Hierarchical On-Line Control Models for Man-Machine Production Systems under Random Disturbances

Doron Greenberg, Dimitri Golenko-Ginzburg

***Abstract* — The problem to be solved is the development of the theory of production control to work out certain mathematical models of optimal planning and control for a multilevel man-machine production system, solving coordination problems at different levels, and working out detailed mathematical models of planning, checking, and control at various levels of the hierarchy.**

***Index Terms* — coordination, inspection moments, multilevel man-machine production system, on-line control, optimal control.**

I. Introduction

In the latest six decades many scientists in the field of cybernetics have focused their research on creating mathematical models for hierarchical man-machine production systems (MMPS) under random disturbances.

Presently, a large number of mathematical models and methods have been developed for optimizing different planning and control functions for various levels of the hierarchy of discrete MMPS, many of which are applied to actual production (see, e.g., [1-3,14-23]). Among such developments, as a rule disconnected methodologically and of various trends of mathematical cybernetics, the overwhelming majority solve problems of planning; only an insignificant part of publications refer to the area of control problems.

It can be well-recognized that although at individual stages and phases of the production process these problems are often quite closely connected, in the general case they should be differentiated. In particular, the planning techniques presuppose a certain goal for each independent element of a multilevel MMPS, a goal which that element, possessing available resources, is intended to reach by the plan deadline.

As for the main control functions, they presuppose drawing up certain control actions ensuring that the preset goals will be reached. As a rule, a certain goal function (objective) or characteristic of the production process is optimized. Thus, methodological questions of control are connected with the methodology of planning, but they have several specific features.

Production is controlled through control actions that cannot be formed without analyzing the results of checking the state of production. In many fields of manufacturing, for example petrochemicals and sugar refining, determination of the quantity of intermediate and finished products is automatic and the personnel can find out at any time the production figures to enhance the progress of the system. However, in fields such as agriculture, construction, metallurgy and mining, as well as in research and development projects, it is quite difficult to evaluate how the program is proceeding. In endeavors for developing computer software and information systems this problem is especially relevant, as quite often this type of project tends to miss the deadline.

The created hierarchical control model includes the following basic conceptions:

- On-line control models.
- Local (internal) control models.
- External control actions in hierarchical control models.

II. On-Line Control Models

The control models to be considered are intended for the outlined above man-machine production systems for which the progress of the systems' advancement towards the goal cannot be inspected and measured continuously, but only at preset inspection (control) points. For all production units (PU) at the lower system's level on-line control has to determine both inspection points and control actions to be implemented at those points to alter the progress of the PU in the desired direction. On-line control is carried out to minimize the number of inspection points needed to meet the target, since inspecting the units' output is usually a costly operation. In certain cases, on-line control for a PU under random disturbances has to be carried out subject to a chance constraint. Thus, the generalized on-line production control model has to be formulated as follows [4-8]: determine both optimal control points t_g to inspect the PU and optimal control actions $CA(t_g, r_g)$ to be implemented at those control (inspection) points (r_g being the index of the control action), in order to minimize the number W of inspection points

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$$\min_{\{t_g, r_g\}} W \tag{1}$$

subject to

$$\Pr\{t_g, r_g\} \geq p^*, \tag{2}$$

$$t_0 = 0, \tag{3}$$

$$t_W = D, \tag{4}$$

$$t_{g+1} - t_g \geq \Delta. \tag{5}$$

Here D is the due date and $\Pr\{t_g, r_g\}$ is the restricted from below probability of meeting the deadline on time, when introducing $CA(t_g, r_g)$.

Note that if implementing control action $CA(t_g, r_g)$ results in determining the *unit's production speed* v_{t_g} to proceed with until the next inspection point t_{g+1} and if *several alternative speeds can be chosen*, then the optimal control action enables adopting the *minimal speed* while honoring chance constraint (2).

It can be well-recognized [4-8] that control model (1-5) is in fact a stochastic optimization problem with a non-linear chance constraint and a random number of optimized variables. Such a problem is too difficult to solve in the general case. Thus, heuristic control algorithms have been developed [4-6] to determine the next inspection point t_{g+1}. Three different classes of algorithms are considered:

I. Using sequential statistical analysis to maximize the time span between two adjacent inspection points $\Delta t_g = t_{g+1} - t_g$ [9].

II. Using the methodology of a risk-averse decision-maker [4-8].

III. Using the methodology of the chance constraint principle [4-6,10-11,13].

Based on on-line control, trajectory curves to inspect the state of the unit's program have to be determined and repeatedly corrected within the production process.

III. Local (Internal) Control Models

After inspecting the state of the unit's program in inspection points the management may decide to speed up the intensity level of the considered unit. This usually happens when a misbalance in the course of the production process is observed. Henceforth we will call such control a local one, underscoring that the velocity of the movement of a system's unit towards the goal changes exclusively by flexible monitoring of the unit's resources and is not connected with any influence or actions of other elements from outside.

The general idea of such a flexible resource monitoring is illustrated on the following example. Assume that after inspecting a production unit at moment $t > 0$ a conclusion has been drawn that the unit, if continues production at the current intensity rate, would be unable to meet its due date on time. The unit at moment t comprises n_t jobs to be operated in a pregiven technological sequence (e.g., in a consecutive chain order). Each job J_k, $k = 1,2,...,n_t$, has a random duration $t(c_k)$ with p.d.f. depending parametrically on the budget value c_k assigned to J_k. Denote:

$c_{k\min}$ and $c_{k\max}$ - the minimal and maximal (non-redundant) budget values to operate J_k;

D - the unit's due date;

C_t - the remaining unit's budget observed via inspection;

$T[c_k, k = 1,2,...,n_t]$ - the random duration to carry out the remaining unit's program on condition that values c_k would be assigned to jobs J_k, $k = 1,2,...,n_t$.

The local control action to be introduced is as follows:

Solve optimal budget reallocation problem to determine values c_k^*, $k = 1,2,...,n_t$, in order to maximize the probability of meeting the unit's due date on time

$$\max_{\{c_k\}} \Pr\{t + T[c_k, k = 1,2,...,n_t] \leq D\} \tag{6}$$

subject to

$$c_{k\min} \leq c_k^* \leq c_{k\max}, \tag{7}$$

$$\sum_{k=1}^{n_t} c_k^* = C_t. \tag{8}$$

Problem (6-8) has been solved by means of simulation [4-8].

If the maximized objective (6) enables meeting the due date on time, budget C_t has to be redistributed among the jobs, $c_k = c_k^*$, new control trajectories have to be determined, and the unit proceeds with the program's realization. Otherwise, if the probability value in (6) is insufficient, external control actions have to be introduced.

However, a conclusion can be drawn from practical studies [12-13] that in many cases a production unit, being behind the plan in heading towards its set goal contains several latent resource reserves, which if mobilized (when the misbalance does not exceed a particular limit), make it possible to overcome the lag. Thus, it is expedient to resort to external control only in cases when local control proves inefficient.

IV. External Control Actions in Hierarchical Control Models

External control actions are always connected with coordination problems at different levels of hierarchical control models.

Note that the problem of coordination can be solved on the basis of the Mesarovich interaction balance principle [17].

The problem is just as urgent, and still insufficiently developed, of devising a scientific basis for determining control actions. Analyzing scientific literature in this field brings to the conclusion that besides for a few studies, there are no clear, formalized conceptions of the basic kinds, types, and categories of control actions.

A conclusion can be drawn that there is a need for mathematical techniques combining local models listed above into a unified integrated model for the optimal control of multilevel production systems. On the other hand, it can be well-recognized that such a model of analytical type is impossible to create at present. Indeed, it is a question of devising a group of non-linear dynamic models with a large number of restrictions imposed. Such models should feature step-by-step decision-taking at inspection (query) moment-points, and models of multicriterial optimization; in several cases dynamic models of the process whereby the system functions are so complicated that they cannot be described analytically at all.

We have developed [6] a virtual three-level analytical production control model with hierarchical levels coordinated by means of Mesarovich interaction balance principle. Each level comprises a variety of complicated optimization models with appropriate linkage. However, due to the complexity of the analytical control model, optimization models cannot be reduced to control algorithms and, thus, are unfit to be used in practice. To simplify the control model, we have substituted the interaction balance principle by another one, namely, the conception of emergency situations [8,12-13] which has been created within the last two decades.

The regarded approach to the interaction submodels in hierarchical MMPS, based on the conception of emergency, is as follows. By using the idea that hierarchical levels can interact only in special situations, the so-called emergency points, one can decompose general and complicated multi-level problems of optimal production control into sequences of one-level problems [4-8]. We will illustrate the general idea of this approach on an example of a four-level MMPS: company $\to$ section $\to$ production unit $\to$ inspection level via on-line control. The unit's description has been outlined above, in Section III.

Problem A, at the factory level, enables optimal budget reallocation and production program reassignment among the sections. The problem's solution, i.e., the budget and target amount, are assigned to each section and serve as initial data for Problem B (at the section level), where budget and target amounts are redistributed among the production units to maximize the probability of meeting the section's deadline. The solution of Problem B serves, in turn, as initial data for Problem C, where budget assigned to the unit, is reassigned among the unit's jobs. Problem D at the inspection level facilitates on-line control, i.e., determines optimal control points to inspect the progress of the production unit. This is done by determining planned trajectories that should be repeatedly corrected in the course of the unit's functioning.

If, at any inspection point, it turns out that a certain unit deviates from the planned trajectory, an error signal at the unit's level is generated and local control action is introduced to reassign the remaining unit's budget among the remaining jobs (see Section III) to maximize the probability of meeting the due date on time. If the problem's solution enables the unit's deadline to be met, subject to the chance constraint, a corrected planned trajectory is determined, the unit proceeds functioning and Problem D is resolved to determine the next inspection (control) pint. Otherwise an emergency signal is generated, and decision-making is carried out at the section level.

First an attempt has to be made to carry out optimal reassignment of both budget values and target amounts among the subordinated units in order to maximize the probability of the section to meet its deadline. This procedure is, in fact, analogous to local control actions at a higher hierarchical level, like the one carried out by means of Problem B. If such an attempt is successful, optimal budget and target amounts are reassigned among subordinated units. The latter reassign the budgets obtained among subordinated units (Problem C). If the section fails to overcome the lag, an overall emergency is declared and Problem A at the company level is resolved under emergency conditions to reassign the remaining budget and the production program among the non-accomplished sections.

It can be well-recognized that optimizing the system from top to bottom at $t = 0$ refers actually to the planning stage. In case of emergency, at $t > 0$, the generated "bottom $\to$ top" signals are converted into control actions to enable the system to meet its due date on time. On our opinion, the outlined research provides a linkage between planning and control stages.

In our example we utilized only one type of resources (the budget value). However, in most practical cases, three-level production systems [12-13] "factory $\to$ section $\to$ production unit" operate usually in a multiproduct and multiresource mode. The outlined below system comprises the factory level, several sections and multiple production units. Within the planning horizon, the factory is required to manufacture several different products with planned target amounts. Each unit can manufacture all kinds of products. In the course of manufacturing, each unit utilizes different types of non-consumable resources which may be reallocated among the sections and later on among the units. Each production unit can manufacture a product at several possible speeds. Those speeds depend only on the degree of intensity of manufacturing and are subject to random disturbances. To carry out the process of manufacturing, the products have to be rescheduled among sections and among the units. This means that for each unit and for each product assigned to that unit, the corresponding planned amount and the planning horizon have to be determined. Controlling the system is carried out at four levels: the factory level, the section level, the unit level and the inspection level. At the unit level, all production units are controlled separately. For each unit and for each product manufactured by that unit, risk averse decision-making centers on determining control points to observe the output of the product and the speeds required to manufacture it. If, at a routine control point, it is anticipated that a unit will be unable to meet its deadline on time, an emergency is called. The section level is then faced with the problem of both resource reallocation and target amount reassignment among the units subordinated to that section. New resource capacities and target amounts for each product and each production unit are decision variables to be determined. The objective at rhe section level is to maximize the probability of the slowest unit to accomplish the planned amounts of its products by the due date. If a certain section cannot reach its target on time, an overall emergency is declared. In such case, both the target amounts and the resource capacities for all sections have to undergo optimal reallocation at the factory level. The objective at the factory level at $t = 0$ is to minimize the budget for renting and utilizing resources within the planning horizon. In case of an overall emergency (at $t > 0$), a dual problem has to be solved at the factory level: to reallocate the remaining target amounts and resources - subject to the remaining limited budget.

The outlined above hierarchical control model has been successfully used in various real production systems [12-13].

V. Conclusions

1. The presented in Section IV both types of multilevel on-line control models for a MMPS are the backbone of our research.
2. The second type of models based on emergency situations can be regarded as a simplified modification of the Mesarovich theory [17]. The model provides coordination between adjacent hierarchical levels, but this coordination is not the optimal one.
3. It can be well-recognized that the multilevel control model based on emergency situations carries out non-optimal, heuristic monitoring, unlike the hierarchical on-line control model based on interaction balance principles which carries out optimal planning and control. However, the first model is in usage over a lengthy period, while the other one can be used nowadays for virtual presentation only. It requires computers of future generations. But in our opinion, the future belongs to this conception. Thus, we decided to present both those principles to create multilevel MMPS.

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