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Automation of Cluster Large-Scale Production Systems

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Abstract: The paper covers the production of capital goods of various types of industrial robots in the context of industrial clusters. It uses a model of production, invariant with the types of technological operations (TOs). The paper examines algorithms for three automation options: full production of capital goods, partial production of capital goods, use of robots purchased outside the cluster.

Keywords: the production of capital goods, industrial robots, level of automation, technological operation, operation performance time, production theory invariant with the types of technological operations, cost dynamics

1. INTRODUCTION

Today, active research is being carried out in Russia to build cluster models in different areas of the economy, in different geographical regions, as well as for the purpose of determining the structure, components and growth potential. The main purpose of the cluster policy is to ensure high rates of economic growth and economic diversification by improving the competitiveness of enterprises, suppliers of equipment, components, specialized production and after-sales services of research and educational organizations that form territorial production clusters [1].

An economic cluster is a geographically concentrated group of interconnected companies, specialised suppliers, service providers, firms in their respective industries and related organisations (e.g. universities, standardisation agencies and trade unions) in certain areas that compete but also work together" [2]. According to M. Porter, the competitiveness of a region or a country should be considered in terms of the competitiveness of clusters - associations of organisations and enterprises in various industries that are able to use internal resources effectively. A cluster takes into account the market mechanism as much as possible and is a flexible form of organisation [3]. This is its main difference from the territorial and industrial complex and the sectoral approach. As an example of a modern cluster established in the Russian Federation, we should mention the petrochemical enterprises cluster of the Republic of Tatarstan [4].

To describe any production system within a cluster, it is necessary to have: a list of all manufactured products (including robots); a description of the production procedure for each type of product; a description of the production procedure for each type of robot; specifications of robots as production elements; a list and specifications of all types of technological operations (TOs) required to produce all types of products and robots; the total number of people involved in the production process. The paper's objective: using the above data, to calculate a production automation scheme within a cluster where human costs are minimal.

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2. PARAMETERS OF THE PRODUCTS AND ROBOTS OF THE CLUSTER SYSTEM

Parameters of the products to be manufactured within the system are determined by the following matrices [5]: $n = \|n_{ij}\|$, of size m×s, $N = \|N_k\|$, of size 1×s, $D = \|d_k\|$, of size 1×s, where n_{ij} is the number of *i*-type TOs that is needed to manufacture one *k*-type product, *S* is the number of types of products, N_k is the number of *k*-type products to be manufactured, d_k is the cost of purchased products needed to manufacture one *k*-type product.

Parameters of the robots are determined by the following matrices [5]: $b = \|b_{ij}\|$ of size *m*×*f*, where b_{ji} is the time during which *i*-type TOs are performed by a *j*-type robot, *f* is the total number of types of robots used in production, *m* is the number of types of TOs needed to manufacture a product, $h = \|h_{ij}\|$ of size *m*×*f*, where h_{ij} is the number of *i*-type TOs needed to manufacture one *j*-type robot.

The service life of robots *T*, the cost of robots *C* and the cost of the working time unit of robots λ are input by the following matrices, where *j*-index stands for the type of robot: $T = \|T_j\|$, of size 1×*f*, $C = \|C_j\|$, $\lambda = \|\lambda_j\|$.

Production capacities of people are contained in the matrix [5]: $G = \|g_i\|$, of size 1×*m*, where g_i is the time needed for a person to perform an *i*-type TO. To shorten the formulae in some places we will regard a person as a 0-type robot — the element $b_0 = \|b_{0i}\|$, of size 1×*m*, of the matrix $b = \|b_{ij}\|$.

A person's working time $T_0(t)$ will be an aggregate of the person's working time while working at the station *t* (for a year, for instance).

3. AUTOMATION MATRIX

The planning of automation of autonomous production is aimed to distribute the operations between people and robots, so that people could save on costs as much as possible. This requires the use of an automation matrix as a management tool: $\mathrm{A} = \|\alpha_{ji}\|$ of size *m*×*f*, where α_{ij} is the level of automation of i-type TOs performed by a j-type robot. The level of automation must meet the following conditions: $0 \le \alpha_{ji} \le 1; i = 1,2,...,m;\ j = 0,1,...,m$. If all i-type technological operations are performed by an automaton then the level of automation $\alpha_i = 1$, and if by a person - $\alpha_i = 0$.

If a particular type of TOs is to be performed while manufacturing a product, it must be done by either a person or one of the types of robots. If this condition is not met, the assembly of the product will not be completed and, as a result, the product will not be manufactured, but will be rejected.

Product manufacture cost C(A) is a function of the automation matrix. The optimal automation matrix A that minimizes the production cost contains only 0 and 1.

4. ROBOT COST CALCULATION

Cost of robot automated manufacture by a system of robots with the use of automation matrix A is calculated according to the formula [5]:

$$C_k(\alpha) = \sum_{i=1}^{m} \alpha_{0i} b_{0i} \lambda_0 h_{ki} + \sum_{i=1}^{m} \alpha_{1i} b_{1i} \lambda_1 h_{ki} + \cdots + \sum_{i=1}^{m} \alpha_{fi} b_{fi} \lambda_f h_{ki}, \tag{4.1}$$

where m is the number of types of TOs required to manufacture a product, b_{ij} is the time needed for a j-type automaton to perform i-type TOs, λ_j is the cost of the working time unit of a j-type automaton, $g_i = b_{0i}$ is the time that a person needs to perform i-type TOs, f is the total number of the types of robots available for automation, h_{ij} is the number of identical i-type TOs needed to manufacture a product $C_k(\alpha)$. The first amount stands for the human costs, the second amount stands for the first-type robot costs and the last amount stands for the f-type robot costs.

5. DYNAMIC EQUATIONS FOR THE COST OF A PRODUCTION OF CAPITAL GOODS

Initial data required for the calculations should contain information on the robots that will be used in the cluster, on the technology of their production and on the available means that will make their production automated.

Cost of manufacturing a robot in case of automated production consists of three components:

$$C = \lambda B(\alpha) + D + G(\alpha)\,, \tag{5.1}$$

where $G(\alpha)$ is the direct cost of a person to assemble the robot, D is the cost of purchased parts, $B(\alpha)$ is the cost of robot time, α is the level of production automation, which is a vector whose components are the level of automation of each specific type of technological operations, λ is the cost of the working time unit of the robot involved in the manufacture of the robot. Let's define the cost of the robot's working time unit as the ratio of its cost C to the robot's lifetime (service time) T:

$$\lambda = C / T\,. \tag{5.2}$$

Given (5.3), let's rewrite (5.2) as follows:

$$C = CB(\alpha) / T + D + G(\alpha)\,. \tag{5.3}$$

Equation (5.3) describes the process of manufacturing a robot by a person and a robot of the *previous* generation. The parameters of the manufacturing robot may differ from those of the manufactured one. To take this into account, let's rewrite (5.3) as follows:

$$C(N) = C(N-1)B(\alpha) / T + D + G(\alpha)\,, \tag{5.4}$$

where C(N) is the cost of the robot of the N-th generation, C(N-1) is the cost of the robot of the (N-1)-th generation.

The solution of the difference equation (5) looks like (assuming that the automation vector α is constant):

$$C(N) = \frac{G+D}{T} \cdot \frac{1-\left(B/T\right)^N}{1-B/T} + C(0)\left(B/T\right)^N\,, \tag{5.5}$$

Automation of robot production with the help of robots is only feasible if the cost of the manufacturing robot $B(\alpha)$ is less than its service life T. In this case, the ratios included in the equation $B(\alpha)/T < 1$, and the asymptotic solution will be equal to:

$$C(\infty) = \frac{G+D}{T-B}\,. \tag{5.6}$$

Provided that $B(\alpha)/T<1$, this solution does not depend on the initial conditions, but only on the automation vector α.

Costs of the person $G(\alpha)$ and the robot $B(\alpha)$ in (5.1) are described by the formulae:

$$G(\alpha)=\sum_{i=1}^{m}(1-\alpha_i)g_ih_i\,, \qquad B(\alpha)=\sum_{i=1}^{m}\alpha_ib_ih_i\,. \tag{5.7}$$

where m is the number of types of TOs required to manufacture a robot. This index in the sums will be omitted, assuming, however, that the summation is done for all types of operations, both automated and manual, g_i is the time needed for a person to perform an i-type TO, bi is the time needed for a robot to perform an i-type TO, h_i is the number of identical i-type TOs needed to manufacture a robot, α_i is the level of automation of the i-type TO, and the vector α, determines the production automation scheme.

6. COOPERATION OF PLANTS

Plant No. 1 manufactures robots of the N-th generation R(N), using structurally similar robots of the previous generation R(N-1) to make their production automated. Plant No. 2 manufactures hydraulic drives M(0). Let's consider cooperation of plants when the robot plant sells its products to the hydraulic drive plant to make its production automated, and the hydraulic drive plant reduces the price for its products purchased by the robot plant (Fig. 6.1).

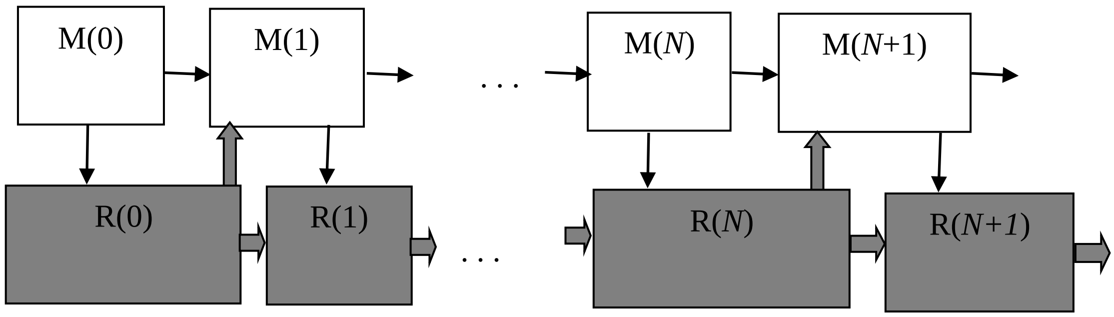

Fig. 6.1. Scheme of cooperation between plants. On the scheme M(N) - hydraulic drive of the N-th generation; R(N) - robot of the N-th generation. In the figure, the upper line produces generations of hydraulic drives; the lower line produces robots.

Cost of automated manufacture of the robot is calculated according to the formulae (5.5) and (6.1). The whole system of cooperation of plants without automation of hydraulic drives production will be described by a system of equations:

$$C(N)=C(N-1)B(\alpha)/T+G(\alpha)+D_R+D_F\,, \tag{6.1}$$

$$F(N)=G_F(\alpha=0)+B_F(\alpha=0)+D_F\equiv F(0)\,, \tag{6.2}$$

$$G(\alpha)=\sum(1-\alpha_i)g_ih_i\,,\quad B(\alpha)=\sum\alpha_ib_ih_i\,, \tag{6.3}$$

$$G_F(\alpha=0)=\sum g_in_i\,,\ B_F(\alpha=0)=0\,. \tag{6.4}$$

where C(N) is the cost of the robot of the N-th generation, g_i is the time needed for a person to perform an i-type TO, h_i is the number of i-type TOs needed to manufacture a robot, n_i is the number of i-type TOs needed to manufacture a hydraulic drive, b_i is the time needed for a robot to perform an i-type TO, D_R is the cost of purchased parts needed to manufacture a robot, D_F is the cost of purchased parts needed to manufacture a hydraulic drive, $F(0)$ is the cost of purchased hydraulic drives that have been manually assembled.

7. INITIAL DATA FOR MODELING

Let's consider how the cost of robots changes across generations. We will assume that manufacturing a robot requires purchased parts and the performance of four types of technological operations (TOs).

Initial data. The robot's lifetime T = 1000. The time needed for a person to perform TOs: $g1$=4, $g2$=3, $g3$=3, $g4$=23. The time needed for a robot to perform TOs: $b1$=5, $b2$=12, $b3$=240, $b4$=4. The number of identical TOs when manufacturing a hydraulic drive: $n1$=$n2$=$n3$=4, $n4$=6. The number of identical TOs when manufacturing a robot: $h1$=12, $h2$=20, $h3$=10, $h4$=8. The cost of purchased parts for hydraulic drives for all TOs Df=10, the cost of purchased parts for robots for all TOs DR = 80. The cost of the working time unit of each robot $\lambda(0)$=0.86.

First, we will calculate the cost of the manual assembly of a hydraulic drive. Using (6.2) and (6.4), we will get

$$F(0) = \sum_{i=1}^{4} g_i n_i + D_F . \tag{7.1}$$

Using the initial data, we will get $F(0) = 218$.

To calculate the cost of the manual assembly of a robot, using (6.1) and (6.3), we will get the formula

$$C(0) = \sum_{i=1}^{4} g_i h_i + D_R + F(0) . \tag{7.2}$$

Using the initial data and (8.1), we will finally get: $C(0)$=860. The cost of the robot's working time will therefore be equal to $\lambda(0)$=0.86.

8. ROBOT COST DYNAMICS FROM GENERATION TO GENERATION

The change in the robot's cost from generation to generation at a fixed cost of purchased hydraulic drives is based on the following equation

$$C(N) = \lambda(N-1)B(\alpha) + G(\alpha) + D_R + F(0) . \tag{8.1}$$

To solve this equation, it is first necessary to determine the optimal automation vector $\alpha(\alpha 1, \alpha 2, \alpha 3, \alpha 4)$ which would allow getting the minimum cost of the robot. For this purpose, we will make Table 8.1 to determine the optimal automation vector for production of the 1st generation robots, using the 0-th generation robots.

Table 8.1. The automation vector for production of the 1st generation robots

A	B	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*I*
Z(1) u α(1)					*C(1)=Z(1)*h+F(0)+ DR*				
TO	*g*	*b*	*λ(0)b*	*Z(1)*	*α(1)*	*h*	*F(0)*	*DR*	
1	4	5	4,3	4	0	12	26	80	154
2	3	12	10,32	3	0	20	22	80	162
3	3	240	206,4	3	0	10	22	80	132
4	23	4	3,44	3,44	1	8	148	80	255,52
								C(1)	703,52
								λ(1)	255,52

First, we will calculate the cost of performing TOs by a robot (column D). Then, from columns D and B we will select the minimum cost of performing TOs by a person or a robot and draw a vector Z(1) of minimum values and the corresponding vector $\alpha(1)$. The cost of any (e.g. the N-th) generation robots will be calculated according to (8.1), but each time $\lambda(N-1)$ and Z(N) must be determined beforehand. After that, we will calculate the cost of the manual assembly of a hydraulic drive (column H). The cost of a robot will be calculated in column I.

Making such calculations for the next generations, we will see robot cost dynamics at a fixed cost of purchased hydraulic drives. The results are given in Table 8.2.

Table 8.2. The robot cost dynamics at a fixed cost of purchased hydraulic drives

Generation number N	*0*	*1*	*2*	*3*	*4*
C(N)	860	704	693	692	692
λ (N)	0,860	0,704	0,693	0,692	0,692

Let's consider the automated production of hydraulic drives with the help of the 0-th generation robots. Using (6.2) and (6.4), we will get:

$$F(1)=\sum(1-\alpha_i)g_in_i+\lambda(0)\sum\alpha_ib_in_i+D_F\,. \tag{8.2}$$

Since the types of TOs used to make the production of both robots and hydraulic drives automated are the same, so are the automation schemes. Therefore, using the initial data, we will calculate the cost of the 1st generation hydraulic drive (Table 8.3).

Table 8.3. The cost of the 1st generation hydraulic drive

TO	*Z(1)*	*α(1)*	*N*	*Df*	*F(1)=Z*N+Df*
1	4	0	4	10	26
2	3	0	4	10	22
3	3	0	4	10	22
4	3,44	1	6	10	30,64
				F(1)	100,64

9. EXCHANGE STRATEGY BETWEEN PLANTS

Plant No. 2 has decided to make the production of hydraulic drives cheaper by automating their production with the help of robots manufactured by Plant No. 1. In general, the automation of hydraulic drive production can be either beneficial or not. It all depends on the capacities of robots and their cost. Let's consider a case when automation has led to a decrease in the cost of hydraulic drives: $F(0)>F(1)$.

In the next generation, plant No. 1, using cheaper hydraulic drives, will reduce the cost of manufacturing robots: the cost of a robot with cheaper hydraulic drives will be reduced by the amount of reduction in the cost of hydraulic drives and will be equal to $C(1)<C(0)$. Accordingly, the cost of the working time unit of the next generation robot is $\lambda(1) = C(1)/T$, which is less than $\lambda(0)$.

We should keep in mind that there is no change in the product design when the production gets automated. Plant No. 2 always produces the same hydraulic drive design, plant No. 1 always produces the same robot model. The hydrodrives of different generations M(0), M(1), M(2) do not differ from each other structurally - they are twins. Similarly, the models of robots of different generations R(0), R(1), R(2) transferred to the hydraulic drive plant do not structurally differ from each other - they are also twins. Symbiosis between the two plants leads to a successive reduction in the cost of both hydraulic drives and robots. The design does not change and the cost is reduced!

We should note that it involves a change of generations. If plant No. 2 has produced a new (e.g. N-th) generation robot, and plant No. 1 is still using the (N-1)-th generation robot whose lifetime is not over yet, it makes no sense to change it. But when the (N-1)-th generation robot dies, it should be replaced with a cheaper robot of the N-th generation. Thus, the evolution rate of a production automation system depends on the lifetime of the robot: the shorter the lifetime of the robot is, the faster the evolution can be.

There is a gradual displacement of people by cheap robots from the production sector. That's what automation is all about.

10. COST DYNAMICS

Let's examine the dynamics of hydraulic drives cost and the robot's working time unit cost in the process of production automation and a change of robot generations. The initial data for the calculations are given above. We have calculated the cost of hydraulic drives and the 0-th generation robots: $C(0)=860$; $F(0)=218$; $\lambda(0)=0.860$.

Difference equations (8.1) and (8.2) allow calculating future values of the robot cost on the basis of the parameters of the previous generation, i.e. the cost of the (N+1) generation robots (Table 10.1).

Table 10.1. The cost of the 1st generation hydraulic drive

TO	*Calculate Z(N+1) and α(N+1)*					*Calculate the cost of the robots C(N+1)*			
	g	*b*	*λ(N) b*	*Z(N+1)*	*α (1)*	*h*	*F(N)*	D_R	*C(N+1)*
1	4	5	4,3	4	0	12	26	80	154
2	3	12	10,32	3	0	20	22	80	162
3	3	240	206,4	3	0	10	22	80	132
4	23	4	3,44	3,44	1	8	148	80	255,52
								C(N+1)	703,52
T	1000							*λ(N+1)*	0,70352

The modeling results are shown in Fig. 10.1. Fig. 10.1 shows a significant reduction in the cost of production of capital goods.

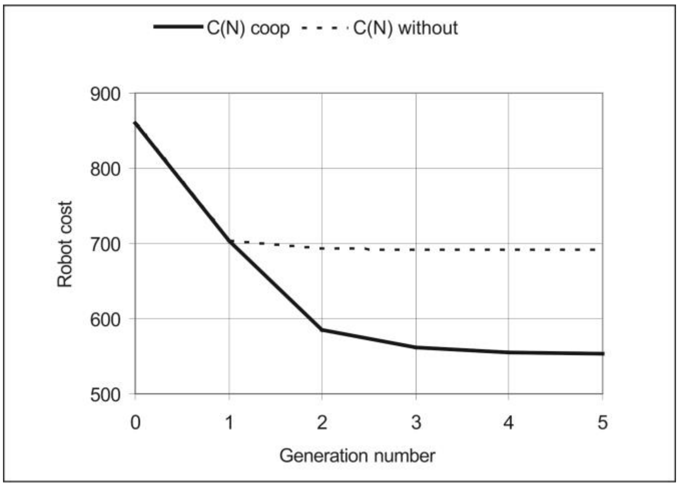

Fig. 10.1. Cost Dynamics. The dashed line shows the change in the cost of a production of capital goods without a component supplier's cooperation, the thick line — with a supplier's cooperation

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