EVOLVING SYSTEMS

# COORDINATED OPERATIONS MANAGEMENT MECHANISMS FOR INDUSTRIAL SYSTEMS. II. FUNCTIONING MODEL FOR AN OPERATIONS MANAGEMENT SYSTEM IN BATCH INDUSTRIES

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We consider some methodological issues of designing coordinated operations management mechanisms for industrial systems using a typical example of a batch industry — the refining division of a lead production plant. The model and the functioning mechanism of the refining industry are described using the methods of active system theory.

## 1. INTRODUCTION

The present article is a continuation of [1], where the problem of coordinated operations management of process industries was formulated and solved for the case of the charge-preparation process. Here we consider the case of a batch industry, examining the methodological issues and describing the mechanisms of coordinated operations management for actual industrial systems.

## 2. STRUCTURAL AND TECHNOLOGICAL MODEL OF THE REFINING INDUSTRY

1. Plant Structure. The refining plant has a two-level structure, as shown in Fig. 1. The plant comprises an industrial management organ (the headquarters), the external environment, and a set $I = \{1, 2, \ldots, n\}$ of active elements subordinated to the headquarters. An active element consists of a refining crew with its line manager, the shift foreman.

2. The State of an Active Element. The technological description of active elements has been studied in considerable detail. There is extensive literature in mathematical economics which focuses on modeling of production technology [1-4]. The method proposed below for the description of the refining technology is applicable to many batch industries and may be generalized to describe various technologies.

The technological diagram of "crude" lead refining is shown in Fig. 2, where the thick line traces the sequence of activities performed for each batch of metal being refined [5]. The notion of activity is basic for the description of a batch technology [6, 7]. Regardless of the concrete physical content, each activity in a batch industry may be characterized by the following factors: 1) the batch (customer, component, etc.) on which the activity is

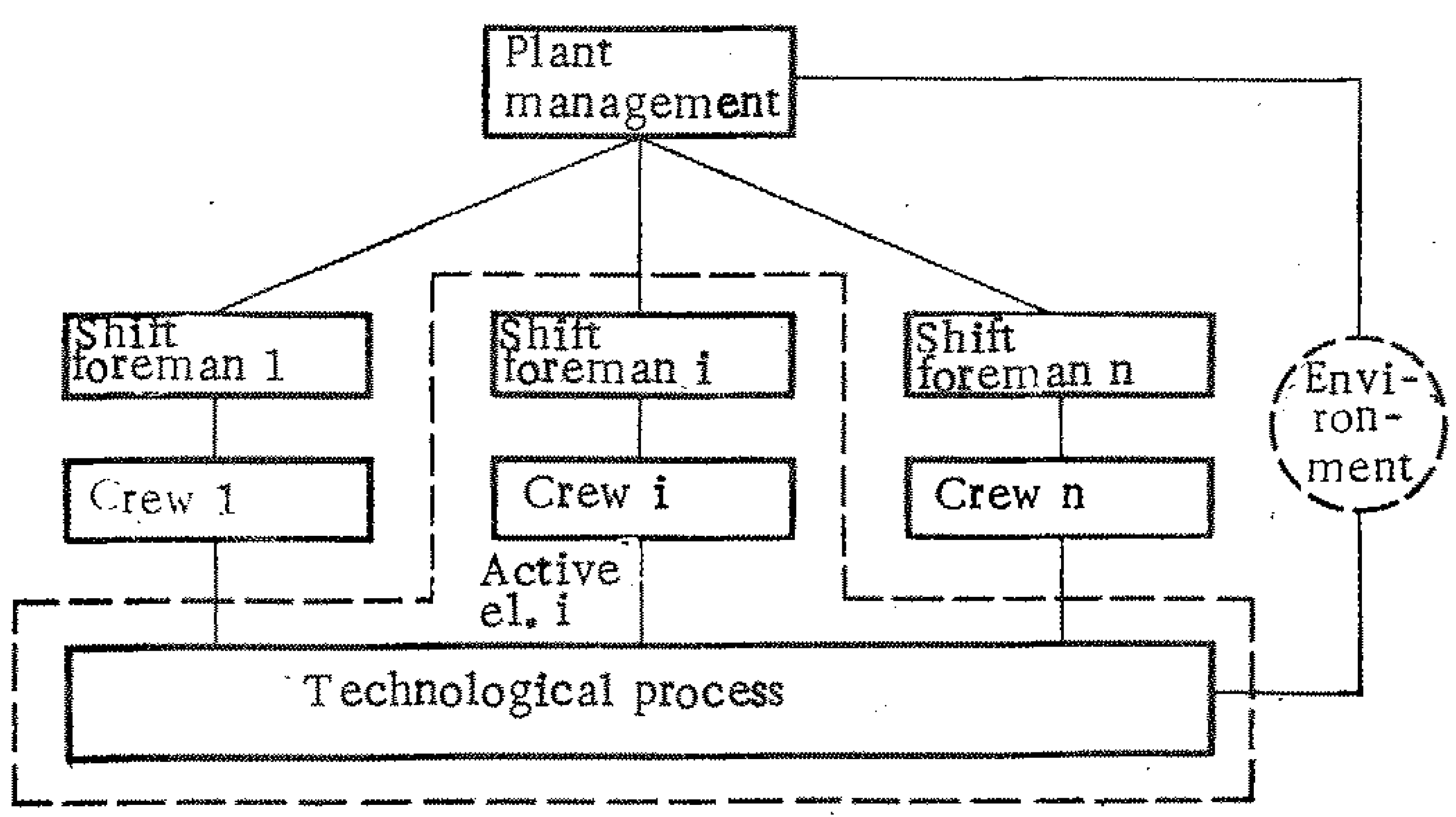


Fig. 1

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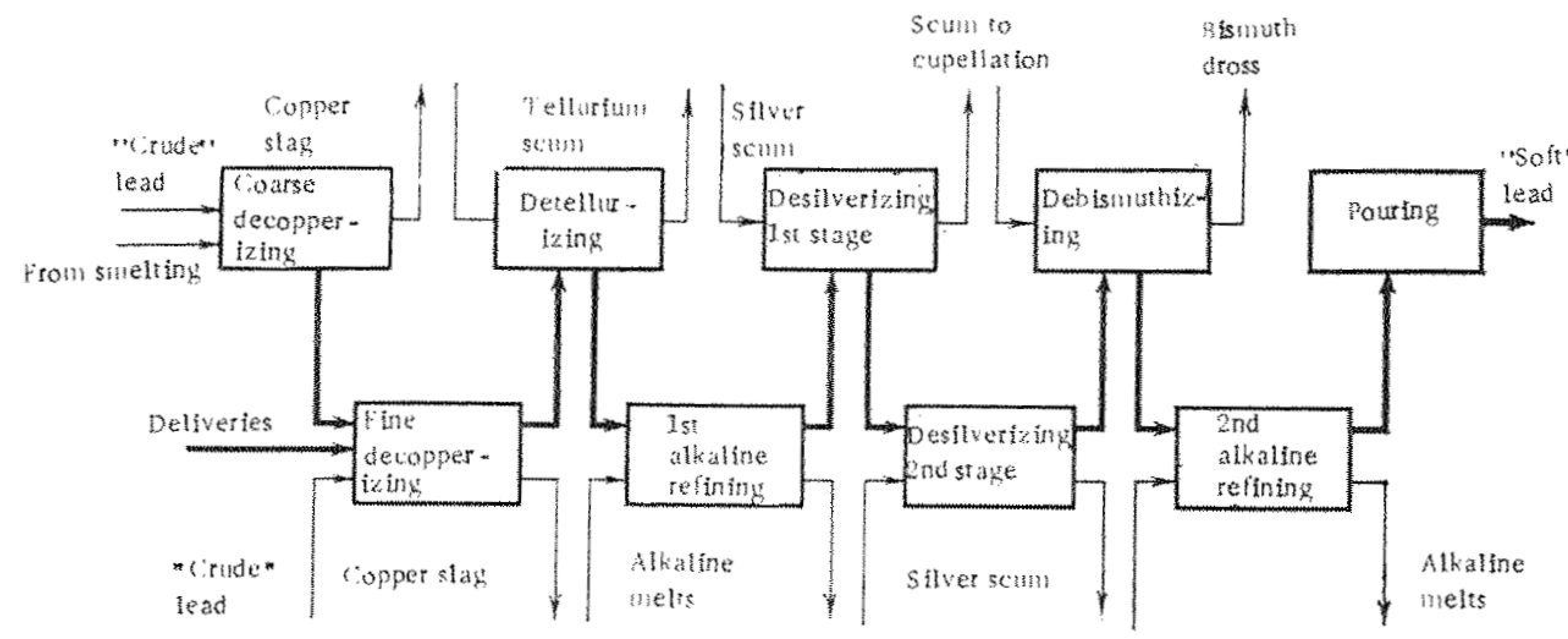



Fig. 2

performed; 2) the equipment (machine) and the operating technology employed in the activity; 3) a number representing the length of the activity.

The equipment in a refining plant includes one collection crucible; M refining kettles, which may be used simultaneously to refine M batches of "crude" lead; a Harris installation on which the first alkaline refining is performed; a pouring system which pours "soft" lead into appropriate molds.

The first alkaline refining eliminates the impurities Sn, As, and Sb from the batch. The refining conditions are such that the Harris installation and the pouring system may serve only one batch at a time. Collection and refining kettles have the same capacity and differ only in their function.

During the planning period, the refining plant receives a set $\mathscr{L}=\{1, 2,\ldots,L\}$ of crude lead batches which are delivered at the times $g_l$, $l = 1, L$. The refining of each batch $l$ involves sequential performance of the following aggregated activities: activity 1 — receiving, decopperizing, detellurizing (removal of Te); activity 2 — first alkaline refining; activity 3 — desilverizing, debismuthizing, qualitative (second alkaline) refining (removal of Ag, Au, Ca, Mg, Zn); activity 4 — pouring.

The length of the refining activity depends on the particular metal being refined and on the refining and pouring methods. We denote by $\delta^{lk}_{\eta_k}$ the length of the k-activity for the $l$-th batch performed using the technology $\eta_k$; it is equal to the sum of the durations $\tau^{lq}_{j_q}$ of the set $Q_k$ of the elementary activities performed by the same technology, $\delta^{lk}_{\eta_k}=\sum_{q\in Q_k}\tau^{lq}_{j_q}$, where $\eta_k\in\Theta_k$, $j_q\in J_q$ $\forall q\in Q_k: J_q=\Theta_k$, $k=\overline{1,4}$, $l=\overline{1,L}$. The elementary activities are indexed in the sequence of their execution. Activity 1 consists of eight elementary activities, $Q_1 = \{1, 2,\ldots,8\}$, activity 2 consists of three elementary activities, $Q_2 = \{9, 10, 11\}$, activity 3 consists of eight elementary activities, $Q_3 = \{12, 13,\ldots,19\}$, and activity 4 consists of two elementary activities, $Q_4 = [20, 21]$. The length of activity 1 is entirely determined by the kind of metal being processed, i.e., $\delta^{l1}_{\eta_1}=\delta^{1}_{\eta_1}$ $\forall l=\overline{1,n}$.. The time of activity 2 is determined by the concentrations of the Sn, As, and Sb impurities in a given batch, i.e., $\delta^{l2}_{\eta_2}=\delta^{l2}$ $\forall\eta_2\in\Theta_2$. The refined batch grade $\eta_3$ determines the length of activity 3, i.e., $\delta^{l3}_{\eta_3}=\delta^{3}_{\eta_3}$ $\forall\eta_3\in\Theta_3$, $\forall l=\overline{1,n}$. The length of the pouring activity depends on the particular mold and the number of pouring machines used, i.e., $\delta^{l4}_{\eta_4}=\delta^{4}_{\eta_4}$ $\forall l=\overline{1,n}$.

Each industrial activity in a lead-refining plant is thus describable by the batch index $l$, the elementary activity q performed on that batch, and the corresponding technology $j_q$, i.e., by the triple ($l$, q, $j_q$) with the associated starting time $t^l_{qj_q}$ of the elementary activity, $\bar{t}^l_{qj_q}$, $\bar{t}^l_{qj_q}=\underline{t}^l_{qj_q}+\tau^l_{qj_q}$, $j_q\in J_q$, $q\in Q_k$, $k=\overline{1,4}$, $l=\overline{1,L}$.

In order to describe the technological constraints, we introduce the Boolean variable $y_{qj_q}$, which is equal to 1 if for the $l$-th batch the elementary activity q is performed by technology $j_q$ and 0 otherwise.

The technological constraints are specified in the following form: Each elementary activity q for any batch $l$ is performed by one technology only, $\sum_{j_q\in J_q} y^l_{qj_q}=1$, $q=\overline{1,21}$, $l=\overline{1,L}$; the set of batches is routed through all the refining stages, i.e., through 21 elementary activities, $\sum_{q=1}^{21}\sum_{j_q\in J_q} y^l_{qj_q}=21,\ l=\overline{1,L}$; all the elementary activities are performed without interruption, following a fixed technological sequence; the initially chosen technology for a particular elementary activity cannot be changed until the elementary activity is completed; the targets specifying the number of batches of all grades $\eta_3$ poured in the molds $\eta_4$, $n_{\eta_3\eta_4}$, must be met.

These conditions define the set of feasible states of the system in every $\nu$-th shift, $Y_\nu$ (the construction of this set is described in the Appendix). To this end, we have to define the following sets: $B_t$, the set of jobs completed at the moment t, $B_t=\{(l,q,j_q)\,|\,\bar{t}^l_{qj_q}=t\}$; $E_t$, the set of jobs that may be started at the moment t, $E_t=\{(l,q,j_q)\,|\,\underline{t}^l_{qj_q}=t,\ j_q\in J_q\}$ ; $C_t$, the set of jobs in process at the moment $t$, $C_t=\{(l,q,j_q)\,|\,\underline{t}^l_{qj_q}<t<\bar{t}^l_{qj_q}\}$.

The state of the system at the beginning of the $\nu$-th shift, i.e., at the moment $t = (\nu - 1)T$, is described by the tuple $y_{\nu-1}$ whose components are the set of jobs finished and in processes at the beginning of the shift $\bar{C}_t=C_t\cup B_t$, and the set of the job completion moments $T(\bar{C}_t)=\{\bar{t}_{qj_q}\,|\,(l,q,j_q)\in\bar{C}_t\}$, $y_{\nu-1}=\{(l,q,j_q),\bar{t}^l_{qj_q}\,|\,y^l_{qj_q}(t)=1\}$, where $y^l_{qj_q}(t)$ is equal to 1 if at the moment t the elementary activity q is performed by the technology $j_q$ on the batch $l$ and 0 otherwise.

3. <u>The Sets of Feasible States.</u> In what follows, we will need the following definitions.

<u>Definition 1.</u> The feasible frontier of the set $L_t=C_t\cup E_t$ is the subset $\bar{L}_t\subseteq L_t$, such that all the technological constraints are satisfied for all $y^l_{qj_q}=1,\ (l,q,j_q)\in\bar{L}_t$ .

<u>Definition 2.</u> The maximal feasible frontier of the set $L_t$ is a feasible frontier $\bar{L}_t$ such that no feasible frontier $\tilde{L}_t$ ($\tilde{L}_t = \bar{L}_t$) exists which contains $\bar{L}_t$ as a proper subset.

A feasible set of an active element at the end of the $\nu$-th shift, $y_\nu$, may be obtained by allowing the initial state $y_{\nu-1}$ to evolve gradually in time subject to the technological constraints. Since the elementary refining activities can be performed in different ways, there exists a whole set $Y_\nu$ of feasible states of the system at the end of the $\nu$-th shift, $\nu = \overline{1, V}$. A procedure to construct the set $Y_\nu$ is given in the Appendix. It follows from the construction that the set $Y_\nu$ of feasible system states at the end of the $\nu$-th shift is a collection of all the maximal feasible frontiers of the system in the time interval $[(\nu - 1)T, \nu T]$, $Y_\nu=Y_\nu(y_{\nu-1})=\{G_p(L_t),\quad T(G_p(L_t))\,|\,p=\overline{1,\ \Pi_t},\quad t\in[(\nu-1)T,\nu T]\}$. The expression $Y_\nu = Y_\nu(y_{\nu-1})$ emphasizes the parametric dependence of the set of feasible system states in the $\nu$-th shift on the initial state of the system $y_{\nu-1}$, i.e., the system state at the end of the $(\nu - 1)$-th shift.

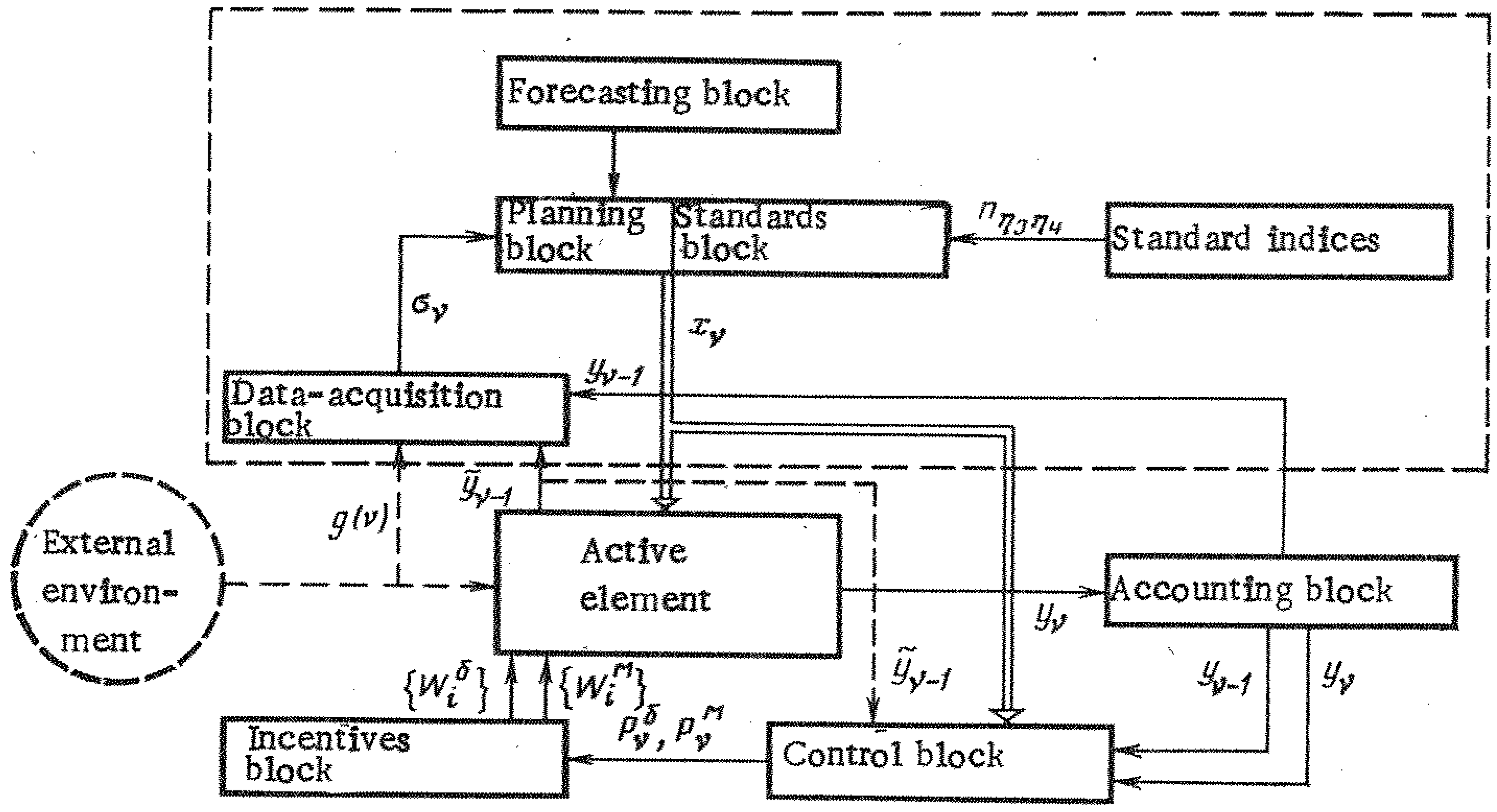
This description of the refining industry in terms of technological activities and the interdependence between the activities provides a general framework for the description of the technology in any batch industry. Although the technological constraints associated with our model are quite complex, they are constructed in a straightforward way by applying simple standard procedures and are conceptually quite obvious.

## 3. ORGANIZATIONAL FUNCTIONING MECHANISM

Let us now consider the development of the coordinated operations management mechanism for the main refining activity.

The functioning mechanism of an industrial system is conveniently described as a collection of separate component pairs, or blocks, corresponding to the basic management functions: data acquisition, generation of standards, planning, accounting, control and performance evaluation, incentives (see Fig. 3).

1. <u>Data-Acquisition Block.</u> It provides the headquarters with information inputs for the planning process. Before initiating operations planning for the $\nu$-th shift, the headquarters receives information of two kinds: a) information from the external environment concerning the delivery dates $g(\nu)$ of crude lead during the planning period; b) information about the status of production at the end of the $(\nu - 1)$-th shift. The latter information is provided by the shift foreman. Thus, the information arriving at the data-acquisition block may be represented in the form $\sigma_\nu = (g(\nu), y_{\nu-1})$. The functioning mechanism is required, among




Fi. 3. Scheme of the coordinated operations management mechanisms for the main refining activity.

other things, to ensure reliability of the reported information. This issue is dealt with in the next article in this series.

2. Standard Block. In this block, the information $y_{\nu-1}$ generated by the accounting block on the basis of system performance in the preceding periods is processed into standards and basic reference data concerning the length and the speed of the various refining activities. In our analysis of the operations management system, we will ignore the standards generating process: We assume in effect that the average performance does not change significantly during a single shift.

3. Planning Block. The planning procedure aims to ensure that the system targets are met. Formally, the targets are specified in two ways: 1) by incorporating the targets in the planning constraints; 2) by defining the objective function and attempting to optimize it. The outcome of the planning process is an operations plan which satisfies the requirements of the headquarters.

Assuming that the planned "crude" lead deliveries are met, the refining plant is required to fulfill the planned production of refined lead with minimum costs. The headquarters references dictate that the plan should be met while minimizing those production costs which have an essential impact on the technical-economic indices of production. These include the costs incurred when the batches are waiting for first alkaline refining and pouring activities to begin, and also idle time and "setup" costs in the pouring system [6]. The setup matrix of the pouring system $\|\gamma_{\eta_3\eta_3'}\|$, the amount of lead lost in each setup $\gamma_{\eta_3\eta_3'} = \Delta W|c_{\eta_3} - c_{\eta_3'}|$, where $\Delta W$ is the weight of lead lost in one setup, $c_{\eta_3}$ is the cost of 1 ton of "soft" lead of grade $\eta_3$, $\eta_3, \eta_3' \in \theta_3$.

The total production costs in shift $\nu$ when the lower-level element actually attains the state $y_\nu$ are formally representable in the form

$$\Phi(x_\nu, y_\nu) = \sum_{l \in M_9^1(\nu) \cup M_9^2(\nu)} \alpha[\min(\bar{t}_9^l, \nu T) - \max(\bar{t}_8^l, (\nu-1)T)] + \sum_{l-1, l \in M_{21}^1(\nu) \cup M_{21}^2(\nu)} \Big\{ \sum_{\eta_3, \eta_3' \in \theta_3} \Delta W | c_{\eta_3} y_{12\eta_3}^{l-1}$$

$$- c_{\eta_3'} y_{12\eta_3'}^l | + \beta_1[\min(\bar{t}_{20}^l, \nu T) - \max(\bar{t}_{19}^l, (\nu-1)T)] + \beta_2[\min(\bar{t}_{20}^l, \nu T) - \max(\bar{t}_{21}^{l-1}, (\nu-1)T)] \Big\}, \tag{1}$$

where $x_\nu = \{(l, q, j_q), \bar{t}_{qj_q}^l \,|\, (l, q, j_q) \in \bar{C}_t^x, t = \nu T\}$ is the plan of the $\nu$-th shift, $\bar{C}_t^x$ is the set of all planned jobs $(l, q, j_q)$ which should be finished or in process at the time moment $t$, $\alpha$ and $\beta_1$ are, respectively, the cost coefficients associated with waiting for activities 2 and 4 to begin; $\beta_2$ is the cost coefficient associated with idle time in the pouring system; $M_9^1(\nu)$, $M_{20}^1(\nu)$ is the set of batch indices for which activities 2 and 4 commence during the shift $\nu$; $M_9^2(\nu)$ and $M_{20}^2(\nu)$ is the set of batch indices waiting for activities 2 and 4 to commence in shift $\nu$; $\bar{t}_9^l = \max(\bar{t}_9^{l-1}, \bar{t}_8^l)$ starting time of activity 2 for batch $l$; $\bar{t}_{20}^l = \max(\bar{t}_{21}^{l-1}, \bar{t}_{19}^l)$ starting time of activity 4 for batch $l$; $\bar{t}_8^l$, $\bar{t}_{19}^l$, $\bar{t}_{21}^l$ completion times of activities 1, 3, 4 by one of the known technologies $\eta_1$, $\eta_2$, $\eta_3$.

A possible objective function of the headquarters for operations planning on the shop level calls for minimizing the total cost during V shifts

$$\Phi(x,y)=\sum_{\nu'=\nu}^{\nu+V}\Phi(x_{\nu'},y_{\nu'}). \tag{2}$$

Unlike an active element, which attempts to improve its own payoff function during a single shift, the headquarters is concerned with the broader consequences for the system of the state actually attained by the active element. This concern is reflected in the objective function (2). Note that the system objective function (2) depends implicitly on the plan $x = \{x_{\nu'}\}$.

When constructing the objective function (2), the headquarters forecasts the states of the active element in each of the next V shifts. The following forecasting model is used: the state of the system in the $\nu'$-th shift, $y_{\nu'}$, coincides with the corresponding shift plan $x_{\nu'}$, and the set of feasible states $Y_{\nu'}$ coincides with the set of feasible plans $X_{\nu'}$, $\nu' = \overline{\nu+1, \nu+V}$. The system objective function thus can be represented in the form

$$\Phi(x,y)=\min_{y_\nu\in Y_\nu(y_{\nu-1})}\Phi(x_\nu,y_\nu)+\sum_{\nu'=\nu+1}^{\nu+V}\Phi(x_{\nu'},x_{\nu'}). \tag{3}$$

Note that the functioning mechanism of a refining plant is a mechanism with partially centralized planning. This means that although all the states of the active elements are fully planned, the actual states selected by the elements do not necessarily coincide with the corresponding planned indices. The reason for these possible deviations from plan is the limited ability of the management to provide incentives that will encourage the production divisions to meet the plan without deviations.

The headquarters is unable to institute "stiff" penalities (large incentives) for underperformance (overperformance) of the plan. Therefore, it is important to ensure that the plan developed for the system is coordinated, or consistent, with the preferences of the divisions. The coordinated planning procedure assigns divisional plans $x_\nu$ from the set $S_\nu$ of coordinated plans, $x_\nu\in S_\nu$ [4]. The construction of the set $S_\nu$ will be considered in the next article.

4. Accounting Block. The function of the accounting block is to monitor the industrial functioning process, to measure the states at the end of each shift, to record this information, and to store and process it for further use. The path of the system states $y_\nu$ at each moment of time is recorded by the shift foreman on the shift report sheet. The reliability of this information is checked at the end of the shift by the next shift foreman. The state information is used to evaluate the performance of the divisions and to determine the incentives earned.

5. Control and Performance Evaluation Block. Performance indices are numerical characteristics which evaluate the degree of fulfillment of the planned targets. These indices are calculated by certain well-defined procedures and are ordered hierarchically to form the performance evaluation system. The planned indices and the actual state indices constitute the basic performance indices. The basic indices are aggregated into local performance evaluation measures, and the local measures are aggregated into overall performance evaluation measures.

Let us concretize the performance evaluation measures for the active elements. The local performance measure of a crew in the $\nu$-th shift, $P_\nu^c = P_\nu^c(x_\nu, y_\nu)$ is the sum of the index of jobs finished by the crew in the $\nu$-th shift, $P_{\nu 1}^c = P_1^c(y_\nu)$, and the index of meeting the shift target, $P_{\nu 2}^c = P_2^c(x_\nu, y_\nu)$, $P_\nu^c = P_\nu^c(x_\nu, y_\nu) = P_1^c(y_\nu) + P_2^c(x_\nu, y_\nu)$. The finished work index $P_1^c(y_\nu)$ is generated by aggregating (adding up) the costs $\lambda = \{\lambda_{qj_q}\}$ of the jobs finished by the crew during the shift, where $\lambda_{qj_q}$ is the cost of performing the q-th elementary activity by technology $j_q$. This index is calculated by the headquarters in the form

$$P_1^c(y_\nu)=\sum_{l\in\mathscr{L}}\sum_{q=1,q\neq 9}^{20}\sum_{j_q\in J_q}\lambda_{qj_q}y_{qj_q}^l(t)+\lambda_9 v_9(\nu)+\lambda_{21}u_{21}(\nu),\quad t\in[(\nu-1)T,\nu T]. \tag{4}$$

Here $v_9(\nu)$ is the percentage of Sn, As, Sb impurities removed during the $\nu$-th shift,

$$v_9(\nu)=\sum_{l\in M_9(\nu)}\alpha_9[\min(\nu T,\bar{t}_9^l)-\max((\nu-1)T,\underline{t}_9^l)],$$

$u_{21}(\nu)$ is the weight of lead poured during the $\nu$-th shift,

$$u_{21}(\nu)=\sum_{l\in M_{21}(\nu)}\sum_{j_{21}\in J_{21}}\alpha_{21j_{21}}y^l_{21j_{21}}[\min(\nu T,\bar{t}^l_{21j_{21}})-\max((\nu-1)T,\underline{t}^l_{21j_{21}})],$$

$M_9(\nu)$ is the set of batches on which activity 2 is performed during the $\nu$-th shift; $M_{21}(\nu)$ is the set of batches poured during the $\nu$-th shift; $\alpha_9$ is the actual output of the Harris installation; $\alpha_{21}=\{\alpha_{21j_{21}}\}$ is the output of the pouring system.

The finished work index $P^C_{\nu 1}$ of the crew in the $\nu$-th shift is thus uniquely determined by the state $y_\nu$, $P^C_{\nu 1}=P^C_1(y_\nu)$. Thus, in order to evaluate the index $P^C_{\nu 1}$, we need only the information supplied by the accounting block. The target fulfillment index is given in the form

$$P^C_{\nu 2}=P^C_2(x_\nu,y_\nu)=H_0 1[y_\nu,x_\nu],$$

where

$$1[y_\nu,x_\nu]=\begin{cases}1, & \text{if}\quad \forall(l,q,j_q)\in \bar{C}^x_t:\bar{t}^l_{qj_q}\leqslant \bar{t}^l_{qj_q}(x_\nu),\\ 0 & \text{otherwise},\end{cases}$$

$\bar{t}^l_{qj_q}(x_\nu)$ is the planned completion date of the job $(l,q,j_q)$, $H_0$ is the incentive that the crew earns for meeting the target. The local performance evaluation measure of the crew in the $\nu$-th shift thus has the form $(t\in[(\nu-1)T,\nu T])$

$$P^C(x_\nu,y_\nu)=\sum_{l\in\mathscr{L}}\sum_{q=1,q\neq 9}^{20}\sum_{j_q\in J_q}\lambda_{qj_q}y^l_{qj_q}(t)+\lambda_9 v_9(\nu)+\lambda_{21}u_{21}(\nu)+H_0 1[y_\nu,x_\nu]. \tag{5}$$

The performance evaluation measure of the shift foreman is the sum of two indices,

$$P^f(\tilde{y}_{\nu-1},y_{\nu-1},x_\nu,y_\nu)=P^f_1(\tilde{y}_{\nu-1},y_{\nu-1})+P^f_2(x_\nu,y_\nu), \tag{6}$$

where $P^f_1(\tilde{y}_{\nu-1},y_{\nu-1})$ is the index of reliability of the reported information about the state of the production process at the beginning of the $\nu$-th shift; $P^f_2(x_\nu,y_\nu)$ is an index quantifying the completion of the shift assignment by the crew, where

$$P^f_1(\tilde{y}_{\nu-1},y_{\nu-1})=\begin{cases}0, & \text{if}\quad \tilde{y}_{\nu-1}=y_{\nu-1},\\ H_1<0, & \text{if}\quad \tilde{y}_{\nu-1}\neq y_{\nu-1},\end{cases} \tag{7}$$

$$P^f_2(x_\nu,y_\nu)=H_2 1[y_\nu,x_\nu]-H_3(1-1[y_\nu,x_\nu]),\quad H_2,H_3>0. \tag{8}$$

6. Incentives Block. The local performance measures generated in the control and performance evaluation blocks are used to calculate the pay of the refining crews and the foremen bonuses from the payroll and incentive funds.

The incentive system $W=(W^C,W^f)$ for the active elements is a function of the overall performance evaluation measures of the crew $P_i^C=\sum_{i=1}^{V_i}P_{i\nu}^C$ and the foreman $P_i^f=\sum_{i=1}^{V_i}P_{i\nu}^f$ during the planning period, where $V_i$ is the number of shifts served by the i-th crew during the planning period. Specifically, for the i-th crew and its shift foreman the incentive system is written in the form $W_i^C(P^C)=\left(P_i^C/\sum_{i'\in I}P_{i'}^C\right)M_1$, $P^f=\{P_i^f\}$, $M_1$ is the total crew payroll, and $W_i^f(P^f)=\left(P_i^f/\sum_{i'\in I}P_{i'}^f\right)M_2$, $P^f=\{P_i^f\}$ ($M_2$ is the total amount of foremen bonuses).

We see from the expression for the incentive system that each active element is motivated to increase the value of the overall performance evaluation measure, which is an additive function of the local shift measures. Therefore, for purposes of operations management, the objective functions of the elements during the $\nu$-th shift naturally may be identified with the local performance evaluation measures $P^C(x_\nu,y_\nu)$ and $P^f(\tilde{y}_{\nu-1},y_{\nu-1},x_\nu,y_\nu)$. Then the game behavior of the crew given the plan $x_\nu$ will attempt to increase the local measure $P^C(x_\nu,y_\nu)$ by selecting the state $y_\nu\in Y_\nu$. It is quite possible that the state $y^*_\nu$ maximizing the value of $P^C(x_\nu,y_\nu)$,

$$P(x_\nu,y_\nu^*)=\max_{y_\nu\in Y_\nu}P(x_\nu,y_\nu), \tag{9}$$

does not coincide with the plan $x_\nu$. This may lead to underperformance of the shift assignment set by the headquarters. The planning procedure should therefore assign a plan $x_\nu$ so as to optimize the system objective function. On the other hand, the planning procedure should ensure that the crew payoff is sufficient to motivate the crew to fulfill the plan.

The objective function of the shift foreman in the ν-th shift is the performance evaluation measure $P_\nu^f$, which in its turn is a function of the system state estimate $\tilde{y}_{\nu-1}$ at the planning point as reported by the foreman, the true system state $y_{\nu-1}$, the shift plan $x_\nu$, and the state $y_\nu$, $P_\nu^f = P^f(\tilde{y}_{\nu-1}, y_{\nu-1}, x_\nu, y_\nu)$.

The shift foreman will attempt to maximize the local performance evaluation measure by reporting reliable state information $\tilde{y}_{\nu-1}$ and by ensuring that this crew achieves the state $y_\nu$.

7. Functioning of the System. The functioning of the refining plant with the mechanism Σ described above is schematically shown in Fig. 3, which identifies all the component blocks of the mechanism and their interconnections. We will describe the sequence of activities for each block and highlight some features of the functioning mechanism which are relevant for operations management of the industrial process.

At the beginning of the ν-th shift, the data-acquisition block receives information from the external environment about the delivery dates $g(\nu)$ of "crude" lead batches during the next V shifts, starting with the ν-th shift. It also receives system state reports $\tilde{y}_{\nu-1}$ from the active element as of the end of the $(\nu - 1)$-th shift. All the input information is aggregated in the form $\sigma_\nu = (g(\nu), \tilde{y}_{\nu-1})$ and is then passed to the planning block.

The reported system state is used because of unavoidable delays in the receipt of actual state information $y_{\nu-1}$ from the accounting block. In addition to the information $\sigma_\nu = (g(\nu), \tilde{y}_{\nu-1})$ from the data-acquisition block, the planning block also receives demand projections from the sales department for the next V shifts. These projections specify the required number of batches of "soft" lead of each grade and mold shape.

The planning block uses the planning procedure $x_\nu = x_\nu(\sigma_\nu)$ to generate a production plan, which is then communicated to the active element. The same information is fed to the control block. The communication of the production plan to the active element and to the control block is shown in Fig. 3 by the double line.

Given the shift plan $x_\nu$, the crew achieves the state $y_\nu$ maximizing its payoff function (9). The state $y_\nu$ achieved by the active element is recorded in the accounting block after the ν-th shift ends.

The actual state information is supplied by the accounting block to the control and performance evaluation block. The control and performance evaluation block compares the plan $x_\nu$ with the actual performance $y_\nu$ in order to calculate the local performance evaluation measure of the crew on the ν-th shift. The shift foreman is evaluated according to the degree of completion of the plan $x_\nu$ assigned to his shift and the reliability of the reported system state information $\tilde{y}_{\nu-1}$. The headquarters identifies the distortion of the information reported by the foreman after the planning stage, when the actual system state $y_{\nu-1}$ becomes known in the accounting block. Therefore the control block monitors the degree of distortion of the reported information, in addition to checking the actual system performance $y_\nu$ against the plan $x_\nu$. To this end, the information $\tilde{y}_{\nu-1}$ reported by the active element to the planning block should also be made available to the accounting block.

The control and performance evaluation block derives the local performance evaluation measures of the crew and the foreman and the shift production costs, i.e., determines the attained values of the objective functions of the active elements and the system as a whole. Information about local performance measures is fed to the incentive block in order to calculate the payroll and the bonuses to the active elements. The information from the control block is also delivered to the planning block for updating the production plan of the active elements given the deviation of actual performance from planned targets.

## APPENDIX

Procedure to Construct the Set $Y_\nu$

1. Take $t = (\nu - 1)T$ and find the set of finished jobs and jobs in process at the moment t, $\bar{C}_t = C_t \cup B_t$.

2. Identify the set of jobs $E_t$ which may begin at the moment t and generate the set of all jobs which are in process or may begin at the moment t,

3. For the set Lt, determine the maximal feasible frontiers $G_p(L_t)$ consisting of the triples $(l, q, j_q)$ such that for $y^l_{qj_q}(t) = 1$ the technological constraints are satisfied and for each maximal feasible frontier determine the completion dates of the included jobs,

$$T(G_p(L_t)) = \{\tilde{t}^l_{qj_q} \mid (l, q, j_q) \in G_p(L_t)\}, \quad p = \overline{1, \Pi_t}.$$

4. From the list $T(G_p(L_t))$ select the nearest completion moment $t = \min \tilde{t}^l_{qj_q}$ over $(l, q, j_q) \in G_p$ and take it as the current moment; include the finished job in the set $B_t$ of finished jobs, $p = \overline{1, \Pi_t}$.

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