V A and Nemtinova Yu V 2005 On an Approach to Designing a Decision Making System for State Environmental Examination *J. Comp. & System Sci. Int.* **45** 389

[3] Pinto T, Barbósa-Póvoa A and Novais A 2006 Decomposition Based Algorithm for the Design and Scheduling of Multipurpose Batch Plants *Poster papers of 16th European Symp. on Comp. Aid. Proc. Eng.* (Garmisch-Partenkirchen, Germany) 1051

[4] Mokeddem D and Khellaf A 2009 Optimal Solutions of Multiproduct Batch Chemical Process Using Multiobjective Genetic Algorithm with Expert Decision System *J. Autom. Meth. & Management in Chem.* Art. ID 927426

[5] Rukhov A V, Tarov D V, Dyachkova T P et al 2019 Methods of designing hardware decoration of productions of carbon nanotubes and by-products on their basis. *Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Khimiya i Khimicheskaya Tekhnologia* **62** 94

[6] Karpushkin S V, Krasnyanskiy M N and Mokrozub V G 2020 Problems of the equipment choice for existing multiproduct chemical plants. *IOP Conf. Ser.: Mater. Sci. and Eng.* **709** 022029

[7] Malygin E N, Karpushkin S V and Borisenko A B 2005 A Mathematical Model of the Functioning of Multi-product Chemical Engineering Systems *Theor. Found. Chem. Eng.* **39** 429