METHODS AND ALGORITHMS OF SHIP-BUILDING MANUFACTORY OPERATION AND RESOURCES SCHEDULING

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ABSTRACT
We present a new multiple-model description and algorithms of ship-building manufactory scheduling. This description is represented as a special case of the job shop-scheduling problem with dynamically distributed jobs. The approach is based on a natural dynamic decomposition of the problem and its solution with the help of a modified form of continuous maximum principle coupled with combinatorial optimization.

Keywords: ship-building manufactory, shop-scheduling problem, optimal control, combinatorial optimization

1. INTRODUCTION
Nowadays the development of computer-aided decision-making procedures, as well as procedures of automatic planning and scheduling, for complex technical-organizational systems (CTOS) design, maintenance, and improvement remains a very important problem. In the paper we investigate problems of operation and resources scheduling for ship-building manufactory (SBM) as a possible variant of CTOS. Scheduling, in the broad sense, is a purposeful, organized, and continuous process including examination of SBM elements, analysis of their current state and interaction, forecasting of their development for some period, forming of mission-oriented programs and schedules. Our investigation have shown that the SBM operation and resources scheduling, as a phase of decision-making, has several peculiarities: scheduling is a preliminary designing of organization make-up and functioning mechanism providing goal achievement by a given time; the result of scheduling is a system of interrelated distributed time-phased decisions, while the function of planning is directly connected with the function of control, since designing and keeping of program trajectories use common resources; the process of scheduling permanently approaches the end but never reach it because of two reasons: firstly, revising of decisions lasts until actual actions are performed; secondly, the system and the environment can change during the planning process, therefore it is necessary to correct plans periodically; scheduling is aimed at prevention of erroneous operations and at decrease of unimproved opportunities.
In a general case, planning is concerned with the following groups of tasks (Ackoff., (1978), Chen Z.-L. and Hall NG, (2007), Ivanov D., Sokolov B. (2012, 2013), Werner F. & Sotskov Y (2014)): 1) forming of SBM goals and objectives, i.e., evaluation of preferable states and time for achievement of goals and objectives; 2) determination of means and instruments for goals and objectives achievement; 3) determination of resources and their sources for implementation of plans, as well as development of principles and methods for resources allocation; 4) design of SBM make-up (first of all, development of SBM main structures) and SBM functioning algorithms providing continuity of integrated scheduling and control.
Three planning approaches (concepts, philosophies) emerged by now: satisfactory (incremental), formal, and system (comprehensive) planning. Formal planning concentrates on prediction of situation in terms of mathematical models, satisfactory planning consider SBM reactions to external impacts, system planning supports SBM interaction with the environment. System planning implies problem resolution and redefinition through learning process, rather than problem solving. This lets interpret planning not as discrete operations, but as continuous adaptive process. That was called adaptive planning. A posteriori, current, and a priori information can be used for plan adaptation (adaptation to the “past”, “present”, or “future”).

In this paper, we mainly consider the only one stage of the described technology, namely scheduling of SBM operation and resources scheduling (Ackoff., (1978), Chen Z.-L. and Hall NG, (2007), Ivanov D., Sokolov B. (2012, 2013).

We used a dynamic interpretation of SBM functioning for formal statement of the problem. This approach resulted in essential reduction of a problem dimensionality and in advantages of the proposed combine algorithms because of its connectivity decrease.

We propose to use two methods for optimization of SBM operation and resources scheduling, and for simulation of SBM operation and optimization of resources scheduling execution: local section method (modification of the L.S. Pontryagin maximum principle) and a method of discrete programming.

The dimensionality of SBM scheduling problem is determined by the number of independent paths in a network diagram of SBM operations and by current spatiotemporal, technical, and technological constraints. In its turn, the degree of algorithmic connectivity depends on a dimensionality of the main and the conjugate state vectors (Chen Z.-L., G.L. Vairaktarakis, (2005), Khmelnitsky E., Kogan K., Maimom O. (1997, 2000)., Ye H. and Liu R (2016), Ivanov D., Sokolov B. (2012, 2013)).

2. MODELS, METHODS AND ALGORITHMS OF SHIP-BUILDING MANUFACTORY OPERATION AND RESOURCES SCHEDULING

We propose a multiple-model description of the ship-building manufactory scheduling problem. The multiple-model complex includes a dynamic model of job and resource control in ship-building manufactory and a dynamic model of flow (material, energy, information) control in ship-building manufactory. Let us consider the proposed multiple-model description in more detail.

2.1. The Dynamic model of job and resource control in ship-building manufactory (model M1)

We consider the mathematical model of job and resource control. We denote the job state variable $x_{i\mu}^{(o)}$, where (o) — indicates the relation to jobs (orders). The execution dynamics of the job $D_{\mu}^{(i)}$ can be expressed as (1).

$$\frac{dx_{i\mu}^{(o)}}{dt} = x_{i\mu}^{(o)} = \sum_{j=1}^{n} \varepsilon_{ij}(t) u_{i\mu j}^{(o)} \tag{1}$$

where $\varepsilon_{ij}(t)$ is an element of the preset matrix time function of time-spatial constraints, $u_{i\mu j}^{(o)}(t)$ is a 0–1 assignment control variable.

Let us introduce equation (2) to assess the total resource availability time:

$$x_{j}^{(o)} = \sum_{i=1}^{\bar{n}} \sum_{\substack{\eta=1 \\ \eta \neq i}}^{\bar{n}} \sum_{\mu=1}^{s_i} \sum_{\rho=1}^{p_i} (u_{i\mu j}^{(o)}) \tag{2}$$

Equation (2) represents resource utilization in job execution dynamics. The variable $x_{j}^{(o)}$ characterizes the total employment time of the j-supplier. The control actions are constrained as follows:

$$\sum_{i=1}^{\bar{n}} \sum_{\mu=1}^{s_i} u_{i\mu j}^{(o)}(t) \le 1, \forall j; \ \sum_{j=1}^{n} u_{i\mu j}^{(o)}(t) \le 1, \forall i, \forall \mu \tag{3}$$

$$\sum_{j=1}^{n} u_{i\mu j}^{(o)} [\sum_{\alpha \in \Gamma_{i\mu_1}^{-}} (a_{i\alpha}^{(o)} - x_{i\alpha}^{(o)}) + \prod_{\beta \in \Gamma_{i\mu_2}^{-}} (a_{i\beta}^{(o)} - x_{i\beta}^{(o)})] = 0 \tag{4}$$

$$u_{i\mu j}^{(o)}(t) \in \{0,1\}; \tag{5}$$

where $\Gamma_{i\mu_1}^{-}$, $\Gamma_{i\mu_2}^{-}$ are the sets of job numbers which immediately precede the job $D_{\mu}^{(i)}$ subject to accomplishing of all the predecessor jobs or at least one of the jobs correspondingly, and $a_{i\alpha}^{(o)}, a_{i\beta}^{(o)}$ are the planned lot-sizes. Constraint (3) refers to the allocation problem constraint according to the problem statement (i.e., only a single order can be processed at any time by a manufacturer). Constraint (4) determines the precedence relations, moreover this constraint implies the blocking of operation $D_{\mu}^{(i)}$ while the previous operations $D_{\alpha}^{(i)}, D_{\beta}^{(i)}$ are being executed. If $u_{i\mu j}^{(o)}(t) = 1$, all the predecessor jobs of the operation $D_{\mu}^{(i)}$ should be executed. Constraint (4) formalize basic ship-building manufactory technology. Note that these constraints are identical to those in traditional mathematical programming (MP) models.

Corollary 1. The analysis of constraints (4) shows that control $\mathbf{u}(t)$ *is switching on only when the necessary predecessor operations are being executed.* $\sum_{j=1}^{n} u_{i\mu_j}^{(o)} \sum_{\alpha \in \Gamma_{i\mu_1}^{-}} (a_{i\alpha}^{(o)} - x_{i\alpha}^{(o)}(t)) = 0$ *guarantees the total processing of all the predecessor operations, and* $\sum_{j=1}^{n} u_{i\mu_j}^{(o)} \prod_{\beta \in \Gamma_{i\mu_2}^{-}} (a_{i\beta}^{(o)} - x_{i\beta}^{(o)}) = 0$ *of at least one of the predecessor operations.*

According to equation (5), controls contain the values of the *Boolean variables*. In order to assess the results of job execution, we define the following initial and end conditions at the moments $t = T_0$, $t = T_f$:

$$x_{i\mu}^{(o)}(T_0)=0;\ \ x_{i\mu}^{(o)}(T_f)=a_{i\mu}^{(o)}; \tag{6}$$

Conditions (6) reflect the desired end state. The right parts of equations are predetermined at the planning stage subject to the lot-sizes of each job.

According to the problem statement, let us introduce the following performance indicators (7)–(10):

$$J_1^{(o)}=\frac{1}{2}\sum_{i=1}^{\bar{n}}\sum_{\mu=1}^{s_i}[(a_{i\mu}^{(o)}-x_{i\mu}^{(o)}(T_f))^2] \tag{7}$$

$$J_2^{(o)}=\sum_{i=1}^{\bar{n}}\sum_{\mu=1}^{s_i}\sum_{j=1}^{n}\int_{T_0}^{T_f}\alpha_{i\mu}^{(o)}(\tau)u_{i\mu j}^{(o)}(\tau)d\tau \tag{8}$$

$$J_3^{(o)}=\frac{1}{2}\sum_{j=1}^{n}(T-x_j^{(o)}(T_f))^2 \tag{9}$$

The performance indicator (7) characterizes the accuracy of the end conditions' accomplishment, i.e. the service level of *ship-building manufactory*. The goal function (8) refers to the estimation of a job's execution time with regard to the planned supply terms and reflects the delivery reliability, i.e., the accomplishing the delivery to the fixed due dates. The functions $\alpha_{i\mu}^{(o)}(\tau)$ are assumed to be known, and characterize the fulfilment of time conditions for different jobs and time points, as the penalties increase due to breaking supply terms. The indicator (9) estimates the equal resource utilization in the *ship-building manufactory*.

2.2. The Dynamic model of flow control in ship-building manufactory (model M2)

We consider the mathematical model of flow control in the form of equation (10):

$$\dot{x}_{i\mu j}^{(f)}=u_{i\mu j}^{(f)}\ ,\ \dot{x}_{ij\eta\rho}^{(f)}=u_{ij\eta\rho}^{(f)} \tag{10}$$

We denote the flow state variable $x_{i\mu j}^{(f)}$, where (f) indicates the relation of the variable *x* to flows.

The control actions are constrained by maximal capacities and intensities as follows:

$$\sum_{i=1}^{\bar{n}}\sum_{\mu=1}^{s_i}u_{i\mu j}^{(f)}(t)\le\tilde{\tilde{R}}_{1j}^{(f)}\ ,\ \sum_{\rho=1}^{p_i}u_{ij\eta\rho}^{(f)}(t)\le\tilde{\tilde{R}}_{1j\eta}^{(f)}\ , \tag{11}$$

$$0\le u_{i\mu j}^{(f)}(t)\le c_{i\mu j}^{(f)}\cdot u_{i\mu j}^{(o)}\ ,\ 0\le u_{ij\eta\rho}^{(f)}(t)\le c_{i\eta\rho j}^{(f)}\cdot u_{i\eta\rho j}^{(o)}\ , \tag{12}$$

where $\tilde{\tilde{R}}_{1j}^{(f)}$ is the total potential intensity of the resource $C^{(j)}$, $\tilde{\tilde{R}}_{1j\eta}^{(f)}$ is the maximal potential channel intensity to deliver products to the customer $\bar{B}^{(\eta)}$ of results of *ship-building manufactory*, $c_{i\mu j}^{(f)}$ is the maximal potential capacity of the resource $C^{(j)}$ for the job $D_\mu^{(i)}$, and $c_{i\eta\rho j}^{(f)}$ is the total potential capacity of the channel delivering the product flow $P_{<s_i,\rho>}^{(j,\eta)}$ of the job $D_\mu^{(i)}$ to the customer $\bar{B}^{(\eta)}$ of results of *ship-building manufactory*.

The end conditions are similar to those in (6) and subject to the units of processing time. The goal functionals of the flow control model are defined in the form of equations (14) and (15):

$$J_1^{(f)}=\frac{1}{2}\sum_{i=1}^{\bar{n}}\sum_{\mu=1}^{s_i}\sum_{j=1}^{n}[(a_{i\mu j}^{(f)}-x_{i\mu}^{(f)}(T_f))^2+\sum_{\substack{\eta=1\\ \eta\ne i}}^{\bar{n}}\sum_{\rho=1}^{p_i}(a_{ij\eta\rho}^{(f)}-x_{ij\eta\rho}^{(f)}(T_f))^2] \tag{13}$$

$$J_2^{(f)}=\frac{1}{2}\sum_{i=1}^{\bar{n}}\sum_{\mu=1}^{s_i}\sum_{j=1}^{n}\int_{T_0}^{T_f}\beta_{i\mu}^{(f)}(\tau)u_{i\mu j}^{(f)}(\tau)d\tau\ . \tag{14}$$

The economic meaning of these performance indicators correspond to equations (7) and (8). With the help of the weighting performance indicators, a general performance vector can be denoted as (16):

$$\mathbf{J}(\mathbf{x}(t),\mathbf{u}(t)=\left\|J_1^{(o)},J_2^{(o)},J_3^{(0)},J_1^{(f)},J_2^{(f)}\right\|^{\mathrm{T}}\ . \tag{15}$$

The partial indicators may be weighted depending on the planning goals and SC strategies. Original methods (Okhtilev M. Y., Sokolov B.V., Yusupov R.M. (2006), Ivanov D., Sokolov B. (2012, 2013)) have been used to transform the vector $\mathbf{J}$ to a scalar form J_G.

The job shop scheduling problem can be formulated as the following problem of OPC: it is necessary to find an allowable control $\mathbf{u}(t)$, $t\in(T_0,T_f]$ that ensures for the model (1)–(2), and (10) meeting the vector constraint functions $\mathbf{q}^{(1)}(\mathbf{x},\mathbf{u})=0$, $\mathbf{q}^{(2)}(\mathbf{x},\mathbf{u})\le 0$ (3)–(5) and (10–11), and guides the dynamic system (i.e., job shop schedule) $\dot{\mathbf{x}}=\boldsymbol{\varphi}(t,\mathbf{x},\mathbf{u})$ from the initial state to the specified final state. If there are several allowable controls (schedules), then the best one (optimal) should be selected in order to maximize (minimize) J_G. In terms of optimal program control (OPC), the program control of job execution is at the same time the job shop schedule. The formulated model is a linear non-stationary finite-dimensional controlled differential system with the convex area of admissible control. Note that the *boundary problem* is a standard OPC problem; see [4-6]. In fact, this model is linear in the state and control variables, and the objective is linear. The transfer of non-linearity to the constraint ensures convexity and allows to use interval constraints.

We propose a method and algorithm of ship-building manufactory which are based on local section method and methods of discrete programming. Scheduling problems of the considered class are usually solved via methods of discrete programming, but when the dimensionality is high, the optimal solution is not provided and heuristic algorithms are needed. We suggest an original approach, based on integration of models and methods of optimal control theory with methods of bivalent programming, to ship-building manufactory scheduling problems of high dimensionality.

Necessary optimality conditions can be derived from the maximum principle (Athans M., & Falb, P.L(1966)). Consider control system (9).

$$\mathbf{x}(t) = f(t,\mathbf{x}(t),\mathbf{u}(t)),\; t_0 \le t \le t_f,$$
$$\mathbf{x}(t_0) = \mathbf{x}_0,\; \mathbf{u}(t) \in U, \tag{16}$$
$$J = F(\mathbf{x}(t_f)) \to \mathbf{min}$$

Let us introduce a scalar Hamiltonian function H and conjunctive vector system $\psi \in R^n$ in Eq. (17).

$$H(t,\mathbf{x}(t),\mathbf{u}(t),\psi(t)) = \psi^{\mathrm{T}}(t)\mathbf{f}(t,\mathbf{x}(t),\mathbf{u}(t)),$$
$$\psi(t) = -\frac{\partial H}{\partial \mathbf{x}}(t,\mathbf{x}(t),\mathbf{u}(t),\psi(t)), \tag{17}$$

$$\psi(t_f) = -\left.\frac{\partial F(\mathbf{x}(t))}{\partial \mathbf{x}}\right|_{t=t_f}, \tag{18}$$

Conjunctive vector system plays the role of dual models in linear programming. Coefficients of the conjunctive systems can be interpreted as Lagrange multipliers. Under assumptions that $\mathbf{u}(t)$ is optimal control and $\mathbf{x}(t)$ and $\psi(t)$ are the trajectory and conjunctive system satisfying (17) and (18), the function $H(t,\mathbf{x}(t),\mathbf{u}(t),\psi(t))$ reaches its maximum for $\mathbf{x}(t)$ at the point $\mathbf{u}(t)$. Then Eq. (19) holds:

$$\mathbf{u} = \mathbf{u}(t,\mathbf{x}(t),\psi(t)) \tag{19}$$

Subsequently, Eq. (19) is brought into correspondence with (17) and (18). In the result, a two-point boundary problem for a system of ordinary differential equations in regard to $\mathbf{x}(t)$ and $\psi(t)$ is formed. The optimal solution is now bounded by this differential system. Note that Eq. (17)-(19) in general case provide only necessary conditions for optimal solution existence whereas for linear control systems these maximum principles provide both optimality and necessary conditions.

The basic peculiarity of the boundary problem considered is that the initial conditions for the conjunctive variables $\psi(t_0)$ are not given. At the same time, an optimal program control should be calculated subject to the boundary conditions. To obtain the conjunctive system vector, the Krylov–Chernousko method of successive approximations for an optimal program control problem with a free right end which is based on the joint use of a modified successive approximation method has been used (Krylov I.A., & Chernousko F.L. (1972)).

Step 1. An initial solution $\bar{\mathbf{u}}(t),\, t \in (t_0, t_f]$ (a feasible control, in other words, a feasible schedule) is selected and $r=0$.

Step 2. As a result of the dynamic model run, $\mathbf{x}^{(r)}(t)$ is received. Besides, if $t = t_f$ then the record value $J_G = J_G^{(r)}$ can be calculated. Then, the transversality conditions (18) are evaluated.

Step 3. The conjugate system (17) is integrated subject to $\mathbf{u}(t) = \bar{\mathbf{u}}(t)$ and over the interval from $t = t_f$ to $t = t_0$. For the time $t = t_0$, the first approximation $\psi_i^{(r)}(t_0)$ is obtained as a result. Here, the iteration number $r=0$ is completed.

Step 4. From the time point $t = t_0$ onwards, the control $\mathbf{u}^{(r+1)}(t)$ is determined ($r = 0,1,2,\ldots$ denotes the number of the iteration). In this case during the maximization of the Hamiltonian different tasks of mathematical programming should be solved. The dimensionality of these tasks is low, and the problem dimensionality is determined by the number of independent paths in a network diagram of ship-building manufactory operations and by current spatial-temporal, technical, and technological constraints. In parallel with the maximization of the Hamiltonian, the main system of equations and the conjugate one are integrated. The maximization involves the solution of several mathematical programming problems at each time point.

The advantage of method of successive approximations is that it allows to implement needle-shape control variations to the whole area of feasible control actions subject to the given constraint system, i.e., the area of feasible schedules [8]. Another advantage of the method is that the search for an optimal control in each iteration is performed in the class of boundary (e.g., pointwise or relay) functions which correspond to the discrete nature of decision making in scheduling. Note that the method of successive approximations in its initial form does not guarantee the convergence.

3. SOFT-WARE PROTOTYPE

In the paper we present a software prototype of SBM operation and resources scheduling. The software has three modes of operation with regard to scheduling and an additional mode to analyze stability of the schedules. The first mode includes the interactive generation/preparation of the input data. The second mode lies in the evaluation of heuristic and optimal SBM operation and resources scheduling. The following operations can be executed in an interactive regime: • multi-criteria rating, analysis, and the selection of SBM plans and schedules; • the evaluation of the influence that is exerted by time, economic, technical, and technological constraints upon SBM structure dynamics control; and • the evaluation of a general quality measure for SBM plans and schedules, and the evaluation of particular performance indicators. The third mode provides interactive selection and visualization of SBM schedule and report generation.

The approach proposed in this article was used while carrying out the research work devoted to the investigation and selection of methods and algorithms of solving tasks of integrated and simulation modeling as well as multi-criteria analysis of the manufacturing systems in shipbuilding industry (Aframchuk E.F., Vavilov A.A., Emel'yanov S.V. et al., (1998), Okhtilev M. Y., Sokolov B.V., Yusupov R.M (2010)). Business Process Modelling Notation (BPMN) was used to develop and perform SBM operation and resources scheduling including technological and auxiliary manufacturing processes. In Figure 1 one can find an extract of specified processes description.

A consistent use of simulation and analytical logic-dynamic model on the basis of BPMN application allowed to extend the set of calculated indices of shipbuilding enterprise functioning and to make computation, multi-criteria evaluation and analysis of structure dynamics of a shipbuilding enterprise under different variants of input effect. It is important to emphasize once again that designed special software of ship-building manufactory scheduling using BPMN represents unified modern automation tool for modeling built on service-oriented architecture and web-technologies.

4. CONCLUSIONS

Problems of ship-building manufactory scheduling may be challenged by high complexity, combination of continuous and discrete processes, integrated production and transportation operations as well as dynamics and resulting requirements for adaptability. A possibility to address these issues opens the embedding of OPC into ship-building manufactory scheduling and using its advantages in combination with advantages of mathematical programming (MP). Under the assumption that the introduction of the dynamic aspect of job arrival can have a significant impact on the solution procedure, this study presented a new original model for ship-building manufactory scheduling as OPC of job execution dynamics coupled with combinatorial optimization and based on a natural dynamic decomposition of the scheduling problem and its solution with maximum principle in combination with MP. The proposed substitution lets use fundamental scientific results of the OPC theory in ship-building manufactory scheduling.

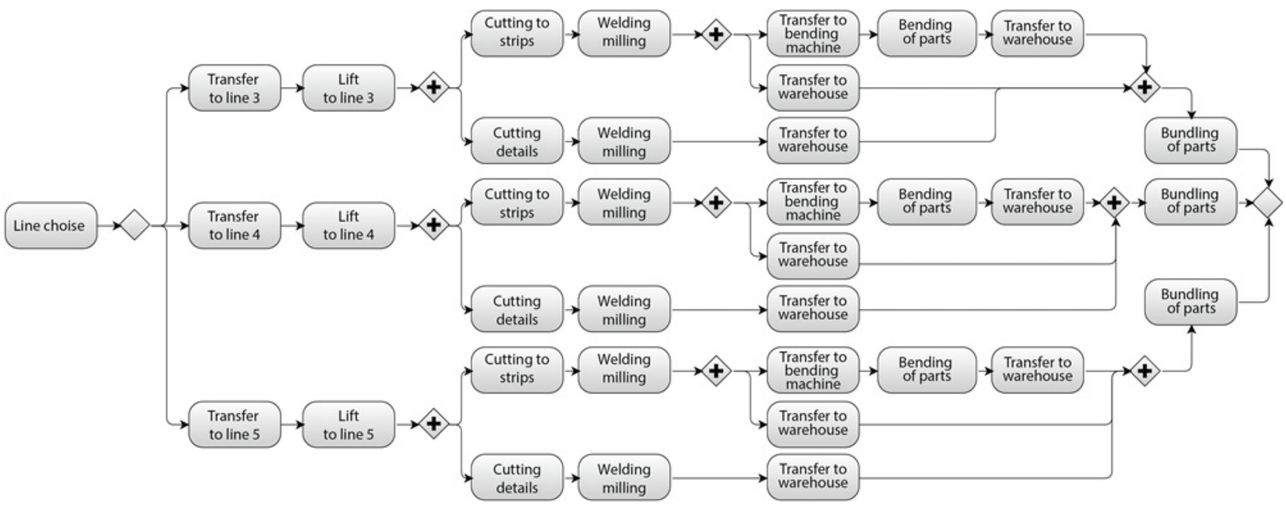

Figure 2: Fragment of ship-building manufactory in BPMN

ACKNOWLEDGMENTS

The research is supported by the Russian Science Foundation (project № 17-11-01254).

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