Simulation-Based Multi-Criterion Approach to Production Processes Control

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Abstract: The basic simulation model for the management of Manufacturing Systems is given. The problem of multi-criteria management of technological process of constructing the simulation model in the corporate information system of the industrial enterprise is solved. The optimization problem is solved in accordance with the principle of Bellman's optimality. The example of solving an optimization problem is given. The application of simulation models for production planning is written.

Keywords: simulation model, multicriteria management, Bellman optimality principle, manufacturing system

1. INTRODUCTION

The advanced control methodology (Novikov, 2013) considers the control of the organization activity, emphasizing the project-and-technological type of the activity, and the knowledge-based type. In the control methodology, a general structure of the control theory and its components is defined, psychological, sociological, philosophical, ethical and esthetical grounds of the activity are developed, what enables one to improve and optimized the organization activity.

The knowledge is a strategic resource of an organization, but information technologies (IT) enables one to improve the knowledge exchange between organizations members/employees. Researches implemented (Mehta, 2014) have shown the efficiency of the information technologies influence on knowledge-based processes, namely the knowledge exchange and knowledge generalization under the design uncertainty conditions.

Information systems are a complicated interaction of the human, social, information, and engineering components that are a connecting gain of organizational processes (Glamazdin, Novikov and Tsvetkov, 2003). An information system (IS) is known to be able to play an important role to provide strategic advantages for an organization. However, as well, a fact is known, that these advantages are not appeared automatically: these require the IS and organization to develop in a coordinated manner (Leonard, 2012).

The information systems development may be considered as an activity creating a new knowledge (Hasan, 2003/2004). Thus, the information systems development may completely be an independent research method. In that case, not a new knowledge about the development process is create only, but, as well, more profound understanding on the organization problem, to solve which the information system is intended, does. For an effective IS development, in the control theory

of social-and-economical systems, under design, for instance simulation models and their software support mathematical models of forming and performing teams, collectives being able to reach purposes in autonomous and coordinated manner under minimal control actions have been studied (Novikov, 2008). Meanwhile, the following characteristics were emphasized: purpose unity, joint activity, consistency of interests, activity autonomy, collective and mutual responsibility for joint activity results, optimal distribution of functions and jobs volumes.

In the general manufacturing control theory, mathematical models of optimal planning and control for multi-level human-machine manufacturing systems are created, coordination problems at different levels are solved, and detailed mathematical models of planning, monitoring, operative control of manufacturing are developed (Golenko-Ginzburg, 2012). Numerous models of control of human-machine manufacturing systems are based on approximate or heuristic approaches and do not assume exact optimal solutions. Thus, these do not provide the optimal control, especially under random disturbances. Nevertheless, such models implement advanced conceptions of control and investigation of the industrial manufacturing and, as a rule, meet all practical requirements (Golenko-Ginzburg, 2013).

The next Sections of the present paper are an implementation of the advanced control methodology under modeling the enterprise manufacturing modeling by use of information system resources.

2. DISTRIBUTED DESIGN OF SIMULATION MODEL

An important task is the optimal enterprise resource planning, an effective tool for the solution of which can be a simulation. For example, enterprise modeling method as a dynamic economic system is designed to develop advanced forms of organization and leadership. In his model, Forrester, (Forrester, 1961) uses six interrelated flows that reflect the industrial activity of the enterprise. Five of them are flows of materials, orders, cash, equipment and manpower (manpower resources). Sixth – the flow of information linking the other threads in a single network.

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There are many computer based discrete event simulators that are well suited to modeling the variability, interrelationships and dynamics exhibited by manufacturing enterprises. These simulators allow complex organizations to be represented in the form of stochastic models built on a networked series of transformation systems.

Models consist of entities (units of traffic), resources (elements that service entities), and control elements (elements that determine the states of the entities and resources). Discrete Event Simulation models facilitate a multidimensional approach to enterprise modeling which can integrate operations and strategic considerations with environmental and social issues (Dawson and Spedding, 2009).

The effective use of different applications in corporative information systems gives one the opportunity to use the iterative approach to simulation models design for decision making support systems in information control system of industrial enterprise.

Unlike the usual approach to simulation model design for decision making support systems basing on closed modeling system (Law, 2015) the principle of distributed design of simulation model using the data from subsystems of enterprise information systems is used.

The design process will be a sequence of a number of stages; verbal modeling, modeling, formal model design, coding, verification, simulation experiments, simulation statistic processing, decision making.

According to this principle, different available products for data analysis may be used at each design stage: MS Excel with macro XLSTAT-Pro (http://www.xlstat.com/); STADIA with necessary statistic functions (http://www.protein.bio.msu.su/ ~akula/index.htm); SPSS (Statistical Package for Social Science) – professional statistic software (http://www.spss.com/); STATA – (http://www.stata.com/); STATISTICA – software application from StatSoft Inc. (http://www.statsoft.com/); JMR for data analysis (http://www.jmp.com/); SYSTAT – statistic system for personal computers (http://systat.com/) and others.

These soft products will be called *p-resources*. The problems at each stage are solved by manpower resources, or *f-resources*, using *p-resources* also.

Both types of resources have special characteristics which influence stage efficiency. As choice of resources is ambiguity, the optimization problem arises.

3. BASIC SIMULATION MODEL STRUCTURE

To support decision making in information control system of industrial enterprise the Basic Simulation Model (BSM) has been developed (Yakimov, 2010, 2011) according to standard MRP II. BSM realized the following functions: Sales and Operation Planning (SOP); Demand Management (DEM); Master Production Scheduling (MPS); Material Requirement Planning (MRP); Bill of Materials (BOM); Scheduled Receipts Subsystem (SRS); Shop Flow enterprise Control (SFC); Capacity Requirement Planning (CRP); Purchasing (PUR); Inventory Transaction Subsystem (ITS); Financial Planning (FPL); Performance Measurement (PEM) (Fig. 1).

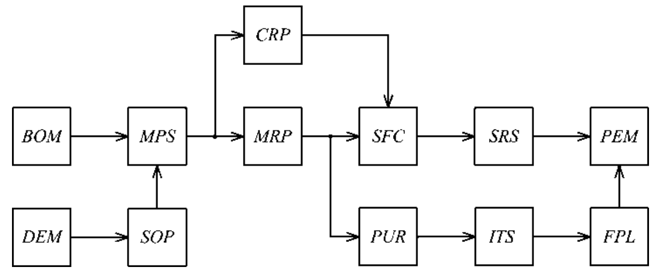

Fig. 1. Generalized structure of basic simulation model.

The functionality of BSM is limited in the sense that several functions of MRP II are not realized: Simulation; Tooling Planning and Control; Resource Planning; Input/output control.

In BSM (Yakimov, 2010) the manufacturing process is modeling globally, which does not allow to implement BSM-based control by instruments Tooling Planning and Control (*TPC*) and control on shop level (Shop Requirement Planning – *SRP*) and supply process (Purchasing – *PUR*) only on the level of whole production process, so not permitting to forecast and eliminate the "bottlenecks" and material requirements on the level of separate production operations.

4. PROBLEM STATEMENT

Let the process (P, or $TexPr$) of design, development and using of simulation model (program tool) contains n stages:

$$TexPr \overset{def}{\equiv} \{St_i \mid i = 1, ..., n\} . \tag{1}$$

Stages St_i, $i = 1, ..., n$, are fulfilled in sequence. Let each of the stages St_i allows to choose one of available technologic modes (TM) $FP_{R(i,k)}$, determined by using specific manpower resources (f -type) and one of available program resources (p-type) on i-th stage:

$$St_i \overset{def}{\equiv} \{FP_{R(i,k)} \mid k = 1, ..., |V_i|\}, \; i = 1, ..., n , \tag{2}$$

Where $R(i,k) \overset{def}{\equiv} (i, f_{ik}, p_{ik}, k)$ stands for notification of technological mode which includes: stage St_i number: i , $i \in \{1, ..., n\}$; code of used f - resources f_{ik} , $f_{ik} \in \{1, ..., |f|\}$; code of used p-resources p_{ik} , $p_{ik} \in \{1, ..., |p|\}$; number of TM in the limits of stage St_i: k , $k \in \{1, ..., |V_i|\}$, where $|V_i|$ is power of the set of TM numbers for i-th stage.

The cost of separate TM includes costs of used resources. Information processing time for different TM depends on knowledge, professional skill, etc., of f-resources and functional possibilities of p-resources.

Let Res, $Cost$ be the sets of f-, p-type of resources and the cost of this resources:

$$Res \overset{def}{\equiv} \{Res_r \mid r = 1, \ldots, |Res|\}, \tag{3}$$

$$Cost \overset{def}{\equiv} \{Cost_r \mid Cost_r \in R, \quad r = 1, \ldots, |Res|\}. \tag{4}$$

Process (1) may be described by loaded directed acyclic graph with TM (2) as vertexes. To obtain such graph interpretation one is to separate (1) to n stages.

The source of graph is zero stage of (1). The vertexes are numerated sequentially from the source (stage 0) to drain (stage n+1). Vertexes are joined by arcs according to stage sequence.

Denote as τ_{uv} the load on the arc (Fig. 2), which begins in vertex s $u \in V_{i-1}$ and ends in vertex $v \in V_i$, where V_i – number set of vertexes of i-th stage of graph (1):

$$V_i \overset{def}{\equiv} \left\{\sum_{j=0}^{i-1}|V_j|+1, \sum_{j=0}^{i-1}|V_j|+2, \ldots, \sum_{j=0}^{i}|V_j|\right\}, i = 1, \ldots, n. \tag{5}$$

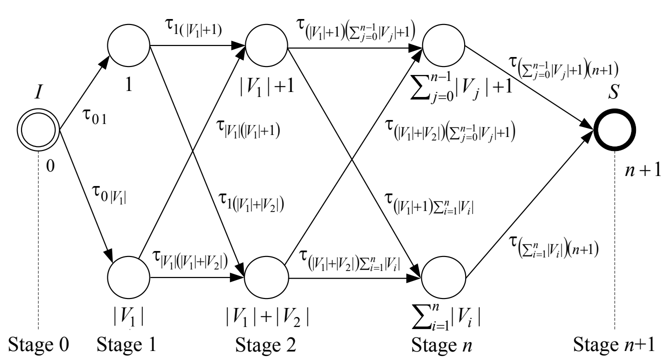

Fig. 2. Arc's loads for oriented graph.

Let the loads τ_{uv} be interpreted as cost and /or loss price of resources needed for information processing w.r.t. $TR_{R(u,v)}$ (2) of P (1).

5. CONTROL PROBLEM SOLUTION USING SIMULATION MODEL

Generally, one of techniques to find optimal TM (2) for P (1) is dynamic programming.

Bellman optimality principle states that optimal control sequence $y_1^*, y_2^*, \ldots, y_i^*$, $i = 1, \ldots, n$, must give max(min) to each of functions:

$$J_i(\tau_{i-1}, y_i, y_{i+1}, \ldots, y_n) = h_i(\tau_{i-1}, y_i) + h_{i+1}(\tau_i, y_{i+1}) + \ldots + h_n(\tau_{n-1}, y_n), \ i = 1, \ldots, n. \tag{6}$$

Let us denote:

$$\varphi_i(\tau_{i-1}) \overset{def}{\equiv} \max_{y_i, y_{i+1}, \ldots, y_n}(\min)\left(J_i(\tau_{i-1}, y_i, y_{i+1}, \ldots, y_n)\right), \ i = 1, \ldots, n. \tag{7}$$

Then (6) and (7) result in following Bellman functional equations:

$$\varphi_i(\tau_{i-1}) = \max_{y_i}(\min)\left(\varphi_{i+1}(g_i(\tau_{i-1}, y_i)) + h_i(\tau_{i-1}, y_i)\right), \quad i = 1, \ldots, n. \tag{8}$$

By solving these equations one gets the sequences of optimal controls and optimal cost functions.

Accounting loads on arcs of graph τ_{uv}, Eq.(8) will take form:

$$\tau_v = \min_u(\max)\{\tau_u + \tau_{uv}\}, \tau_0 = 0, \tag{9}$$

where $u \in V_{i-1}$ – numbers of initial vertexes of $(i-1)$-th stage's arcs; $v \in V_i$ – numbers of final vertexes of (i)-th stage's arcs.

The loaded arcs beginning at the same vertex are equivalent, so following relations take place:

Relation 1. Let $\tau_{uv} \in R$, then for P (1) next equations are true:

$$\forall u \in V_{i-1} \forall v_1 v_2 \in V_i [\tau_{uv_1} = \tau_{uv_2}], i = 1, \ldots, n. \tag{10}$$

Relation 2. Let $\tau_{uv} = (\tau_{uv}^{(1)}, \tau_{uv}^{(2)}) \in R^2$, $\tau_{uv_1} = (\tau_{uv_1}^{(1)}, \tau_{uv_1}^{(2)})$, $\tau_{uv_2} = (\tau_{uv_2}^{(1)}, \tau_{uv_2}^{(2)})$.

Then for P (1) next equations are true:

$$\forall u \in V_{i-1} \forall v_1 v_2 \in V_i [(\tau_{uv_1}^{(1)} = \tau_{uv_2}^{(1)}) \wedge (\tau_{uv_1}^{(2)} = \tau_{uv_2}^{(2)}) \Leftrightarrow \Leftrightarrow (\tau_{uv_1} = \tau_{uv_2})], i = 1, \ldots, n. \tag{11}$$

Statement 1. Let for $\tau_{uv} \in R$, relations (10) are true, then Eq.(9) would take form

$$\tau_v = L_i = L_{i-1} + \min_{u \in V_{i-1}}(\max)\{\tau_{uv}\}, \tag{12}$$

where L_i – optimal state for i-th step, $L_i \in R$, $L_0 = \tau_0 = 0$, $u \overset{(5)}{\in} V_{i-1}$, $v \overset{(5)}{\in} V_i$, $i = 1, \ldots, n$,

what can be proved by induction.

Statement 2. Let for $\tau_{uv} = (\tau_{uv}^{(1)}, \tau_{uv}^{(2)}) \in R^2$ relations (11) are true then from Eq. (9) follows

$$L_i = \begin{cases} \left.\begin{pmatrix} L_{(i-1)1} + \underset{u\in V_{i-1}}{Fm_1}\{\tau_{uv}^{(1)}\} \\ L_{(i-1)2} + Fm_2\left\{\tau_{u_i v}^{(2)} \middle| \tau_{u_i v}^{(1)} = \underset{u\in V_{i-1}}{Fm_1}\left(\{\tau_{uv}^{(1)}\}\right)\right\} \end{pmatrix}\right| pOpt = 1, 2; \\ \\ \left.\begin{pmatrix} L_{(i-1)1} + Fm_1\left\{\tau_{u_i v}^{(1)} \middle| \tau_{u_i v}^{(2)} = \underset{u\in V_{i-1}}{Fm_2}\left(\{\tau_{uv}^{(2)}\}\right)\right\} \\ L_{(i-1)2} + \underset{u\in V_{i-1}}{Fm_2}\{\tau_{uv}^{(2)}\} \end{pmatrix}\right| pOpt = 2, 1; \end{cases} \quad (13)$$

where $L_i = \left(L_{i1} \quad L_{i2}\right)^{\mathrm{T}}$, $L_0 = \left(0 \quad 0\right)^{\mathrm{T}}$, $u \in V_{i-1}$, $v \in V_i$, $i = 1, \ldots, n$; $pOpt$ – high priority criterion optimization of (1) components w.r.t. the first (time) or second (cost) components of vectors $\tau_{uv} \in R^2$; $Fm_1, Fm_2 \in \{\min, \max\}$ – ordered w.r.t. $pOpt$ optimization criteria of P for first and second state measurement respectively.

The choice of optimal control sequence (optimal TM for P, or optimal route on the graph) is determined by predicates:

$$Fl \overset{def}{\equiv} \left\{fl_{ij} \;\middle|\; fl_{ij} \in \{True, False\}, i = 1, \ldots, n, j = 1, \ldots, |V_i|\right\}. \quad (14)$$

6. AN EXAMPLE OF SIMULATION MODEL DESIGN

Let consider simulation model design for management system of industrial enterprise (Fig. 3).

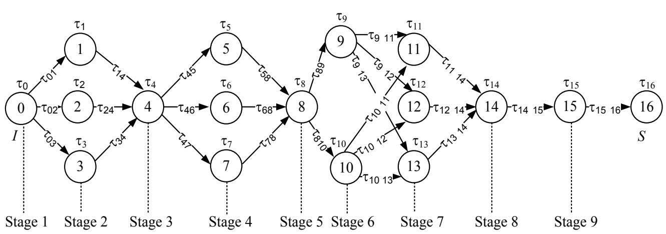

Fig. 3. Oriented graph with *n* modes.

Let the process $TexPr$ (1) of simulation model design consist of $n = 8$ stages St_i, $i = 1, \ldots, 8$: St_1 – verbal modeling; St_2 – conceptual modeling; St_3 – formal model design; St_4 – coding; St_5 – verification; St_6 – simulation experiments; St_7 – simulation statistic processing; St_8 – decision making. Each stage admits the choice one of several technologic modes, as follows – stage 1: $|V_1| = 3$; stage 2: $|V_2| = 1$; stage 3: $|V_3| = 3$; stage 4: $|V_4| = 1$; stage 5: $|V_5| = 2$; stage 6: $|V_6| = 3$; stage 7: $|V_7| = 1$; stage 8: $|V_8| = 1$.

TM's for each stage are determined both by *f*- and *p*-resources, namely:

FP_1 = <f_{11}, BPwin>, FP_2 = <f_{11}, Rational Rose>, FP_3 = <f_{11}, Power designer>, FP_4 = <f_{21}, BPwin>, FP_5 = <f_{31}, Enterprise Architect>, FP_6 = <f_{32}, Enterprise Architect>, FP_7 = <f_{33}, Enterprise Architect>, FP_8 = <f_{41}, MS Visual Studio>, FP_9 = <f_{51}, MS Visual Studio>, FP_{10} = <f_{52}, MS Visual Studio>, FP_{11} = <f_{61}, MS Visual Studio>, FP_{12} = <f_{62}, MS Visual Studio>, FP_{13} = <f_{63}, MS Visual Studio>, FP_{14} = <f_{71}, Statistica>, FP_{15} = <f_{71}, SPSS>, FP_{16} = <f_{81}, MS Excel Solver>.

Let the time expenses for each of the P are defined. Below the time T_i (hours), $i = 1, \ldots, 8$ is represented, needed to process information for solving a problem in the simulation stages of P (1):

Stage 1: $T_1 = (5{,}2;\ 7{,}8;\ 10{,}3)$; stage 2: $T_2 = (6{,}0)$; stage 3: $T_3 = (6{,}4;\ 6{,}4;\ 6{,}4)$; stage 4: $T_4 = (8{,}7)$; stage 5: $T_5 = (10{,}7;\ 10{,}1)$; stage 6: $T_6 = (8{,}6;\ 8{,}6;\ 4{,}3)$; stage 7: $T_7 = (15{,}0;\ 19{,}0)$; stage 8: $T_8 = (12{,}8)$.

Let resources costs S_i (rubles), $i = 1, \ldots, 8$ for information processing while solving single problem in each stage are as follows: stage 1: $S_1 = (1499{,}0;\ 1543{,}0;\ 1485{,}0)$; stage 2: $S_2 = (5934{,}0)$; stage 3: $S_3 = (9877{,}0;\ 9598{,}0;\ 9429{,}0)$; stage 4: $S_4 = (2431{,}0)$; stage 5: $S_5 = (5577{,}0;\ 5220{,}0)$; stage 6: $S_6 = (8584{,}0;\ 8544{,}0;\ 2287{,}0)$; stage 7: $S_7 = (16539{,}0;\ 15475)$; stage 8: $S_8 = (130{,}0)$.

Taking into account $T_i = (t_{i1}, \ldots, t_{i|V_i|})$, $S_i = (s_{i1}, \ldots, s_{i|V_i|})$, $i = 1, \ldots, 8$, one can find the loads $\tau_{ij} \in R^2$:

$\tau_{01} = \tau_{02} = \tau_{03} = (0{,}0)$; $\tau_{14} = (t_{11}, s_{11})$, $\tau_{24} = (t_{12}, s_{12})$, $\tau_{34} = (t_{13}, s_{13})$; $\tau_{45} = \tau_{46} = \tau_{47} = (t_{21}, s_{21})$; $\tau_{58} = (t_{31}, s_{31})$, $\tau_{68} = (t_{32}, s_{32})$, $\tau_{78} = (t_{33}, s_{33})$; $\tau_{89} = \tau_{810} = (t_{41}, s_{41})$; $\tau_{911} = \tau_{912} = \tau_{913} = (t_{51}, s_{51})$, $\tau_{1011} = \tau_{1012} = \tau_{1013} = (t_{52}, s_{52})$; $\tau_{1114} = \tau_{1115} = (t_{61}, s_{61})$, $\tau_{1214} = \tau_{1215} = (t_{62}, s_{62})$, $\tau_{1314} = (t_{63}, s_{63})$; $\tau_{1416} = (t_{71}, s_{71})$, $\tau_{1516} = (t_{72}, s_{72})$, $\tau_{1617} = (t_{81}, s_{81})$.

Optimal TM (1) are determined by Bellman's principle using functions (14). The sequence of two-dimensional vectors is constructed

$$\begin{pmatrix}0\\0\end{pmatrix} \to \begin{pmatrix}L\_1[1]\\L\_1[2]\end{pmatrix} \to \begin{pmatrix}L\_2[1]\\L\_2[2]\end{pmatrix} \to \ldots \to \begin{pmatrix}L\_8[1]\\L\_8[2]\end{pmatrix},$$

where $L\_1,\ldots,8[1]$, $L\_1,\ldots,8[2]$ are the optimal stage duration and cost respectively. Optimal route on the graph will be a predicate sequence of type (14):

$$\begin{pmatrix}fl_{11}\\fl_{12}\\fl_{13}\end{pmatrix} \to (fl_{21}) \to \begin{pmatrix}fl_{31}\\fl_{32}\\fl_{33}\end{pmatrix} \to (fl_{41}) \to \begin{pmatrix}fl_{51}\\fl_{52}\end{pmatrix} \to \begin{pmatrix}fl_{61}\\fl_{62}\\fl_{63}\end{pmatrix} \to \ldots$$

$$\ldots \begin{pmatrix}fl_{71}\\fl_{72}\end{pmatrix} \to (fl_{81}).$$

Optimization problem solution results in following optimal TM's for this problem:

1) minimal time and minimal cost ($pOpt = 1$ – optimization w.r.t. time has high priority; $Fm_1, Fm_2 = \min$): $L^*_{\min} = \mathrm{L\_8} = (68{,}5;\ 43469{,}0)$, time is 68,5 hours, cost is 43469 rubles; graph route is $< 0-1-4-7-8-10-13-14-16-17 >$.

2) minimal cost and minimal time ($pOpt = 2$ – optimization w.r.t. cost has high priority $Fm_1, Fm_2 = \min$): $L^*_{\min} = L\_8 = (77{,}6;\ 42391)$, time is 77,6 hours, cost is 42391 rubles; graph route is $< 0-3-4-7-8-10-13-15-16-17 >$.

6. INDUSTRIAL IMPLEMENTATION OF PRODUCTION PLANNING SIMULATION MODEL

The basic simulation model was realized in soft product BelSim for decision making support in shoes production.

The planning problem for production shop of joint-stock company "ShagoVita" (Alkhovik et al., 2011) consist in production schedule construction when production date $ProdDate_i$ is given. The schedule is to provide maximal daily load of production capacities ($\sum_i ProdCap_i \to \max$) for fulfilling in time $SaleDate_i$ the maximal volume of orders $ProdDate_i \le SaleDate_i$ with minimal cost.

In case when the single production shop has several identical production lines (or the factory has several identical shops) with different production cost or different production limitations, the problem of prime cost minimization may be actual.

Shop-level planning with given production capacity maxCap of each shop is done by algorithm

$$\forall V_{is} \begin{cases} V_{is} = V_i \begin{cases} \sum_i V_i < \max\, Cap \begin{cases} \sum_i V_i := \sum_i V_i + ProdCap_i; \\ Date_i := prodDate_i; \end{cases} \\ \text{else} \begin{cases} \sum_i V_i = 0; \\ prodDate_i := prodDate_i + 1; \end{cases} \end{cases} \\ \text{else } \{ Date_i := Date_i + waitTime. \end{cases}$$

If the time PC_i, needed to produce the unit of each type is known, the maximal production power max*SumTime* of each shop (line) is given, then planning may be done by algorithm

$$\forall V_{is} \begin{cases} V_{is} = V_i \begin{cases} SumTime < \max\, SumTime \\ \begin{cases} SumTime := SumTime + V_i \cdot PC_i; \\ Date_i := prodDate_i; \end{cases} \\ \text{else} \begin{cases} SumTime = 0; \\ prodDate_i := prodDate_i + 1; \end{cases} \end{cases} \\ \text{else } \{ Date_i := Date_i + waitTime. \end{cases}$$

Basic simulation model is implemented in the software package BelSim for decision support in the shoe manufacturing.

7. CONCLUSIONS

The problem of multi-criterion control of production processes with simulation model design based on Bellman optimality principle is considered. The optimal solution is given for one- and two-dimensional cases using graph description. The validity of the optimal solution is shown for one- and two-dimensional flow characteristics on the arcs a directed acyclic graph.

The example of solving an optimization problem using resources *f*- and *p*-type in enterprise information system shows the need to define the priority criteria for the final selection of the route along the graph, i.e. optimal resource allocation choices.

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