Automating preparation of small-scale production for reliable net-centric IoT workshop

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Abstract: This work describes digital modeling as the approach to automation of the technological preparation of small-scale engineering IoT workshop. This type of manufacturing is characterized by a serious imbalance between the time of preparation of production and the production process itself, which must be leveled using the hierarchy of success criteria for the production process. The proposed concept eases the work on the preparation of small-scale production and allows creation of technological processes based on promising typical and group modular technologies of mechanical engineering.

Keywords: Internet of Things-aware workshop, small-scale mechanical engineering production preparation, automation of technological processes

1 Introduction

The main value of modern production is information, the amounts of which have become too large for a human to process effectively. Technologies are changing faster than enterprises manage to integrate them; the level of automation is constantly growing. However, it is not enough only to provide modern equipment for a factory, it is necessary to ensure the efficiency of its work [1]. This can be achieved by an adequate analysis of the incoming information and its subsequent processing. At the modern mechanical engineering site, the main work on the manufacturing of products is carried out on equipment with computer numerical control, therefore the optimization of the technological process often comes down to the optimization of the program code for these machines. At the same time, the work on the analysis and processing of information is not always fully automated due to the need to operatively adapt to the production environment, especially for small enterprises with small-scale production. In this area, it is necessary to quickly create production plans that can change depending on the state of the process equipment and manufactured products, and the implementation of plans should be effectively automated.

Usually, the tasks of operational planning and automated production management are carried out by the manufacturing execution systems (MES) [2]. They occupy an intermediate place in the hierarchy of enterprise management systems between the level of information collection from equipment in workshops done by supervisory control and data acquisition (SCADA) systems [3] and the level of operations over a large amount of administrative, financial and accounting information done by enterprise resource planning (ERP) [2] systems. Nowadays on the Russian market there are three most popular largest solutions: PHOBOS system, YSB.Enterprise.Mes system and PolyPlan system. PHOBOS is traditionally used in large and medium-sized mechanical engineering enterprises. YSB.Enterprise.Mes originated from the woodworking industry and focuses on the sector of medium and small enterprises. The PolyPlan system has a smaller set of MES functions, but is positioned as an operational scheduling system for automated and flexible manufacturing in engineering [4].

However, with all the attractiveness of such systems, due to the extensive set of functions provided and deep integration into the production processes in the enterprise at all stages, their practical implementation is a whole complex and expensive project in itself that not all enterprises, especially small-scale and individual, can afford. In addition to this, in order to work effectively with MES, high qualification of its operator is required.

The developed solution given in this work is designed to solve a narrower class of problems - to simplify the technological preparation of production for small-scale mechanical engineering site, which can be based on the introduction of operative digital modeling and analysis of the technological process of the production site in order to optimize and generate programs for managing and monitoring the production process.

2 IoT Automation Object Architecture

A promising direction in the organization of automation of small-scale mechanical engineering production sites is their focus on network-centric control and management. The advantages of this approach are indisputable provided that complex network-centric systems will have high reliability of operation and flexible control of technological processes. Figure 1 shows an example of a network-centric architecture of a production site.

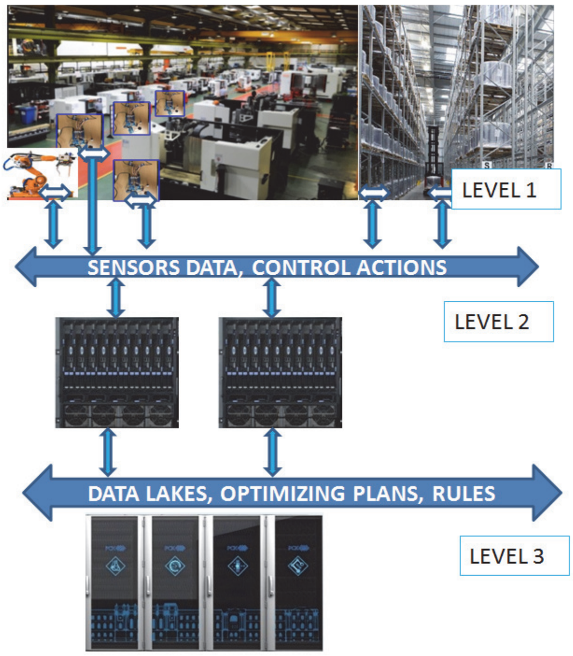


Figure 1 – Three levels of network-centric control of a mechanical engineering working site

The levels depicted are as follows:

1. The level of technological operations for CNC machines, robots and other objects that provide control actions and collect data on the state of network objects.
2. The level of technological processes (management of technological routes, which contain sequences of technological operations).
3. The level of multi-criteria hierarchical optimization and production planning.

Modern implementations of distributed production networks [5] are usually based on special platforms that provide automation of technological process logistics while control of the technological processing phases in appropriate modes is carried out by instructions loaded via the network to CNC machines, robots and automated warehouses. Such solutions use pre-developed plans that exclude both operational adaptation necessary for changing nomenclature of small-scale or individual orders and operational monitoring of states of working equipment and resources. This approach has proven itself in the automation of mass production, while the IoT feature is the use of intelligent data center components that provide predictive and adaptive behavior of the workshop's technological processes based on the analysis of "data lakes" coming from production equipment.

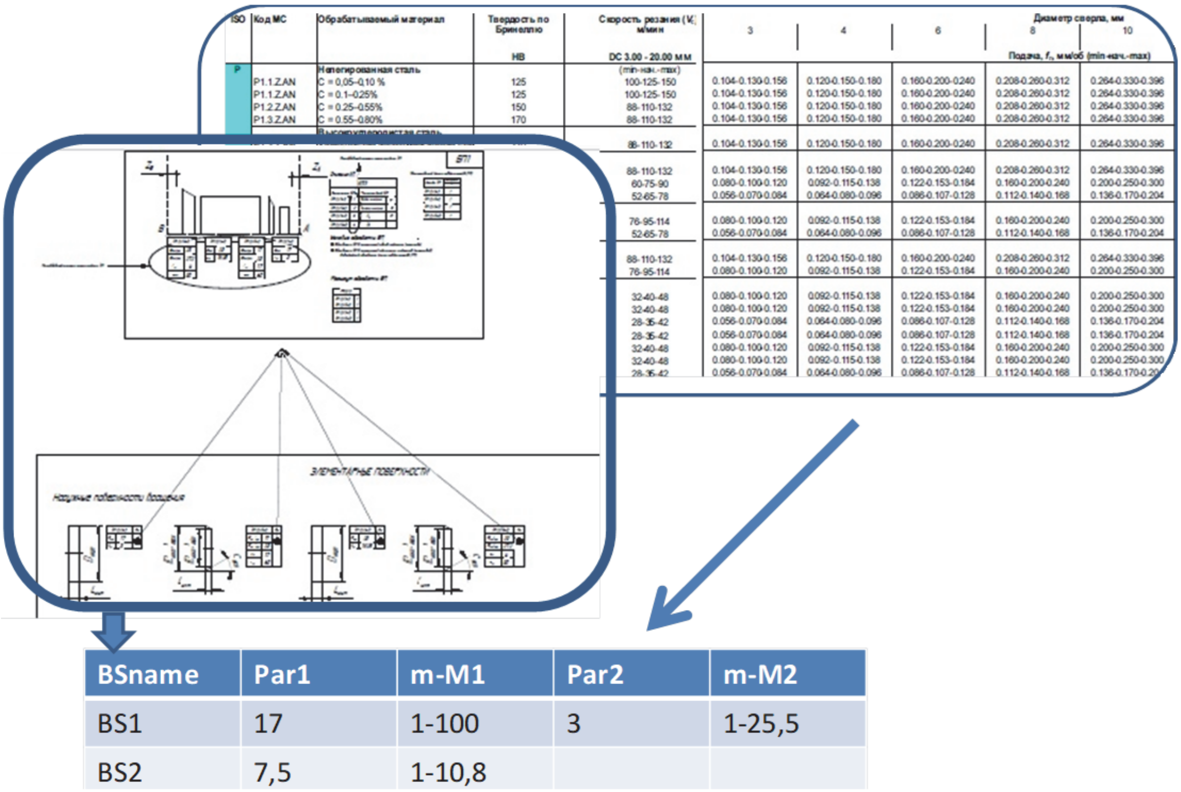
In the following, we describe the features of the Industrial Internet of Things platform for small-scale production.

3 Formalization: From Drawing to Technological Route

Formalization of a detail uses modular technology, which implies an effective adaptation of the technological process to the product. The choice of surface and compound modules (SMs and CMs) of a detail as objects of classification allows resolving the contradiction between continuous change of products and the desire for consistency in technological equipment. Since the detail is represented by a set of SMs and CMs, the technological processes of details manufacturing are built by assembling them from the modules of technological processes. In this case, the task of the technologist is to provide each SM and CM with standard modules of technological equipment [6].

The process of the formalization is carried out by the technologist on the basis of its drawing. He should highlight the modules to be processed in the drawing and provide the description of each with a variety of design and technological parameters, such as geometry, dimensional accuracy, surface hardness, processing method, necessary equipment, cutting tools, cutting modes etc.

For these purposes, the automated workplace of the technologist (AWT) is used (Fig.2).



BSname	Par1	m-M1	Par2	m-M2
BS1	17	1-100	3	1-25,5
BS2	7,5	1-10,8		

Figure 2 – Using AWT to select a cutting tool and its parameters

The technologist obtains the necessary parameters from the drawing, reference catalogues or other documentation. For a number of parameters, ranges of possible values are specified.

In addition to the surface modules, the modules for the technological process of manufactured detail, the modules for equipment and gear, the modules for instrumental adjustment and the modules for measuring instruments are described in a similar way.

Using modular formalization in AWT, the construction of technological blocks, modules to be processed in which use the same tool for the processing, and technological groups, which divide processing blocks into phases, is automated. As a result, technological routes (TRs) for manufacturing of a detail are formed from technological groups.

All this information is recorded in a specialized database. Info about each technological route contains a list of surface modules with specified values of parameters. Information of each surface module contains a detailed description of the manufacturing operations necessary for its processing with symbolic parameters. By creating queries to the database, a route with symbolic parameters, on the basis of which a specific detailed route will be created, is automatically formed.

In the approach presented here we use the MSC language [7] for the encoding of the technological route. MSC is a standardized language for describing behaviors using message exchange diagrams between parallel-functioning objects (CNC, robots). The diagram example is shown in the Figure 3.

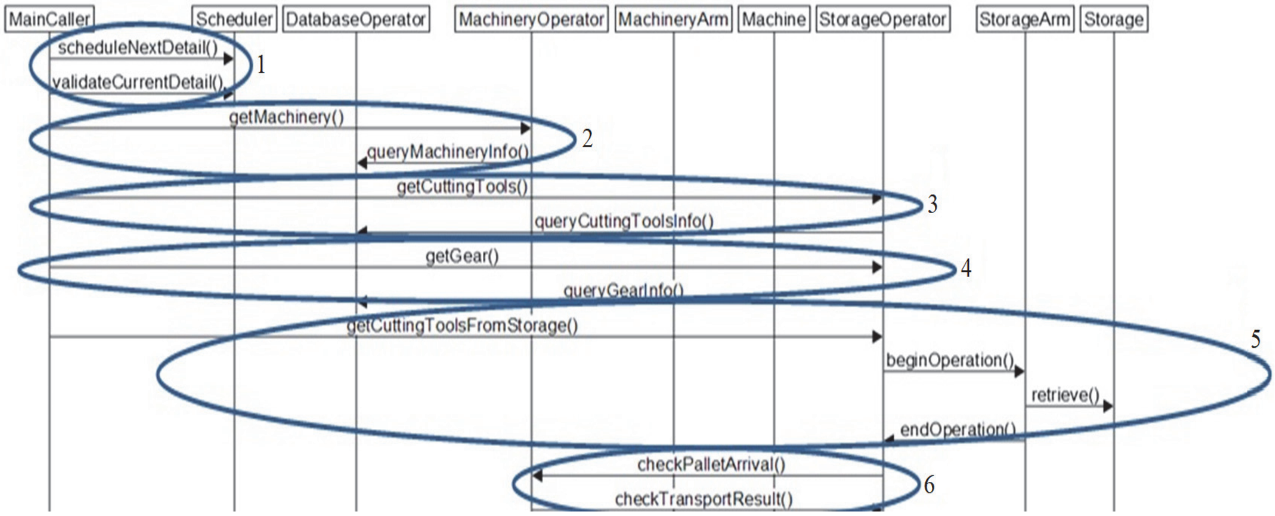


Figure 3 – Example MSC diagram of a technological route

The following messages are used in the diagram:

1. Messages about the preparation of the next detail for processing and verification of its suitability to the requirements of the route.
2. Messages checking the requirements for the necessary machinery and the availability of the machine.
3. Requests about processing tools and their working modes.
4. Requests about mounting fixtures.
5. Messages requesting a set of cutting tools from the storage to the CNC.
6. Messages about their retrieval on a pallet from the storage.

4 Technological Route Optimization

Technological route with symbolic parameters can be converted to a specific one by replacing the character variables with their values. In a case when the range for a value is specified, it is necessary to check its boundaries for the out-of-range error, which is implemented using a symbolic verifier [8]. In the process of proving the correctness of a route, it is possible to check various constraints on the sequence of surface modules within the route formulated by means of the first order logic. The contradictions found in the process of proof can be corrected by imposing additional restrictions on the stated sequences in the route or on the ranges of the parameter values.

For the correct technological route with the help of the formulas stored in the database, the technologist can estimate the time and cost of its processing. The fragment of the set of such formulas is shown in the Table 1.

Table 1 – Formulas for turning time calculations

Formulas	Parameters description
$T_m = \frac{L}{n \cdot s} \cdot i$	T_m - machining time L - estimated length of processing in mm n - workpiece rounds per minute s - cutter feed per round in mm i - the number of passes of the cutter
$L = l + l_1 + l_2$	l - the length of the workpiece in the feed direction, mm $l1$ - cutting-in length of the tool $l2$ - the length of the tool exit, mm
$n = \frac{1000 \cdot v}{\pi \cdot d}$	v - the speed of the cutting, mm per minute d - the diameter of the processed workpiece, mm
$i = \frac{h}{t}$	h - the amount of overmeasure in mm t - cutting depth in mm

The relative estimate of the route (Fig.4) can be obtained as the sum of the estimates of each operation on each individual surface module that make up the route, which is sufficient for ranking alternative solutions on the choice of parameters of the route. To obtain absolute values, it suffices to use the multiplicative and additive correction factors obtained on the basis of statistical estimates of the technological processes of a particular production.

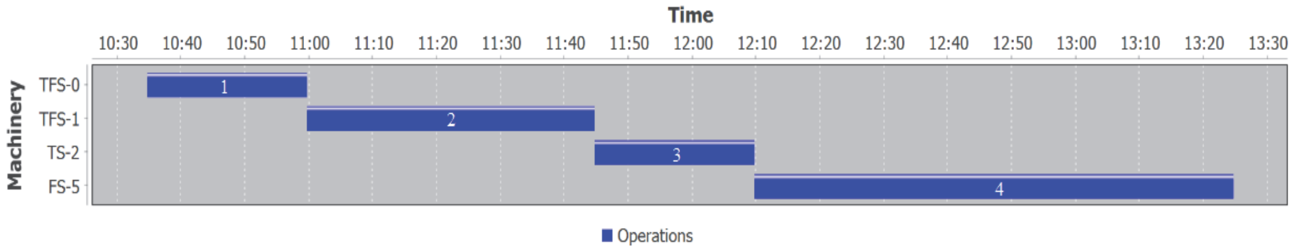


Figure 4 – Illustration of a technological route consisting of 4 operations performed on 4 machines

The correct route can be optimized. By changing the parameters of the route within the allowable ranges and re-calculating the indicators of processing time and cost, the technologist can get a solution that meets the limitations of the management on a particular job or get the Pareto-optimal solution [9]. However, it should be noted that the mentioned optimization is valid provided that the production by the route is carried out without taking into account the current state and restrictions on the resources of the production site. Obtaining more realistic estimates is possible with the help of simulation modeling of the distribution of resources for the routes simultaneously performed at the production site.

5 Digital Modeling of Technological Processes at the Production Site

The digital model of the production site simulates the implementation of the production of different batches of details by different specified technological routes. The site model is built on the basis of information on the resources of the production site (CNC machines, transport robots, warehouses, staff etc.) which include amounts of time for their usages. The size of the batch of details is also associated with the route.

The model uses the method of dynamic priorities to simulate the workload of resources of the production site and determine the duration of the realization of the technological process for orders.

The result of simulation modeling is a schedule for the implementation of the technological process (Fig.5), which provides an estimate of the time to manufacture a batch of details in accordance with a specific route along with an estimate of the lead time for all routes (Fig.6). A set of estimates of the time of execution of the route can be analyzed for the fulfillment of certain criteria and restrictions characterizing the conditions of the order.

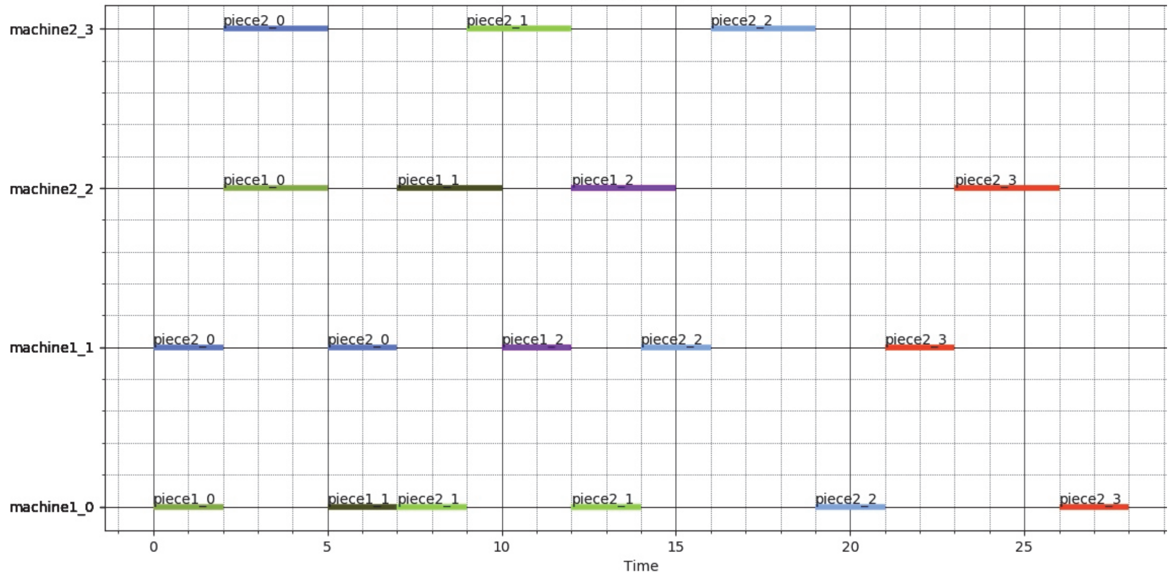


Figure 5 – Example of the production schedule chart

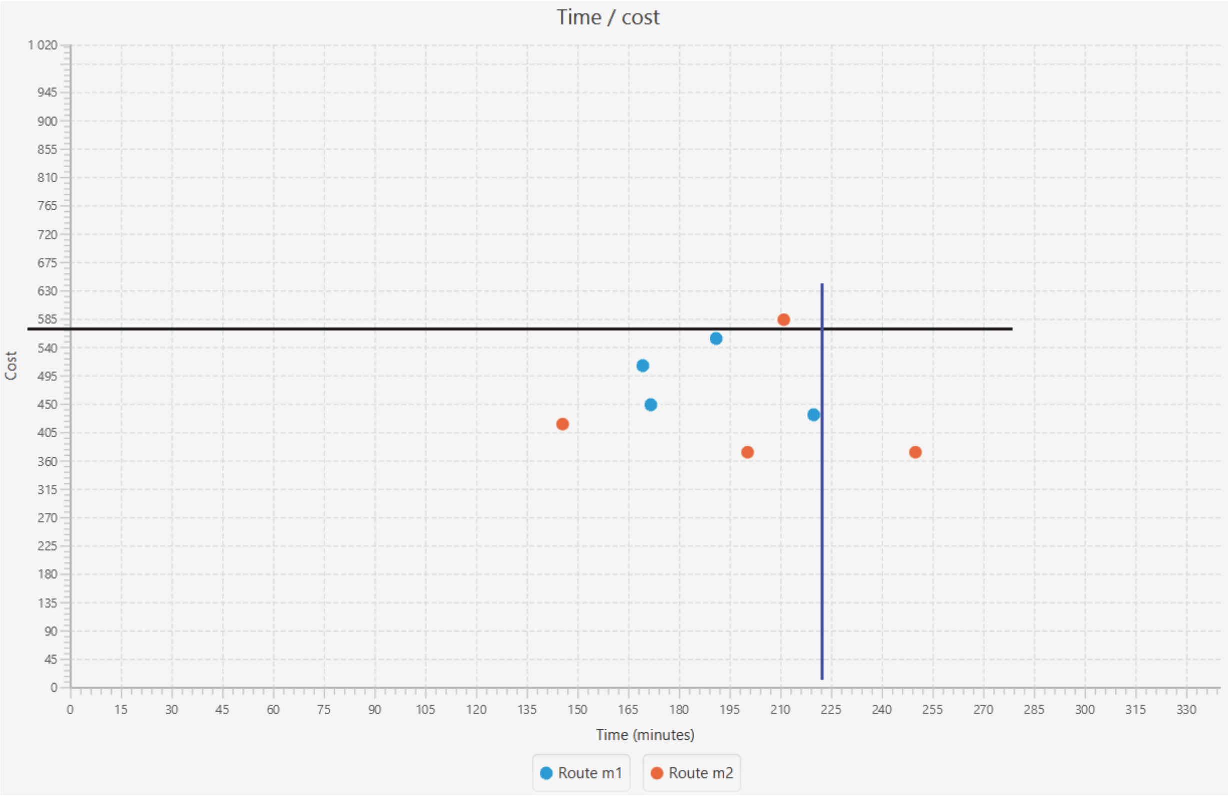


Figure 6 – Time and cost estimations example of two technological routes

In this regard, the following tasks can be solved:

1. Estimation of the minimal amount of additional resources that need to be allocated so that the total time for the implementation of the route is not more than the specified value T_0.
2. Redistribution of processing tools between individual operations in order to minimize the total implementation time of the route (optimal transfer of resources from non-critical operations to critical ones).
3. The use of time reserves T_0 - T arising when the calculated time T of the implementation of the route is less than the specified value T_0 in order to further improve the process.

In the process of implementing a specific work schedule (in a certain sense, optimal), various unforeseen failures are possible: machine breakage, shortage of components, unforeseen delays in performing individual operations, etc. Therefore, the management system should continuously monitor the entire process and should have a mode for operative changing of the schedule for the implementation of the remaining work in the new environment in order to optimize it. Thus, it turns out that it is necessary to correct the process of implementing the set of necessary operations in real time taking into account the set requirements for optimization and the formulated criteria of optimality.

In addition, when forming the structure of the management system, it is necessary to take into account the possibility of multi-criteria formulation of optimization problems, when several particular indicators of the quality of the production site are set [10]. In this case, the task of ensuring the work of the production site in some Pareto-optimal mode can be set. Usually it is advisable here to use some physically justified form of the convolution of the vector optimality criterion and proceed to optimization by the corresponding generalized criterion.

When solving problems of managing the work of a production site with a hierarchical structure, it is necessary to take into account the organization of interactions of processes at different hierarchical levels, both among themselves and with the main control center. For this reason, it is advisable to refer to the principles of network-centric management and methods of coordination in hierarchical systems. It is also advisable to use the methods of hierarchical construction of Pareto sets at various technological levels.

6 Analysis of Simulation Results

The analysis of the results of modeling a set of technological routes consists in solving a multi-criteria task of selecting implementation options for a technological process of the IoT system. It is assumed that the direct solution of the original multi-dimensional problem with a set of difficultly computable criteria is either impossible or impractical because of the limitations determined by the requirement of execution time and consumed resources balance. The main difficulties are connected with the high dimension of the vector of tunable (selectable) parameters of the IoT system and with a large number of partial optimality criteria. The proposed approach is based on the application of well-known system analysis procedures to the specific subject area under consideration [9].

It is necessary to develop a common, uniting all the technological processes, target criterion of the IoT system and an algorithm built on its basis - a management plan for the entire system, which distinguishes the network-centric control system.

7 Solution of the Problem of Multi-criteria Management

The major task to be solved has the form:

$$f_0^1(x_0) \to \max, \ldots, f_0^{n_0}(x_0) \to \max,$$
$$x_0 \in X_0 \subset R^{N_0}, x_0 = x(0) = (x_1(0), \ldots, x_{N_0}(0)),$$

where $f_0 = (f_0^1, f_0^2, \ldots, f_0^{n_0})$ is a set of objective criteria, which define requirements to the output parameters of the system being optimized, and X_0 is a set of variants of the considered system which are realizable physically and algorithmically.

A solution of the optimization task (selection of optimal variants) is understood as a set

$$\varPi_{f_0}(X_0) = \varPi_0(X_0) \subset X_0$$

of efficient (Pareto-optimal) solutions from X_0.

Applying the described constructive approach assumes solving the aggregation task, which requires taking into account the following specifics:

1. General multi-level models of optimization processes allow reducing the initial complex task to a series of efficiently decidable tasks using sequential aggregating (abstracting).
2. The aggregation process starts at the zero, most detailed (low) level of system description where a direct solution of the task is inefficient because of its complexity and high dimension.
3. The number of aggregation levels is selected in such a way, that the final dimension of the vector of adjustable parameters was acceptable for applying standard procedures of optimization [11, 12].
4. One can obtain more and more algorithmically simple objective functions (which are introduced informally at each level derived by experts from the consistency conditions) with aggregation.

7.1 Levels of the process of multi-criteria optimization

A model of levels of multi-criteria optimization is given in Fig.7:

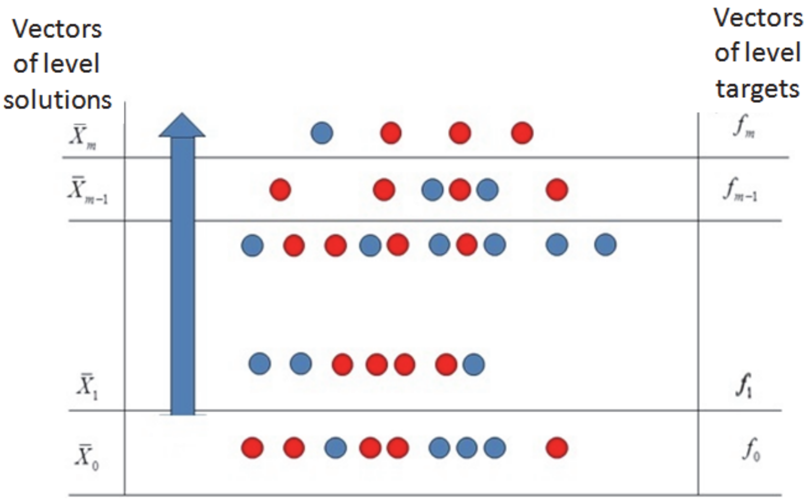


Figure 7 – Levels of the process of multi-criteria optimization

In the considered model the initial low level corresponds to the most detailed description of the system with a big number of arguments and another big number of particular criteria, usually of high computational complexity. As mentioned above, it is hard to solve the problem of constructing the set $\Pi_{f_0}(X_0) = \Pi_0(X_0) \subset X_0$ directly.

According to the algorithm described below, a successive enlargement of the problem description is performed through transition to the next (higher) level which contains less variables and particular criteria. As a result, an observable set of particular criteria depending on a relatively small number of arguments is obtained at the highest (strategic) level. Constructing a Pareto set at this level becomes algorithmically feasible. Thus, moving upward is accompanied at each level by introduction of aggregated variables and new sets of particular criteria, consistent with the criteria of the adjacent lower level in the sense specified below. This process of successive aggregation and decomposition is described below.

7.2 Aggregation levels

Let's introduce aggregated parameters of the next 1st level:

$$x(1) \in X_1, X_1 \subset R^{N_1}, N_1 < N_0,$$
$$x(1) = \varphi_1(x(0)), X_1 = \varphi_1(X_0),$$

where φ_1 are aggregation functions which define the structures of parameters of level 1 through parameters of level 0.

Then experts should specify criteria of level 1:

$$f_1(x(1)) = (f_1^1(x(1)), \dots, f_1^{n_1}(x(1))).$$

As $N_1 < N_0$ the set $x(1)$ provides more integrated and enlarged description of the planning process than the set $x(0)$. Functions φ_1 and f_1 should be consistent with $f_0, x(0), X_0$ in such a way that plan 1, which is Pareto-better than plan 2 w.r.t. criteria of level 1, was better than plan 2 w.r.t. criteria of level 0 as well.

As a result of continuing the aggregation process, the following chain is obtained:

$$\begin{aligned}
&x(0) \in X_0 \subset R^{N_0}, f_0(x(0)) \in R^{n_0};\\
&x(1) = \varphi_1(x(0)) \in X_1 \subset R^{N_1}, N_1 < N_0, f_1(x(1)) \in R^{n_1};\\
&-----------------------\\
&x(k+1) = \varphi_{k+1}(x(k)) \in X_{k+1} \subset R^{N_{k+1}}, N_{k+1} < N_k,\\
&f_{k+1}(x(k+1)) \in R^{n_{k+1}};\\
&-----------------------\\
&x(m) = \varphi_m(x(m-1)) \in X_m \subset R^{N_m}, N_m < N_{m-1},\\
&f_m(x(m)) \in R^{n_m}.
\end{aligned}$$

where

$$\begin{aligned}
&X_{k+1} = \varphi_{k+1}(X_k) = \{x(k+1) = f_{k+1}(x_k) / x(k) \in X_k\},\\
&0 \le k \le m-1.
\end{aligned}$$

Selecting the number m of aggregation steps (in real practice not greater than 4) is determined by the fact that the dimension of N_m should not exceed 50 and criteria $f_m(x(m))$ should be algorithmically simple.

After specifying all aggregation steps from bottom to top, the top-to-bottom very process of parameterized optimization starts (Fig.8). At the upmost (strategic) level m a respective Pareto set is constructed in accordance with the introduced criteria of the upmost level. Then one goes down in the planning graph in accordance with the above equations until level 0 is reached and the resulting Pareto set (a subset of it, to be exact) is constructed. The described process of optimization is a process of successive narrowing the set of considered (controlled) vectors on the basis of additional information in form of intermediate vector criteria of optimality introduced at each hierarchical level. The introduced "level-ranked" criteria of optimality reflect the level of task details. As a result (and this is the main point), variants rejected "from general considerations" at the previous hierarchical level are not analyzed at subsequent levels with more numerous and complete sets of particular criteria.

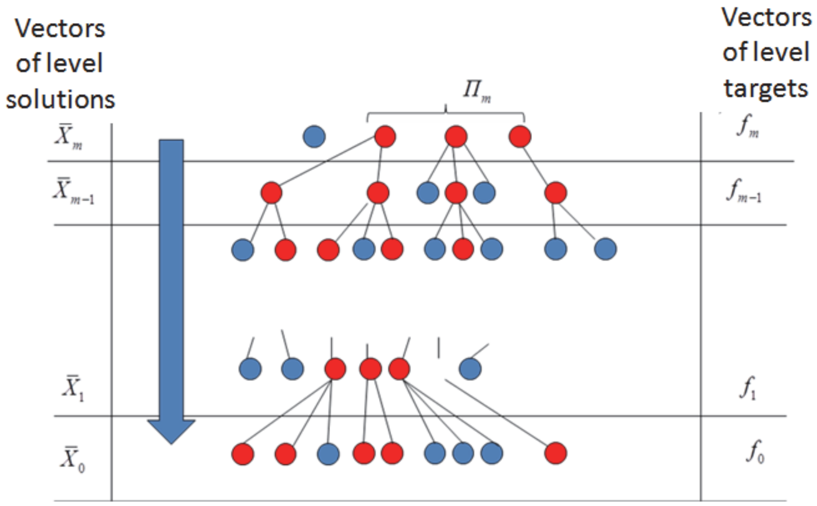


Figure 8 – Example of the process structure of objective optimization with net-centric control

7.3 The master equation (algorithm) of the optimization process

Upon execution of all aggregation steps, i.e., upon introducing $x(k), X_k, f_k, 0 \le k \le m,$ the multi-criteria component of the optimization task may be solved as follows.

Let's find

$$\Pi(X_m) = \Pi_{f_m}(X_m) = \Pi_m(X_m) = \Pi_m$$

and all solutions of the equation

$$\varphi_m(x(m-1)) = x(m), \forall x(m) \in \Pi_m \subset X_m.$$

These solutions define the set $\overline{X}_{m-1} = \varphi_m^{-1}(\Pi_m)$.

Then let’s find the sets

$$\Pi_{m-1}(\overline{X}_{m-1}) = \Pi_{m-1}, \overline{X}_{m-2} = \varphi_{m-1}^{-1}(\Pi_{m-1}).$$

The result of this process is $\Pi_0(\overline{X}_0)$.

All this may be formalized in form of the master equation of multi-objective optimization:

$$\Pi_k = \Pi_{f_k}(\overline{X}_k) = \Pi_k(\varphi_{k+1}^{-1}(\Pi_{k+1})),$$

$$k = m-1,\ldots,0. \Pi_m = \Pi_{f_m}(\overline{X}_m)$$

Approbation of the described approach has demonstrated its applicability for deploying and managing technological processes within an industrial workshop with 8 adjustable criteria for its effective functioning.

8 Inputs to the Process Control and Monitoring Module

The supervision sequences are generated from the extended MSC diagram, in which specially marked nodes containing descriptions of alternative behaviors are expanded by analysis blocks, in the conditions of which the transition events to the alternative routes are encoded. The monitor module with a specific control and monitoring program is loaded on-line into the process controller (Level 2 of the network-centric architecture, see Fig.1) and ensures that the work is performed in accordance with the optimized schedule. Its task is to send and receive messages both to the machines and to the smartphones of the staff.

9 Conclusion

The final result of the work is the creation of a software system for the automation of the preparation and control of the technological processes of the mechanical engineering production site. Currently, a working prototype of the system has been implemented, on which the following properties have been tested:

1. Ability to quickly adapt to specific production conditions: equipment, resources and orders.
2. Optimization of the characteristics of specific production processes in accordance with the selected set of criteria for its success, carried out on-line.
3. Efficiency assessment of the execution time and cost of the order, which is very important for the small-scale production manager with the flow of orders for small batches of different products that require different technological routes to be performed.

The platform provides a significant increase in the productivity of the technologist at the technological preparation phase of production. Total preparation time decreases to approximately 1 day per order.

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