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The Problem of the Flows of Raw and Related Materials and of Semifinished-Products in the Chemical Industry*)

"Calculation is useful in all works linked with wordly affairs, vede-(knowledge) or with other similar affairs... The science of calculation is much appreciated in the science of love, in architecture, in prosody and poetry, in logic and grammar and in other things ..."

Magavira

an Indian mathematician (the 9th century)
of town of Maisor

The calculation of the necessary raw and related materials and semi-products within a technological flow of an enterprise of the chemical industry has a specific character. Thus, within the basic production, a relatively reduced number of raw and related materials and of semi-products is being processed, resulting an equally reduced number of products. It is an advantage because models with relatively small dimensions may be elaborated, a fact which allows bringing up to date at shorter intervals.

In certain cases, a semi-product can become its own component part, directly or indirectly. There are circumstances when with the manufacturing of a product or semi-product another product should also result, a product which is not at all necessary or which is only partly necessary. All this has led to the necessity for the problem of the flows of raw and related materials and of semi-products to be studied distinctly.

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*) Continuation to the article *"Considerations on the General Problem of Operative Programming of Production with Applications in the Chemical Industry"* by the same collective of authors-in Economic Computation and Economic Cybernetics Studies and Research, no. 3, 1972 (pa, ges 73—79).

The general scheme of the flow of raw and related materials and of semi-products in a chemical enterprise is relatively simple (see Fig. 1). In the first place, the raw and related materials: M_1, M_2, ... M_n are supplied in the quantities X_1, X_2, ... X_n. These raw and related materials are processed, entering into combination with one another on installations I_1, I_2,... I_μ. The semi-products S_1, S_2, ... S_m are obtained in the quantities Y_1, Y_2, ... Y_m. In some cases, the raw and related materials together with the semi-products may enter into reaction. A number of inadequate semi-products result on some installations, semi-products which are sent to the recuperation installations. One pursues to recuperate on these installations an ever bigger quantity R_k, which should re-enter the circuit of the installations. Only those quantities D_k which could not be recuperated represent waste.

Finally, in the last stage of fabrication, through the combination of the raw and related materials with the semi-products, the products P_1, P_2, ..., P_p are obtained in the quantities Z_1, Z_2,... Z_p.

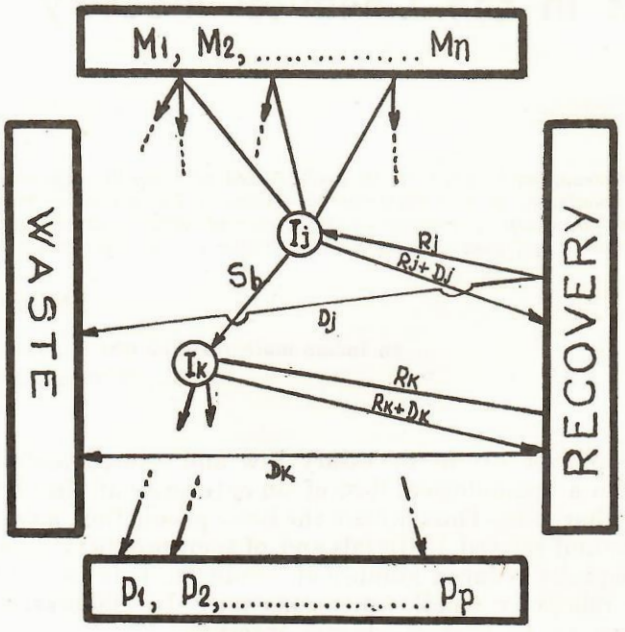

Fig. 1

Taking into account the characteristics of the general scheme of the technological flow and the objectives of the operative programming of production in the chemical industry, we propose to examine the following problems:

1. The establishment of the necessary raw and related materials for a given production plan (the case of a known demand);

2. The bringing up to date of the production plan for a given reserve of raw and related materials (in various hypotheses: without and with capacity restrictions, etc.);

1. THE ESTABLISHMENT OF THE NECESSARY RAW AND RELATED MATERIALS FOR A GIVEN PRODUCTION PLAN

To facilitate the understanding of this kind of problem, we shall take the following hypotheses into account.

Thus, we shall suppose that the raw materials derive from the same source and have the same characteristics. This makes that for a short plan period — for example, up to one year inclusively — there should be no significant variations of the specific consumptions. Hence, the specific consumptions will be considered as constant and the recipe of the product as unique.

A perfect correlation is considered to exist between the production plan and the proportions in which the products (the semiproducts) result following the chemical reactions. For example: if 40% product A and 60% product B result from the raw material M, the production plan will be: $40\ P$ for product A and $60P$ for product B (where P is a multiplicative factor).

The structure of the products must be known for calculating the necessary raw and related materials, setting out from a given plan. This structure can be very suggestively represented with the aid of a graph. To this purpose, the raw materials, the semi-products and the products are considered as tops of the graph. The following convention of representation is made: if a substance i enters into the composition of another substance j, top i is joint to top j by an arc (i, j) directed from i to j. The set of tops representing the raw materiale is $\{M_1, M_2, \ldots M_n\}$. The set of tops representing the semiproducts is $\{S_1, S_2, \ldots, S_m\}$. The set of tops representing the products is $P_1, P_2, \ldots P_m\}$. With these conventions and notations the graph in Fig. 2

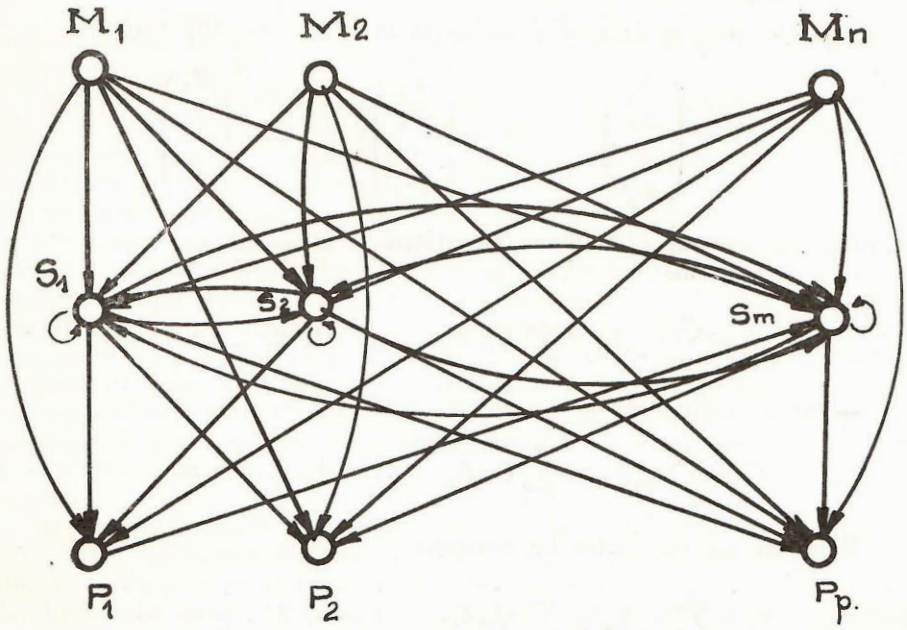

Fig. 2

is obtained. Examining this graph, one notes the existence at tops M_i of only incident arcs outwards and at tops P_k of only incident arcs inwards. This is due to the fact that the raw materials have no component parts and the products do not enter into the structure of any substance. Incident arcs inwards or outwards as well as loops may appear at top S_j. This means that the semi-products have component parts and, at the same time they may be component parts of other products or semi-products or even their own component parts.

Noting:

c_{ij} — the specific consumption of the raw material M_i for the semi-product S_j.

q_{ij} — the specific consumption of the semi-product S_i for the semi-product S_j;

C_{ik} — the specific consumption of the material M_i for the product P_k;

Q_{ik} — the specific consumption of the semi-product S_i for the product P_k.

These specific consumptions are attached to the arcs of the graph in Fig. 2. A null specific consumption will be translated by the absence of the respective arc.

Considering matrices:

$c = \|c_{ij}\|$ of dimensions $n \times m$;
$q = \|q_{ij}\|$ of dimenions $m \times m$;
$C = \|C_{ik}\|$ of dimensions $n \times p$;
$Q = \|Q_{ik}\|$ of dimensions $m \times p$;

E = the unit matrix of dimensions $m \times m$; and the vectors:

$$X = \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{pmatrix}; \qquad Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{pmatrix}; \qquad Z = \begin{pmatrix} Z_1 \\ Z_2 \\ \vdots \\ Z_p \end{pmatrix}$$

the following system of balance equations is obtained:

— for materials:

$$X_i = \sum_{j=1}^{m} c_{ij}\, Y_j + \sum_{k=1}^{p} C_{ik} Z_k, \qquad i = 1,\ 2,\ \ldots,\ n \tag{1}$$

— for semi-finished products:

$$Y_j = \sum_{h=1}^{m} q_{jh} Y_h + \sum_{k=1}^{p} Q_{jk} Z_k, \qquad j = 1,\ 2,\ \ldots\ m \tag{2}$$

Relation (2) may also be written:

$$Y_j = \sum_{h=1}^{m} q_{jh} Y_h = \sum_{k=1}^{p} Q_{jk} Z_k, \qquad j = 1,\ 2,\ \ldots\ m \tag{3}$$

Taking into consideration that:

$$\sum_{h=1}^{m} q_{jh} Y_h = \sum_{\substack{h=1 \\ j \neq h}}^{m} q_{jh} Y_h + q_{jj} Y_j \tag{4}$$

relation (3) may also be written:

$$\sum_{\substack{h=1 \\ j \neq h}} q_{hj} Y_h + (1 - q_{jj}) Y_j = \sum_{k=1}^{p} Q_{jk} Z_k, \qquad j = 1, 2, \ldots m \tag{5}$$

In the matrical notation, relations (1) and (5) become:

$$X = cY + CZ \tag{6}$$

$$(E - q)Y = QZ \tag{7}$$

The equation systems (6) and (7) represent the model of a balance resembling the model in physical expression of the balance of the relations among branches. In the field of microeconomy, this model represents a "balance of the relations among sections".

From the point of view of matrices, model (6), (7), differ from the balance of the relations among branches by:

— dimensions (in some cases much bigger than with the balance of the relations among branches);

— the number of null elements (much bigger than with the balance of the relations among branches);

— the formation of elements on the diagonal (most often $q_{jj} = 0$, in contradistinction to the balance of the relations among branches, with which, in most cases $q_{jj} \neq 0$).

Although model (6), (7) may have very big dimensions, however, the absence of many elements allows the solving of the model in an acceptable period of time. In most industrial branches, as a semiproduct cannot enter into its own composition, the terms on the diagonal q_{jj} are null. In the chemical or food industry — as has already been shown-this is possible and therefore loops exist in the graph in Fig. 2, thus $q_{jj} \neq 0$. Other times it is possible that there should be no loops ($q_{jj} = 0$) but, there should be circuits, for example S_j enters into the composition of S_{j_1}, S_{j_1} into the composition of S_{j_2}, and S_{j_2} enters into the composition of S_j, that is: $q_{jj_1} \neq 0$; $q_{j_1 j_2} \neq 0$ and $q_{j_2 j} \neq 0$. This fact leads to the impossibility of obtaining, through mutations of lines and columns, corresponding to the re-arrangement of the semi-products, a matrix with the elements on the diagonal and under the diagonal null. Thus, system (7) cannot be solved in this case by simple recurrence relations. From those shown above, it results that we distinguish two cases:

a) A semi-product does not enter into its own composition, directly or indirectly. It means that the graph in Fig. 2 has neither loops nor circuits. Matrix q may be brought, by convenient re-arrangements, to the triangular form (the elements on the diagonal and under the diagonal null). If the convention is reached for the same semi-product or material to be repre-

sented as a separate top, when it recurs several times, an arborescence is obtained (Fig. 3). The drawing may be simplified in this arborescence, namely to represent once the structure of a semi product S_i and if it recurs in the composition of another semi-product — the corresponding subarborescence should no longer be represented (Fig. 3). In this representation, the component

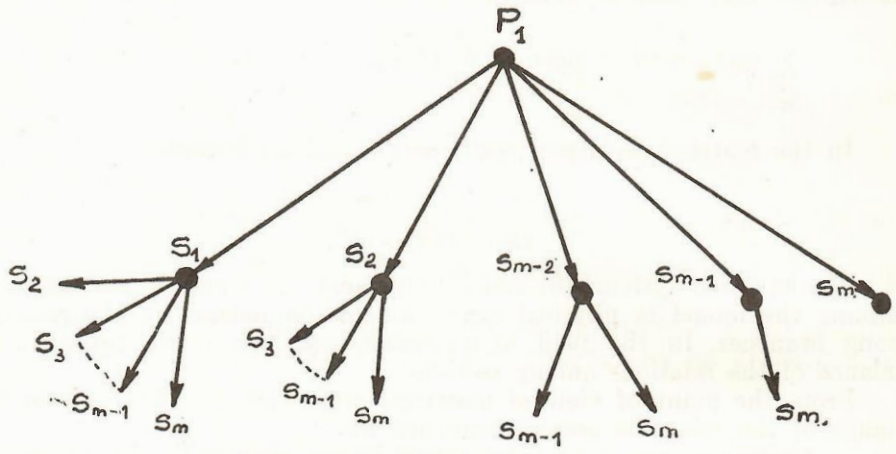

Fig. 3

parts appear at various levels. The products appear at level O, the semiproducts at the first and the last but one levels and the raw and related materials at the last level.

In these conditions, the equation system (2) may also be written in the form:

$$Y_j = \sum_{h=j+1}^{m} q_{jh} Y_h + \sum_{k=1}^{p} Q_{jk} Z_k, \qquad j = 1,\ 2,\ ...,\ m \tag{8}$$

This system is easily solved, without the inversion of matrix E-q being necessary. Starting from the last relation, all the quantities of semiproducts may be calculated by recurrence.

As part of the automatic management systems (PICS, PROMPT, ORACLE), the subsystem of calculating the needs exists. The description of the computing methods is expounded at length in the documentation placed at the disposal of the users by the computing equipment building firms [23], [24], [25].

b) The semi products may enter into their own composition either directly ($q_{ii} \neq 0$) or indirectly. In this case, the inversion of matrix (E-q) is necessary. From the technological point of view, the inverse of this matrix must be non-singular because otherwise we could not calculate the comsumption of semi-product in the product. From the mathematical point of view, the possibility moreover exists for the determinant corresponding to matrix E-q to be null. In this case, a specific consumption may be changed (within the limits of the admissible errors) so that the determinant corresponding

to matrix E-q be no longer null. Thus, in any situation we may come to a matrix E-q which has an inverse. Consider α the inverse of this matrix, namely:

$$\alpha = (E - q)^{-1} \tag{9}$$

Various methods can be used for calculating the inverse of the matrix. If the number of semi-products does not exceed a hundred, the Gauss-Jordan method can be used. For the IBM computer there exists a standard subroutine—the MINV subroutine—as part of the SSP programme deck. For a bigger number of semiproducts—of the order of hundreds—partitioning methods can be used, which would reduce the problem of inversion of the matrix of big dimensions to the inversion of several matrices of dimensions below 100 $\times$ $\times$ 100. At the same time, through the convenient change of the measure units a matrix can be obtained in which $0 \leqslant q_{ij} \leqslant 1$. Under these conditions, if the matrix is non-singular, we have:

$$\alpha = (E - q)^{-1} \cong E + q + q^2 + \ldots + q^N \tag{10}$$

where N depends on the necessary precision. This algorithm can be programmed only on computers with big internal storage (in case that the number of semi-products is of the order of hundreds) namely from 128 k upwards.

It should be pointed out that it is less probable to exceed in practice the dimensions 100 $\times$ 100 with the matrix to inverse for calculating the outfits of a single product.

Taking into consideration relations (7) and (9), the component parts of the vector of the necessary semi-products are calculated with the aid of expression:

$$Y = (E - q)^{-1} QZ = \alpha QZ \tag{11}$$

The components of matrices α and Q have variations only together with the change in the specific consumptions, that is at relatively big intervals. A matrix β of the matrical product between α and Q may be obtained, that is:

$$\beta = \alpha Q \tag{12}$$

thus, relation (11) becomes:

$$Y = \beta z. \tag{13}$$

By replacing in (6), we obtain:

$$X = c\beta z + CZ = (c\beta + C)Z = \gamma Z \tag{14}$$

where we noted:

$$\gamma = c\beta + C \tag{15}$$

Matrix γ represents the matrix of the total specific consumptions of materials. This matrix changes just as matrix α at big time intervals.

The vector of the plan Z may suffer changes at shorter intervals than matrix γ, in keeping with the planning horizon. Taking into account the frequency of the calculation of relations (9), (12), (13), (14) and (15), two programmes have been drawn up at the Department of Economic Cybernetics, namely:

— a preliminary programme for calculating the necessary raw and related materials and semi-products;

— a final programme for calculating the necessary raw and related materials and semi-products.

The preliminary programme for calculating the necessary raw and related materials and semi-products inverts matrix E-q, according to relation (9), appealing to subroutine MINV and achieves the matrical products (12) and (14) appealing to subroutine GMPRD. Matrixes α, β and γ are printed together with the names and codes of the components. In addition, a deck of cards in which the elements of matrix α and β are perforated is automatically obtained.

The final programme for calculating the necessary raw and related materials and semi-products, by using the results of the deck of cards (matrix α and γ), calculates on the basis of relations (13) and (14) the necessary semi-products, respectively the raw and related materials for a given plan Z. Taking into consideration that α and γ change only annually, it means that, in fact, for a current circulation of the programme only vector Z is changed, that is a number of elements which, as a rule, is of the order of the hundreds, a fact which does not raise difficult problems in connection with the handling of input data.

The limits of these programmes are: maximum 100 materials and maximum 100 semi-products. Practically, there are no limits for the number of products.

As part of the experiments made at the Borzeşti G.I.P., it was noted that for a product with $10 \div 15$ semi-products and $30 \div 50$ raw materials, the length of the circulation of the computation programme is of about 5′.

2. THE BRINGING UP TO DATE OF THE PRODUCTION PLAN FOR A GIVEN RESERVE OF RAW AND RELATED MATERIALS

a. *Without Capacity Restrictions*

In the course of the various stages of the drawing up of the plan or after a period of time since its application, the necessity may occur of taking into consideration a certain reserve of materials. In this situation, the problem is changed: the reserve of material X is known and the optimum quantitities Z of products which can be manufactured should be stablished, that is the optimum plan. The condition for not exceeding the reserve of raw and related materials may be inferred from relation (14):

$$\gamma Z \leqslant X \tag{16}$$

The production plan must satisfy the conditions for not exceeding some maximum quantities $Z_{i\,max}$ which can be delivered and for surpassing some minimum quantities ($Z_{i\,min}$) imposed by the higher body or by contracts:

$$Z_{i\,min} \leqslant Z_i \leqslant Z_{i\,max} \qquad i = 1, 2, \ldots, p \tag{17}$$

Relations (16) and (17) represent restrictions of the model. In certain cases these restrictions are incompatible. In such cases, the input data of the problem must be re-analysed in view of obtaining a compatible model. The number of the possible solutions of this model is infinite. To obtain a uni-

que solution, it is necessary to attach to relations (16) and (17) an objective function, such as for example:

— the maximization of the commodity output;

$\sum_{i=1}^{p} PV_i Z_i$ (PV_i) = the delivery price of a unit of the product P_i);

— the minimazation of the cost price:

$\sum_{i=1}^{p} K_i Z_i$ (K_i = the cost price of a unit of the product P_i)

— the maximization of profits:

$\sum_{i=1}^{p} b_i Z_i$ (b_i = the profit for a unit of the product P_i).

In some cases, by applying the theory of multidimensional decisions, the condition may be put for maximizing the utility:

$$\sum_{i=1}^{p} V_i Z_i$$

where V_i represents the utility of the product P_i.

The problem is thus reduced to a linear programming model. Standard programmes may be used for solving it (for example, the LPS programme — Linear Programming System — can be applied for the IBM computer.

b. *With Capacity Restrictions*

It is considered that each installation (section) produces a single semi-product (respectively, a single product). We note by CI_{jh}, respectively QI_{kh}, the capacity of the installation I_h of producing the semi-product S_j (respectively, the product P_k) and by T_h the available time of installation I_h. It is supposed that all installations can contribute to obtaining the optimum quantities Y_{j0} (respectively, Z_{k0}) which are produced in the enterprise. In the ideal case, for which the equilibrium relations are checked:

— in the case of semi-products

$$\sum_{h=1}^{\mu} CI_{jh} T_h = Y_{j0}, \qquad j = 1, 2, \ldots, m \tag{18}$$

— in the case of products

$$\sum_{h=1}^{\mu} QI_{kh} T_h = Z_{k0}, \qquad k = 1, 2, \ldots, p \tag{19}$$

(where the number of installations was noted by μ), each installation I_h is planned to produce the quantity $CI_{jh} T_h$ (respectively $QI_{kh} T_h$), that is, it is loaded to its maximum capacity. For compatibility we must have:

$$Z_{k\,max} \leqslant \sum_{h=1}^{\mu} QI_{kh}\, T_h\,, \; k = 1, 2, \ldots p, \tag{20}$$

If:

$$\sum_{h=1}^{\mu} CI_{jh} T_h \geqslant Y_{j0}, \qquad j = 1, 2, \ldots, m \tag{21}$$

or

$$\sum_{h=1}^{\mu} QI_{kh} T_h \geqslant Z_{k0}, \qquad k = 1, 2, \ldots, p \tag{22}$$

the enterprise must look for customers for delivering the surplus it can produce.

A more complicated problem arises if:

$$\sum_{h=1}^{\mu} CI_{jh} T_h \leqslant Y_{j0}, \qquad j = 1, 2, \ldots, m \tag{23}$$

$$\sum_{h=1}^{\mu} QI_{kh} T_h \leqslant Z_{k0}, \qquad k = 1, 2, \ldots, p \tag{24}$$

In this situation restrictions (17) are changed:

$$Z_{i\,min} \leqslant Z_i \leqslant min\left(Z_{i\,max}, \sum_{h=1}^{\mu} QI_{ih} T_h\right), \qquad i = 1, 2, \ldots, p \tag{25}$$

and the capacity deficit of semi-products is completed by supplying from outside some quantities Y_{ja}. By using restrictions (16) and (25) and a function of optimum, an optimum solution $\widetilde{Z}_0$ is obtained. The vector of the quantities of semi-products also results:

$$\widetilde{Y}_0 = \beta \widetilde{Z}_0. \tag{26}$$

In some cases, the supply of a quantity Y_{ja} can be ensured so as to cover the entire capacity deficit, that is:

$$Y_{ja} = \widetilde{Y}_{j0} - \sum_{h=1}^{\mu} CI_{jh} T_h = \sum_{h=1}^{p} \beta_{jk} \widetilde{Z}_{k0} - \sum_{h=1}^{\mu} CI_{jh} T_h \qquad j = 1, 2, \ldots, m \tag{27}$$

where $\widetilde{Y}_{j0}$ represents the component of the level j of vector $\widetilde{Y}_0$.

In other cases, however, only a quantity $Y_{s\,max}$ can be supplied which covers only partly the capacity deficit:

$$Y_{s\,max} \leqslant \sum_{k=1}^{p} \beta_{sk} \widetilde{Z}_{k0} - \sum_{h=1}^{\mu} CI_{sh} T_h, \qquad s = 1, 2, \ldots, m \tag{28}$$

Consider Y_{se} the effectively necesarry quantity of semi-product which is supplied from outside. Noting by Z_{ke} the quantities of products which can effectively be achieved, the following restrictions are obtained:

$$\sum_{k=1}^{p} \beta_{sk} Z_{ke} \leqslant \sum_{h=1}^{\mu} CI_{sh} + Y_{s\,max}, \qquad s = 1, 2, \ldots, m \tag{29}$$

Restrictions (1) become.

$$\sum_{j=1}^{m} c_{ij} Y_{je} + \sum_{k=1}^{p} C_{ik} Z_{ke} \leqslant X_{ie}, \qquad i = 1, 2, \ldots, n. \tag{30}$$

For the quantities of semi products which are supplied, the following equations are obtained:

$$\sum_{k=1}^{p} \beta_{sk} Z_{ke} - Y_{se} = \sum_{h=1}^{\mu} CI_{sh} T_h \tag{31}$$

From relation (1) we obtain:

$$Y_{je} = \sum_{k=1}^{p} \beta_{jk} Z_{ke} \tag{32}$$

Attaching an optimum function to restrictions (30), (31), (32) and (25), a linear programming problem is obtained.

In case that an installation I_h can manufacture several semifinished products S_j or products P_k, the number of restrictions and of the materials is considerably increased. One notes by U_{jh} respectively V_{kh} the quantity of the semiproduct j, respectively the product k affected to the installation I_h. Knowing the available time T_h for each installation and the condition being put for not surpassing it, one obtains:

$$\sum_{j=1}^{m} \frac{U_{jh}}{CI_{jh}} + \sum_{k=1}^{p} \frac{V_{kh}}{QI_{kh}} \leqslant T_h, \qquad h = 1, 2, \ldots, \mu. \tag{33}$$

The total semi-products (products) achieved on each installation will have to balance the total quantities effectively achieved:

$$\sum_{h=1}^{\mu} V_{jh} = Y_{je}, \qquad j = 1, 2, \ldots, m; \tag{34}$$

$$\sum_{h=1}^{\mu} V_{kh} = Z_{ke}, \qquad k = 1, 2, \ldots, p. \tag{35}$$

The optimum condition is:

$$\sum_{j=1}^{m} \sum_{h=1}^{\mu} \sigma_{jh} U_{jh} + \sum_{k=1}^{p} \sum_{h=1}^{\mu} \Gamma_{jk} V_{kh} = min \tag{36}$$

where σ_{jh} and Γ_{jk} are cost prices corresponding to U_{jh} respectively V_{kh}

Restrictions (33), (34), (35) and the optimum condition (36) represent a linear programming problem. But, taking the particularities of restrictions (34) and (35) into consideration, Blanchard's algorithm can be used or it may be considered as a generalized transport problem.

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PROBLEMES DES FLUX DE MATIERES PREMIERES, DE MATERIEL ET SEMI-FABRICATS DANS L'INDUSTRIE CHIMIQUE

Prenant comme point de départ le fait que la programmation opérative de la production dans l'industrie chimique implique la résolution de plusieurs problèmes, dans le présen ouvrage les auteurs examinent deux types de problèmes, à savoir: l'établissement du nécessair de matières premières et de matériel pour un plan de production donné et l'actualisation d plan de production ayant une disponibilité de matières premières et de matériel.

ВОПРОС ПОТОКОВ СЫРЬЯ, МАТЕРИАЛОВ И ПОЛУФАБРИКАТОВ В ХИМИЧЕСКОЙ ПРОМЫШЛЕННОСТИ

Исходя из того, что оперативное программирование производства в химической промышленности требует разрешения некоторых задач, авторы настоящей статьи рассматривают два типа задач, а именно: определение потребности в сырье и материалах для данного плана производства и актуализация плана производства, имеющего некоторое располагаемое количество сырья и материалов.