УПРАВЛІННЯ
У ТЕХНІЧНИХ СИСТЕМАХ

УПРАВЛЕНИЕ
В ТЕХНИЧЕСКИХ СИСТЕМАХ

CONTROL
IN TECHNICAL SYSTEMS

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DEVELOPMENT OF A COORDINATION METHOD FOR EFFECTIVE DECISION-MAKING IN A HIERARCHICAL MULTILEVEL INDUSTRIAL SYSTEM

In modern conditions of manufacturing the ever increasing size of enterprises leads to objective changes in the interdependence of their subordinated structures. The resulting complexity requires modernization of the process management systems. One important direction task in this modernization is the development of effective methods of coordination. Therefore, this article addresses the problem of coordination in decision making among a group of autonomous production units. The object of study is the local decision making process on a dairy plant, which operate with three production lines. The subject of study is the coordination of operations when there is only one packaging machine. The objective of this work is to increase the overall effectiveness index of a system of production units by means of optimal resource allocation and synchronization of operations of technological processes. For effective coordination it is proposed a method that ensures the optimization of processes while considering the particular preferences of each local decision-making unit. For each subordinated decision unit or coordinator, an objective function measures the effectiveness of the subprocesses activities. The coordinator affects the lower-level decision-making so that the performance of the whole system is optimized. It incorporates a hierarchical multilevel system for the management of activities, and the detailed mathematical modeling of the sequencing of operations. The method proposed is based on the theory of fuzzy sets and fuzzy logic. The decision-making process is accomplished by a minimax estimation of the membership functions. The coordinated operations give as result a higher global effectiveness. Additionally, for the comparison of preferences, the normalized criteria of effectiveness based on the technological characteristics of each process are suggested.

Keywords: coordination of subprocess, fuzzy method, hierarchical multilevel system, decision-making.

NOMENCLATURE

opt is an optimal (desired or acceptable) value of the performance of the whole system for the problem being solved;

B_i is a volume of buffer i;
$B_{\max i}$ is a maximum capacity of the temporary stores;
C is a production cost;
E is a effectiveness criterion of the system;
eff_i is a value of a normalization constant;
K_0 is a central coordinator;
K_{1-3} are the subordinated coordinators;
K_4 is a coordinator of the packing device;
P is a revenue;
p_i is a performance of the production lines;
p_u is a performance of the packing device;
R_r is a finished product;
R_o is a raw material;
R_{0i} is a coordination vector (resource allocation);
S is a vector of sequencing of activities;
T is a completion time;
t_{01} is a start time of the first subprocess;
t_{0u} is a start time of operation of the packing and transfer device;
t_{li} is a buffer i loading time;
t_f is a moment of completion of the process;
t_{ui} is a buffer i unloading time;
t_{fu} is an end time of operation of the packing and the transfer device;
t_{pi} is a processing time;
X_{oi} is a decision vector (raw material request);
α_i, λ_i are coordination variables;
σ_{pi} is a measure that takes into account the statistical characteristics of the subprocess.

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INTRODUCTION

In modern conditions of manufacturing the ever increasing size of enterprises leads to objective changes in the interdependence of their subordinated structures. The resulting complexity requires modernization of the process management systems. One important direction task in this modernization is the development of effective methods of coordination.

The objective of this paper is to increase the overall effectiveness index of a system of production units by means of optimal resource allocation and synchronization of operations of technological processes.

1 PROBLEM STATEMENT

Given a system comprised of a set of subprocesses (production lines) $<SP_1, SP_2, \ldots, SP_n>$ with the inputs (raw material) $<R_{01}, R_{02}, \ldots , R_{0n}>$ intermediate outputs (produced units) $< R_{r1}, R_{r2}, .. R_{ri} >$ and the following restrictions: buffers $<B_1, B_2, \ldots, B_n>$; production line performances $< p_1, p_2, \ldots p_n>$, performance of a shared single packing and transfer mechanism p_u. Taking into account the physical and technical constraints the problem of system coordination is to find a decision vector $< R_{01}, R_{02}, \ldots , R_{0n} >$ in order to obtain $E = F(\mathrm{eff}_i) \rightarrow \mathrm{opt}$, where in E is the effectiveness criterion of the system and eff_i the effectiveness criteria of the different subprocesses.

As the object of study let's consider the problem of coordination of local decisions of a dairy plant, which produces three types of dairy products. The technological process of preparation and packaging of milk is a complex technological task automation, which should provide some technological operations: receiving, separation, homogenization, normalization, packaging and packing. Each operation is a time-consuming process that requires continuous monitoring. The objective of the management system is the coordination of the operations when there is only one packaging machine. The presence of only one packaging device makes it very difficult the parallel operation of all the lines, and therefore it leads to downtime and loss of profits. Figure 1 shows the typical scheme of coordination of the dairy plant.

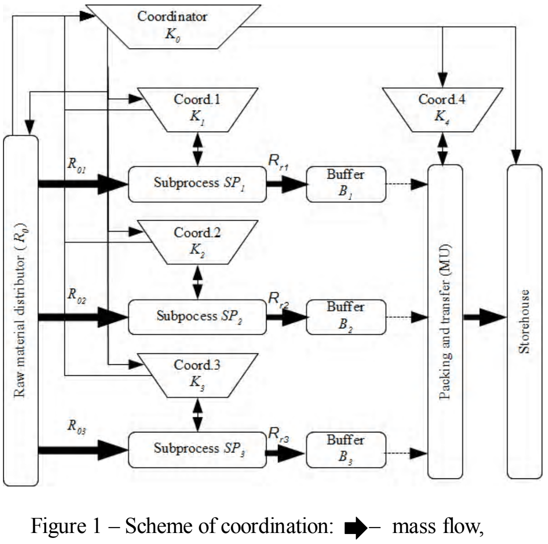

Figure 1 – Scheme of coordination: ➡– mass flow, →– data flow,⇢– subprocess pending for packing and transfer

2 REVIEW OF THE LITERATURE

The problem of development of science-based hierarchical management systems becomes relevant in a continuous adaptation of modern industries to external changes. It is important to highlight the Mesarovic's theory of management of hierarchical multilevel systems [1] among one of the most significant developments in the field of hierarchical structures of a different nature. Also significant contributions were made in the work of the following researchers, T. Malone and K. Crowston, A. A. Voronin, S. P. Mishin, V. N. Burkova, D. A. Novikov, M. B. Gubko, M. J. Beckmann and several other researchers [2–9]. The basis of most of these works on classical is the methods of mathematical programming, game theory, the theory of dynamic systems. The study of hierarchical systems has a number of basic problems of operation and control. In particular, the problem of decomposition of the system, the task of coordinating the system, the task of accounting for uncertainty of parameters and variables in hierarchical decision-making systems are of interest [10].

The coordination method of the multi-level hierarchical system, of course, has an impact on its most important characteristics, such as efficiency, reliability, and cost. Therefore, the determination of the optimal coordination method is an important task in the design of complex process control systems [1–10].

The principal methods focus mostly on iterative and non-iterative algorithms for deterministic coordination. However, the variety of problems of coordination, the large size of the problem, the uncertainty in estimating the state of the coordinated processes requires further research. In particular, the published studies do not consider the problem of resource allocation in relation to the task of synchronizing parallel processes [10–13].

3 MATERIALS AND METHODS

The main task in the development of a multi-level system is the specification of system elements. In the simplest case, a coordinator K can be modeled by input/output relation $K \subset I \times O$, I is the set of inputs and O the set of outputs. In most cases, the mapping from one set to another is not expressed explicitly. The input and output variables and parameters of the coordinators are showed in fig. 2.

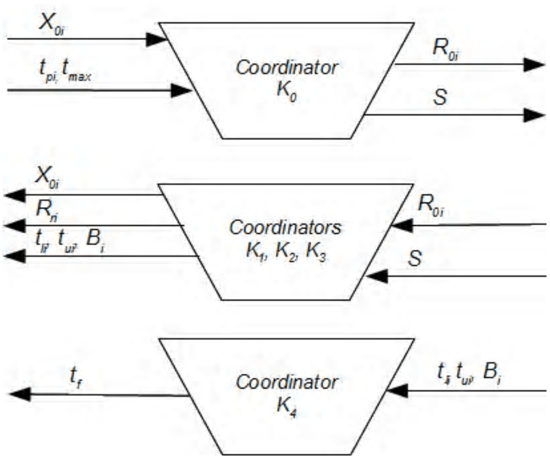

Figure 2 – Coordinators' input and output variables and parameters

One key factor in process management systems is the performance analysis. This analysis ensures that the system meets the technical requirements; the final products are delivered on time, and manufactured within reasonable costs. For each subordinated decision unit or coordinator, an objective function *eff*, measures the effectiveness of the subprocesses activities and is a function of the sub-systems input and output variables. The objective of the coordinator is to affect the lower-level decision-making so that the performance of the whole system is optimized. Having a performance index for each subprocess allows to make the sub-system decision-making problems independent from each other and to remove the possible «conflicts» caused by the interconnections between the sub-systems.

The full use of productive capacity is an objective optimization of industrial processes. The amount of resources allocated to each subprocess determines the degree of utilization. However, if the assignment exceeds the performances then the lines work in low-efficiency regimes. The efficiency criterion must, therefore, consider these factors, equation (1):

$$eff_i = eff_{0i} \exp\left[\frac{-\left(\frac{X_i}{p_i} - T\right)^2}{\sigma_{pi}}\right]. \tag{1}$$

One of the issues when measuring effectiveness criteria of the different subprocesses concerns the scale, fig. 3. Scaling coefficients are used to represent all numerical quantities to comparable orders of magnitude; in this case they are normalized to one.

To formalize the effectiveness criterion of the packing and transfer device, it is necessary to formulate the model of the process, a Gantt chart is shown in fig. 4.

A wide range of problems, including the coordination of production activities are solved using search methods. These methods aim to find an optimal solution within a search space Ω, defined by a series of constraints. In most cases, the search requires high computational costs. Analytical methods, such as gradient-based methods are not applicable when the space is multidimensional search or the task has a combinatorial nature. For this reason researchers prefer heuristic methods such as genetic algorithms or random search methods [10, 12–14].

Then the criterion of effectiveness of the packing machine can be written as follows in the equation (2):

$$eff_4 = \frac{\sum_{i=1}^{n} \frac{R_{ri}}{p_u}}{t_{fu} - t_{ou}}. \tag{2}$$

The task of the coordinator of the packing machine is to minimize coefficient eff_4. The sequencing of the operations is carried out as follows:

1. Finding the number k of subprocesses that can work in parallel, equation (3):

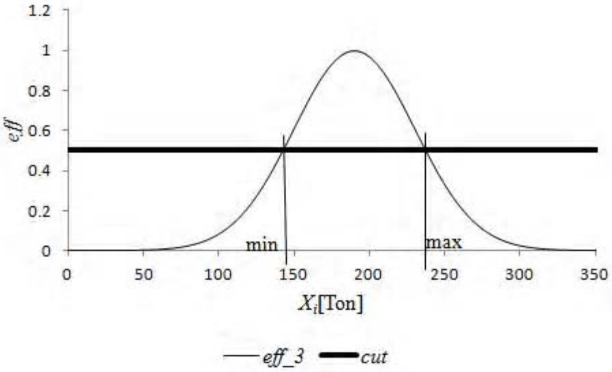

Figure 3 – Effectiveness criteria of the different subprocesses

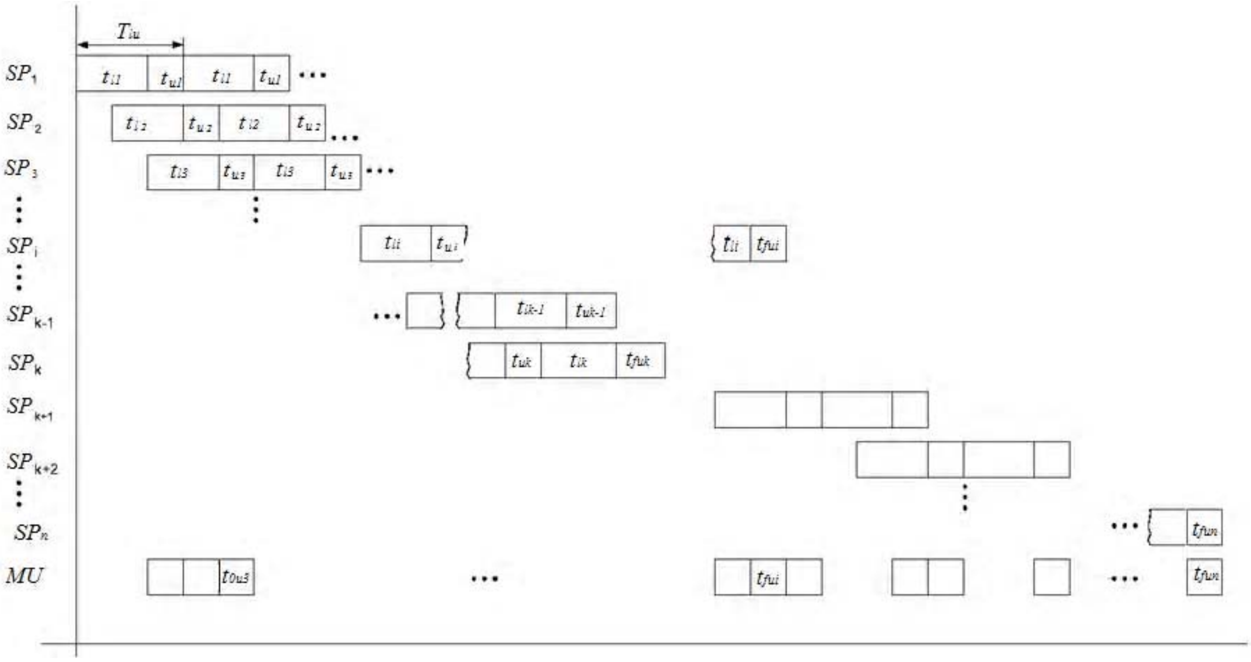

Figure 4 – Model of the process

$$\sum_{i=1}^{r\in(1,n)} p_i = p_i \le p_u < \sum_{i=1}^{k+1} p_i. \quad (3)$$

2. The k subprocesses are sequenced according to the value of the buffer load time so that if $t_{li} > t_{lj}$ then $t_{0i} < t_{0j}$,

3. The remaining $n–k$ subprocesses are sequenced from the lowest to the highest according to the buffer loading time.

4. The start time of the subprocess $k+1$ is equal to equation (4):

$$\max_{i\in(1,k)} (t_{fi}) - t_{l(k+1)}. \quad (4)$$

For the calculation of the start time and final time of operations, the following procedure is proposed:

Let to consider the parallel processes. The start time of the process is equal to the start time of the first subprocess $t_{01}=0$, and the start time for the i subprocess is given equation (5):

$$\underset{i\in(1,k)}{t_{oi}} = (i-1)T - \sum_{j=2}^{i} t_{lj}. \quad (5)$$

where T_{lu} is the sum of t_{li} and t_{ui}. The completion time of the sub-processes is written as $t_{fi}=t_{oi}+t_{pi.}$ And the process time t_{pi} is given by equation (6):

$$t_{pi} = \frac{R_{ri}}{p_i}. \quad (6)$$

From these equations, the completion time of the parallel subprocesses k is given by equation (7):

$$t_{f\max} = \underset{i=\arg(t_{p\max})}{t_{0i}} + \max_{i\in(1,k)} \frac{R_{ri}}{p_u}. \quad (7)$$

For subprocesses $n–k$, that work in series, the start time and the completion time are calculated by equations (8) and (9):

$$t_f(k+j) = t_0(k+j) + t_p(k+j), \quad (8)$$

$$t_0(k+j) = t_{fk} - t_l(k+j). \quad (9)$$

Therefore,

$$t_{fn} = k t_{f\max} - \sum_{i=k+1}^{n} t_{li} + \sum_{i=k+1}^{n} t_{pi}, \quad (10)$$

The start time of the packing device $t_{ou}=t_{l1}$ and the completion time $t_{fu}=t_{fn}$.

A number of sub-processes can work in parallel if the conditions illustrated in fig. 5 are met by equation (11):

$$\begin{cases} t_{li} + t_{ui} = T_{lu}, \\ \sum tui = T_{lu}, \\ \sum_{i=1}^{n} t_{li} = (k-1)\sum_{i=1}^{k} t_{ui}. \end{cases} \quad (11)$$

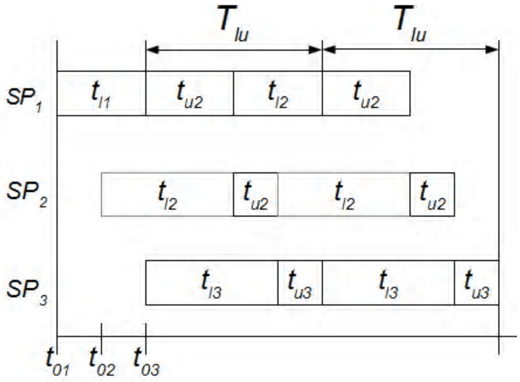

Figure 5 – Gant diagram of the analysis for the completion time of the subprocesses

The coordination can be achieved through the variation of the quantities stored in temporary spaces and the variation of the performance of the lines. By the introduction of the coordination variables α_i for temporary store B_i and λ_i for machines performance, equation (11) can be rewritten in the parametric form as the equation (12):

$$\begin{cases} T_{lu} = f(\alpha_i, \lambda_i), \\ s.t. \\ \sum_{i=1}^{n} \frac{\alpha_i B\max_i}{\lambda_i, p_i} = (n-1)\sum_{i=1}^{n} \frac{\alpha_i B\max_i}{p_u \lambda_i, p_i}. \end{cases} \quad (12)$$

Thus, the coordination task is reduced to finding a vector $X(\alpha_i, \lambda_i)$, which satisfies the above-mentioned conditions:

$$\begin{cases} \min\left|\sum t_l(\alpha_i, \lambda_i) - (n-1)\sum t_u(\alpha_i, \lambda_i)\right|, \\ s.t. \\ \alpha \in [\alpha_{\min}, \alpha_{\max}], \\ \lambda \in [\lambda_{\min}, \lambda_{\max}]. \end{cases} \quad (13)$$

The values $\alpha_{\min}$, $\alpha_{\max}$, $\lambda_{\min}$, $\lambda_{\max}$, ensure that the subprocesses operate in the rank of better efficiency. Equation (13) is solved either by genetic algorithms or a random search method, based on sampling and local search.

As the criterion for evaluating the effectiveness of the upper-level coordinator, it is proposed the relationship between the net profit and maximum completion time in the equation (14):

$$E = \frac{P - C}{T}. \quad (14)$$

It is worth noting that the execution time T depends on the amount of raw material, designated by each line and its technical parameters. Thus, the selected criterion is a function of the resources allocated to each line and the sequencing of operations.

The overall decision-making is based on the coordination of the decision of the subprocesses. These decisions are the result of the optimization procedures. The value of optimization problems can be modified with a set of weight coefficients, in order to make the subprocesses decision problems independent from each other.

When designing complex systems, there is often ambiguity in one or more of the following elements: constraints, demands or objectives. This imprecision arises because of the scarcity of information or the same nature of processes, which does not allow a satisfactory formulation of the design goals, and thus the inability to assess the relative importance objectives.

4 EXPERIMENTS

To coordinate the making decision process of the object of this study it applied the proposed a mechanism based on fuzzy sets [11]. Formulating a fuzzy coordination problem entails developing membership functions м for each constraint and each objective. It is important that the membership functions are normalized to comparable value, usually 1. The membership function of a subprocess is the coordination function of that subprocess. On the other hand, the criteria of effectiveness, which act as the degree of satisfaction of the subprocess is the coordination function.

It is desirable to find a solution that maximizes the value of each criterion. However, such a situation occurs only in ideal cases, therefore, for real problems a compromise solution is required. This leads to the need to specify the sequence of application of the criteria and the relative importance. The minimax criterion for the solution of the decision-making problem allows overcoming the disadvantages that appear when applying the additive and multiplicative indicators. The intersection of the membership function of subprocesses objectives, including the upper-level coordinator, yields the membership function of the system:

$$\mu_g = \min(\mu_0, \mu_1, \mu_2, ..., \mu_n). \quad (15)$$

The value that maximizes the global decision is defined as follows:

$$\max_{x \in X} \mu_g(x) = \max_{x \in X} \min \mu_g(\mu_0, \mu_1, \mu_2, ..., \mu_n). \quad (16)$$

The block diagram shows the management process, with the resolution of optimization problems of local subprocesses and the coordination of the isolated solutions.

1. Begin.
2. Selection of the solution vector.
3. Selection of weight coefficients.
4. For i=1 to n subprocess:
   a) assigning solution vector to lower levels subsystems;
   b) solution of local optimization problems;
   c) calculation of membership functions.
5. End for.
6. Calculation of the global membership function μ_g.
7. If $\mu_g < \min\mu_g$ repeat from step 2.
8. End.

5 RESULTS

Figures 6 and 7 show the evolution of the values of the coefficient of effectiveness as a function of the iterations of the process of coordination. The top figure corresponds to system index and lower figure to subprocesses. At the point of coordination, all subprocesses operate within the ranges set forth in the optimization process and under these conditions the overall effectiveness is higher for the case with coordination compared with the case without coordination.

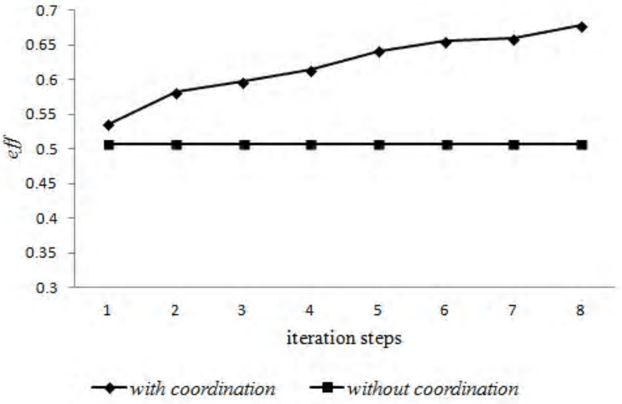

Figure 6 – Coefficient of effectiveness of system with coordination and without coordination

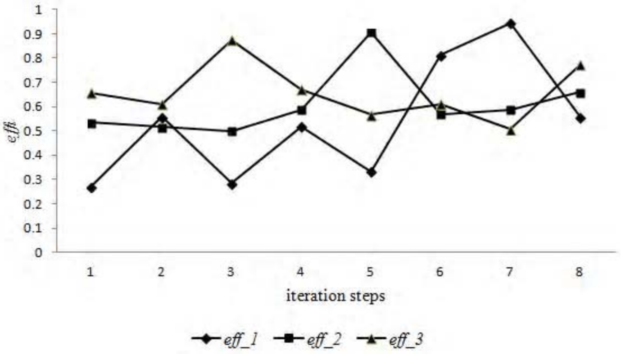

Figure 7 – Coefficient of effectiveness of subprocesses

6 DISCUSSION

The results fully support that coordination has a positive effect on the performance of control systems. However, the determination of the effectiveness criteria exerts a large influence on the results. For example, if to take the balance of the criteria of effectiveness as the stopping condition then in the second iteration the program would have stopped. This fact would have led to a suboptimal result as it is clearly illustrated in Figures 6–7. Another important aspect that we have found is the stability of the algorithm. Even though, the behavior of the curves for the indices of effectiveness for each subsystem seems to be erratic, the overall result has a monotonous improvement in each iteration. The method was developed with the characteristics and peculiarities of a specific application under certain conditions; therefore is necessary to take into consideration these conditions for other applications.

CONCLUSION

A fuzzy method for the coordination of the activities of a dairy plant was developed. It incorporates a hierarchical multilevel system for the management of activities, and the detailed mathematical modeling of the sequencing of operations. The decision-making process was accomplished by a minimax estimation of the membership functions. The coordinated operations give as result a higher global effectiveness.

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РАЗРАБОТКА КООРДИНАЦИОННОГО МЕТОДА ДЛЯ ЭФФЕКТИВНОГО ПРИНЯТИЯ РЕШЕНИЙ В ИЕРАРХИЧЕСКОЙ МНОГОУРОВНЕВОЙ ПРОМЫШЛЕННОЙ СИСТЕМЕ

В условиях современного производства происходят объективные изменения в функционировании промышленных предприятий, что связано с ростом их размеров и сложностью во взаимозависимости подчиненных структур. Поэтому на предприятии необходима модернизация систем управления процессами. Одним из важных заданий в этой модернизации является разработка эффективных методов координации. Поэтому в данной статье рассматриваются проблемы координации в принятии решений в группе автономных производственных единиц. Объектом исследования являются процессы принятия локальных решений на молокозаводе, на котором работает три производственные линии. Предметом исследования является координация операций, когда имеется только одна упаковочная машина. Цель данной работы – увеличить общий индекс эффективности системы производственных единиц за счет оптимального распределения ресурсов и синхронизации операций технологического процесса. Для эффективной координации предлагается метод, который обеспечивает оптимизацию процессов при рассмотрении конкретных предпочтений каждого локального блока принятия решений. Для каждого подчиненного блока принятия решений или координатора, целевая функция измеряет эффективность деятельности подпроцессов. Координатор влияет на процесс принятия решений более низкого уровня, так что производительность системы в целом оптимизируется. Координатор содержит иерархическую многоуровневую систему для управления деятельностью, а также детальное математическое моделирование последовательности операций. Предложенный метод основан на теории нечетких множеств и нечеткой логики. Процесс принятия решений осуществляется посредством минимаксной оценки функций принадлежности. Координированные операции дают в качестве результата более высокую глобальную эффективность. Кроме того, для сравнения предпочтений предложены нормированные критерии эффективности, основанные на технологических характеристиках каждого процесса.

Ключевые слова: координация подпроцесса, нечеткий метод, иерархическая многоуровневая система, принятие решений**.**

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РОЗРОБКА КООРДИНАЦІЙНОГО МЕТОДУ ДЛЯ ЕФЕКТИВНОГО ПРИЙНЯТТЯ РІШЕНЬ В ІЄРАРХІЧНІЙ БАГАТОРІВНЕВІЙ ПРОМИСЛОВІЙ СИСТЕМІ

В умовах сучасного виробництва відбуваються об'єктивні зміни у функціонуванні промислових підприємств, що пов'язано з ростом їхніх розмірів і складністю у взаємозалежності підлеглих структур. Тому на підприємстві необхідна модернізація систем керування процесами. Одним з важливих завдань у цій модернізації є розробка ефективних методів координації. Тому в даній статті розглядаються проблеми координації в прийнятті рішень у групі автономних виробничих одиниць. Об'єктом дослідження є процеси прийняття локальних рішень на молокозаводі, на якому працює три виробничі лінії. Предметом дослідження є координація операцій, коли є тільки одна пакувальна машина. Мета даної роботи – збільшити загальний індекс ефективності системи виробничих одиниць за рахунок оптимального розподілу ресурсів і синхронізації операцій технологічного процесу. Для ефективної координації пропонується метод, що забезпечує оптимізацію процесів при розгляді конкретних переваг кожного локального блоку прийняття рішень. Для кожного підпорядкованого блоку прийняття рішень або координатора, цільова функція вимірює ефективність діяльності підпроцесів. Координатор впливає на процес прийняття рішень більш низького рівня так, що продуктивність системи в цілому оптимізується. Координатор містить ієрархічну багаторівневу систему для керування діяльністю, а також детальне математичне моделювання послідовності операцій. Запропонований метод заснований на теорії нечітких множин і нечіткої логіки. Процес прийняття рішень здійснюється за допомогою мінімаксного оцінювання функцій належності. Координовані операції дають як результат більш високу глобальну ефективність. Крім того, для порівняння переваг запропоновані нормовані критерії ефективності, засновані на технологічних характеристиках кожного процесу.

Ключові слова: координація підпроцесу, нечіткий метод, ієрархічна багаторівнева система, прийняття рішень.

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