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Algorithmisation methods for scheduling in high-performance assembly manufacturing

The authors analysed the most popular production planning and scheduling software systems. Their main disadvantage is that they lack lean manufacturing tools. There exists a demand for client-oriented systems based on lean principles. The paper describes a unique algorithm for computing the optimum takt time, which forms the basis of the scheduling system developed by the authors. We present methods of algorithmising the scheduling process and results of generating schedules using several algorithms.

Keywords: production scheduling, takt time, algorithmisation of scheduling, lean manufacturing, high-performance enterprise.

Automation of the production planning process is mandatory for industrial enterprises that strive to maintain the quality of manufactured products and increase the demand for the same. Despite development of numerous production planning methods, their introduction into the production process and practical application pose significant challenges. In particular, this is a challenge for high-performance enterprises with a flow-line production. *MRP* II [1] and *ERP* [2] systems, including more advanced *CSRP*, *MES*, and *APS* systems, became best known. Depending on the purpose of planning and functions subject to automation, the management selects one or several systems to be implemented. It should be pointed out that a significant number of developments are related to the operational planning systems. This area of planning is one of the most studied, but at the same time it is the most difficult due to a number of factors, such as particular characteristics of manufactured products and production processes. It should be pointed out that the specified systems do not feature lean manufacturing tools necessary for effective production management. Some systems feature functions for the plan correction [2] based on certain criteria, but this correction is conventional. The key lean manufacturing tools and methods mandatory for planning include the following:

- *PDCA* cycle implemented in the form of elements of an automated system that includes scheduling of data collection for the plan and its plotting, mandatory plan assessment, analysis of process deviations, and measures to address these deviations;
- standardised work expressed in the form of production and production process planning based on the optimal takt time calculation;
- process of continuous information sharing called *Nemawashi*, i. e., operational data exchange through the use of a unified information environment;
- visualisation consisting in the system capability to present the results of the finished plan in the form of illustrative graphs and tables.

It should also be pointed out that these systems belong to push type (*push systems*) [1], which contradicts the lean manufacturing in general.

Despite a large number of publications on organisation of flow-line production and development of automated planning systems, it should be pointed out that the ideas of effective plotting of plans with a floating planning horizon based on the calculation of the optimal takt time in an automated system have not been defined. The existing research is aimed at the automation of planning [3, 4] of a high-performance enterprise featuring a flow-line production.

A key element in the process of flow-line production planning is the takt time (TT) [5]. The TT is the rate at which one needs to complete a product in order to meet the customer's demand, which is generally calculated as the ratio of time available for production to the total number of ordered units.

Besides, based on the collected statistical data on the production downtime, certain correction factor (operational productivity factor K_{OP}) can be incorporated in the formula.

Taking into account the operational productivity factor, production output can be calculated by the formula

$$Q_M = \frac{t_{\text{avail.op.}}}{TT} K_{OP}, \qquad (1)$$

where Q_M – number of manufactured products;

$t_{\text{avail.op.}}$ – time available for production;

TT – takt time;

K_{OP} – operational productivity factor.

The time available for production is calculated by the formula

$$t_{\text{avail.op.}} = t_{\text{tot.}} - t_{\text{pl.shut.}},$$

where $t_{\text{tot.}}$ – total working time;

$t_{\text{pl.shut.}}$ – planned shutdown.

It should be pointed out that the resulting value needs to be rounded downward, otherwise the output per shift will always be less than the planned one. In particular, this is a challenge for high-performance industries, since, due to large volumes, little importance is given to the quantities of 1–2 production units, but incorrect application of the formula results in a lag of dozens of production units per month. These errors occur most often when a plan is plotted in *Microsoft Office* package, since in the absence of explicit rounding downward in the calculation formula, the value is automatically rounded upward. As a result, seemingly minor calculation errors lead to continuous overtime work, i. e., working over the established time, and, as a consequence, this affects moral and physical condition of production workers.

The time available for production ($t_{\text{avail.op.}}$) is the total shift working time minus planned shutdown.

The factor K_{OP} makes it possible to include in the plan the risks of unplanned shutdown caused by possible defects, introduction of various projects into the production, production of test batches of products, testing of new equipment, etc.

The developed planning system allows each participant (workshop, department) to set their own goals of K_{OP} with mandatory indication of the cause. In this case, when plotting a plan, the system identifies minimum K_{OP} (K_{OPmin}) for each shift and uses it for the calculations.

Ideally, the production output fully corresponds to the production order, i. e., the products shall be delivered just in time (*Just In Time*), but in almost all cases this condition is not met due to the manufacturer's intention to make the best possible use of existing resources; therefore, the following criterion for plan plotting was introduced:

$$\begin{cases} \Delta = Q_M - Q_O; \\ \Delta \to \min, \end{cases} \qquad (2)$$

where Q_O – number of ordered products.

When plotting a plan, the following inequality shall be solved:

$$\sum_{i=0}^{n} Q_{Oi} \le \sum_{j=0}^{m} K_{OP\min_j} \frac{t_{\text{avail.op.}_j}}{TT_j}, \qquad (3)$$

where i — type of product, $i \in 1 \ldots n$;

j – number of shifts.

If this inequality can not be solved, additional working shifts are introduced:

$$\sum_{i=0}^{n} Q_{Oi} \le \left(\sum_{j=0}^{m} K_{OP\min_j} \frac{t_{\text{avail.op.}_j}}{TT_j} + \sum_{k=0}^{l} K_{OP\min_k} \frac{t_{\text{avail.op.}_k}}{TT_k} \right), \qquad (4)$$

where k – number of additional shifts.

In addition, the task of plotting an optimal plan can be solved using the theory of graphs [6], where the vertices weight is the output per shift ($Q_{a,b,c}$, where a – week number in a year; b – day number in a week; c – shift number), and the edge weight is the complexity of shift organization (W) determined using Delphi method. In order to make the graph easier to read, indices x and y, indicating the previous and next shifts, respectively, are introduced for the vertices weight W.

Fig. 1 shows a graph describing the algorithm for production plan plotting.

A week was selected as the time unit for the plan plotting. This unit is optimal for describing the selected algorithm, since it takes into account all basic plan-plotting criteria preset by a planner (number of shifts and work on weekend). It should be pointed out that this type of graph makes it possible to take into account the peculiarities of the Russian legislation related to the Labour Code of the Russian Federation, i. e., to add work on weekends to the work plan and change the work schedule (shift schedule), taking into account certain time requirements preset by a planner.

Fig. 2 shows an example of plotting a production plan for one workweek with 3.2-minute TT and a planned production shutdown on Friday.

During this graph traversal, it is possible to create routes with the required weight indicators and choose the optimal route.

It should also be pointed out that during software engineering process, the development of the algorithm underlying the automated system was carried out in several stages. Initially, we used algorithm (A1) that calculates ideal TT for certain time intervals preset by the workshops and subunits of the enterprise as the minimum time interval (T_{shift}) with one TT, i. e., the time

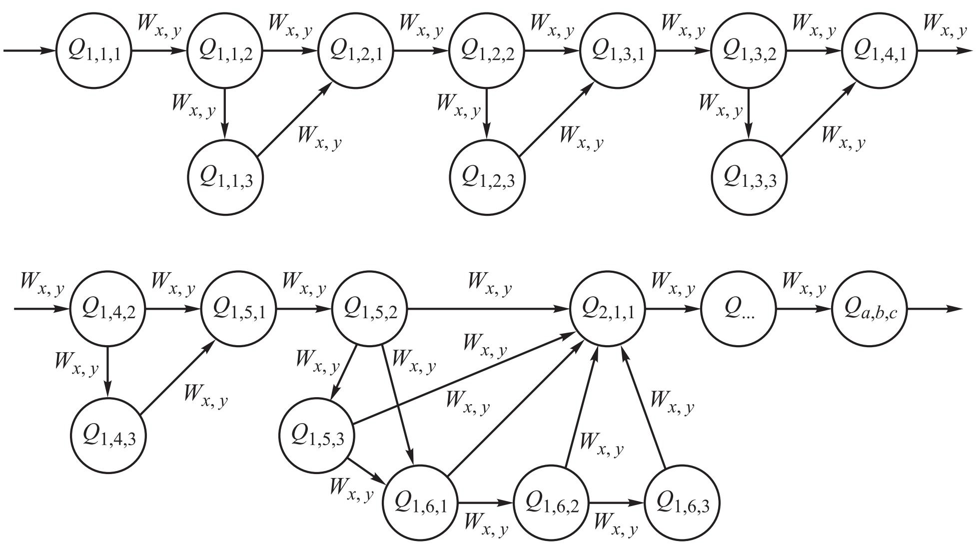

Fig. 1. Oriented graph of production plan plotting

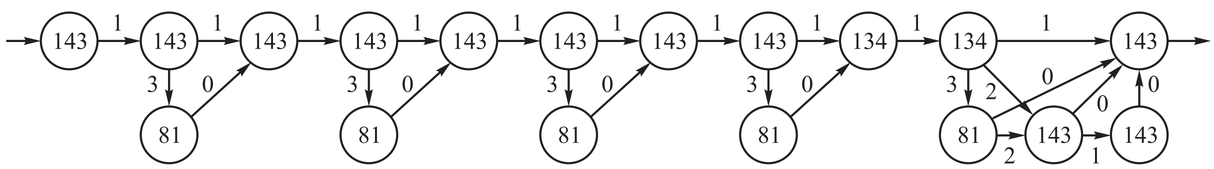

Fig. 2. Representation of task of production plan plotting in the form of an oriented graph

interval during which a workshop or production subunit can prepare for the transition to a new TT. The preparation is carried out as follows: based on the current standard operation process charts [7], the cycle time of each operation is analysed and new production processes are developed with a cycle time most close or equal to the TT, to which the transition is planned.

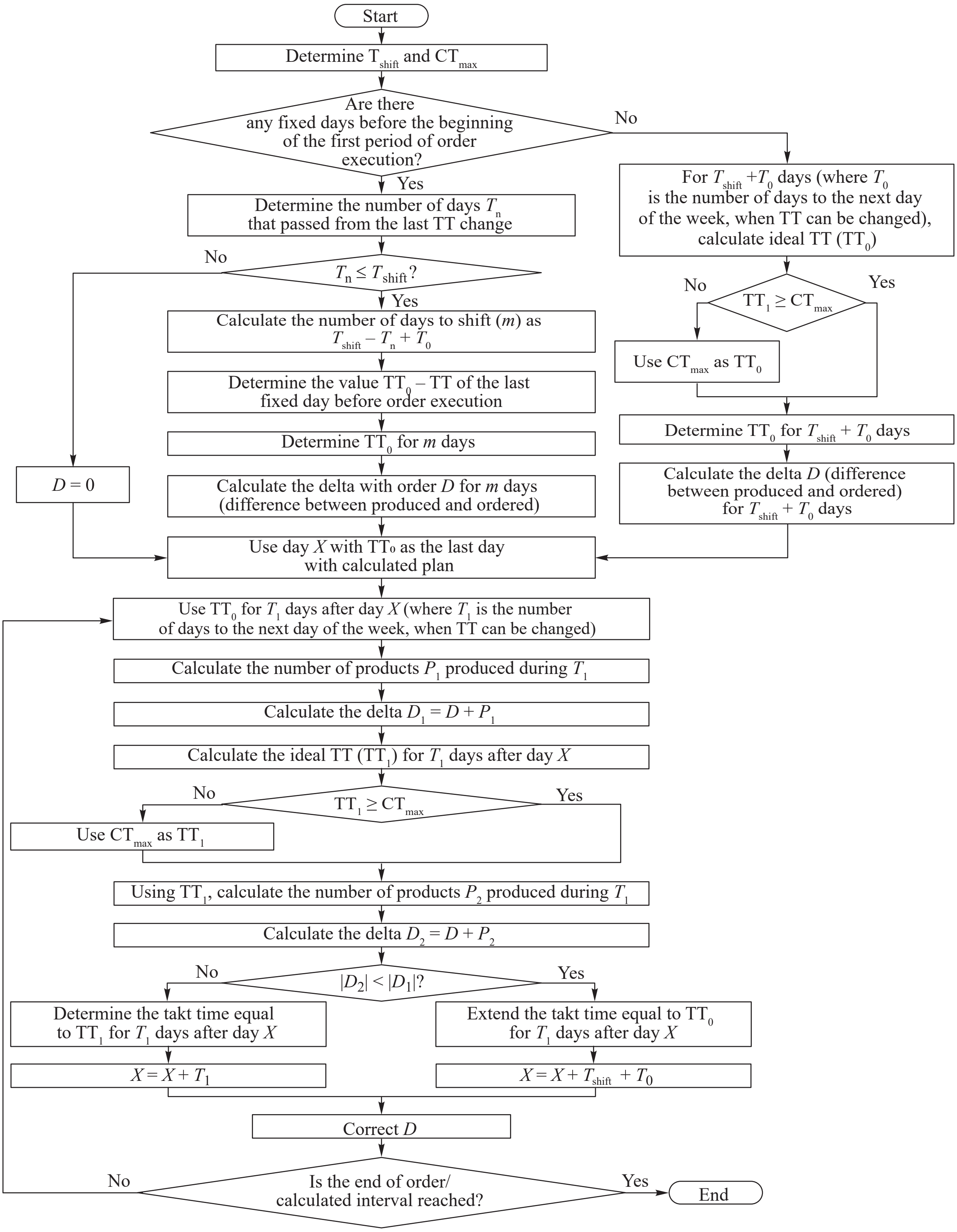

Fig. 3. Algorithm of TT calculation for different time intervals

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As an alternative, we developed algorithm (A2) (Fig. 3) that takes into account T_{shift}, but for searching an ideal ∅ (designation D is used for the delta of different intervals), it calculates different TT options for the intervals with different duration. The interval is a fixed value, time intervals using one takt time shall meet the following condition:

$$T_i \geq T_{shift} \quad \text{at} \quad i \in 0 \ldots n, \qquad (5)$$

where T_i – time intervals of different duration.

Besides, the following condition, limiting the TT possible to be used for the order fulfilment, shall be met:

$$TT_i \geq CT_{max} \quad \text{at} \quad i \in 0 \ldots n, \qquad (6)$$

where TT_i – takt time, calculated for different time intervals;

CT_{max} – maximum cycle time based on the information from production subunits (maximum equipment speed or manual process limitations).

T_{shift} and CT_{max} are determined based on a summary table in the automated system database.

In order to identify an optimal algorithm, the research results were assessed in the course of production planning. To test the algorithms of identifying the best, the plans were plotted for order (O1), which takes into account the products demand forecast for 24 production intervals, and order (O2), which is characterized by a significantly increased demand in the middle of order execution (Fig. 4). Initial data are as follows: T_{shift} – 60 calendar days; CT_{max} – 160 s; $t_{tot.}$ – 480 min. The day of possible transition to a new TT is Monday.

Data on working hours, planned production shutdown and factor K_{OP} for each working shift for two years represent a large array, therefore, they are not presented in this article.

To plot plans in order to identify an optimal algorithm, three options of plotting production plans were compared: manual plan plotting (MPP), algorithm 1 (A1) and algorithm 2 (A2).

The orders were executed in three ways: only TT, TT and possible weekend work (TT + weekend work), TT, possible weekend work and introduction of additional shift (TT + weekend work + additional shifts).

The experiment results are presented below. Thus, Fig. 5, a, shows cumulative value ∅ of plans plotted to fulfil the first order in two ways: only TT and TT + weekend work. Only one graph is shown for the second order (Fig. 5, b), indicating cumulative value ∅ (cumulative ∅) for the plan plotted using TT + weekend work + additional shifts; since the second order significantly exceeds the production capacity and cumulative ∅ of the plans plotted in other ways, and has too wide scatter, the obtained graphs are not illustrative.

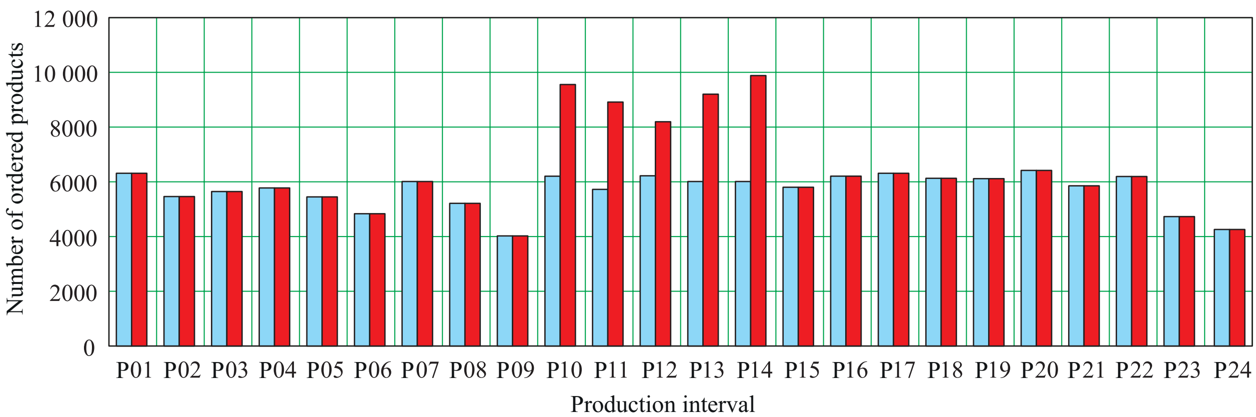

Fig. 4. Production orders:
– O1; – O2

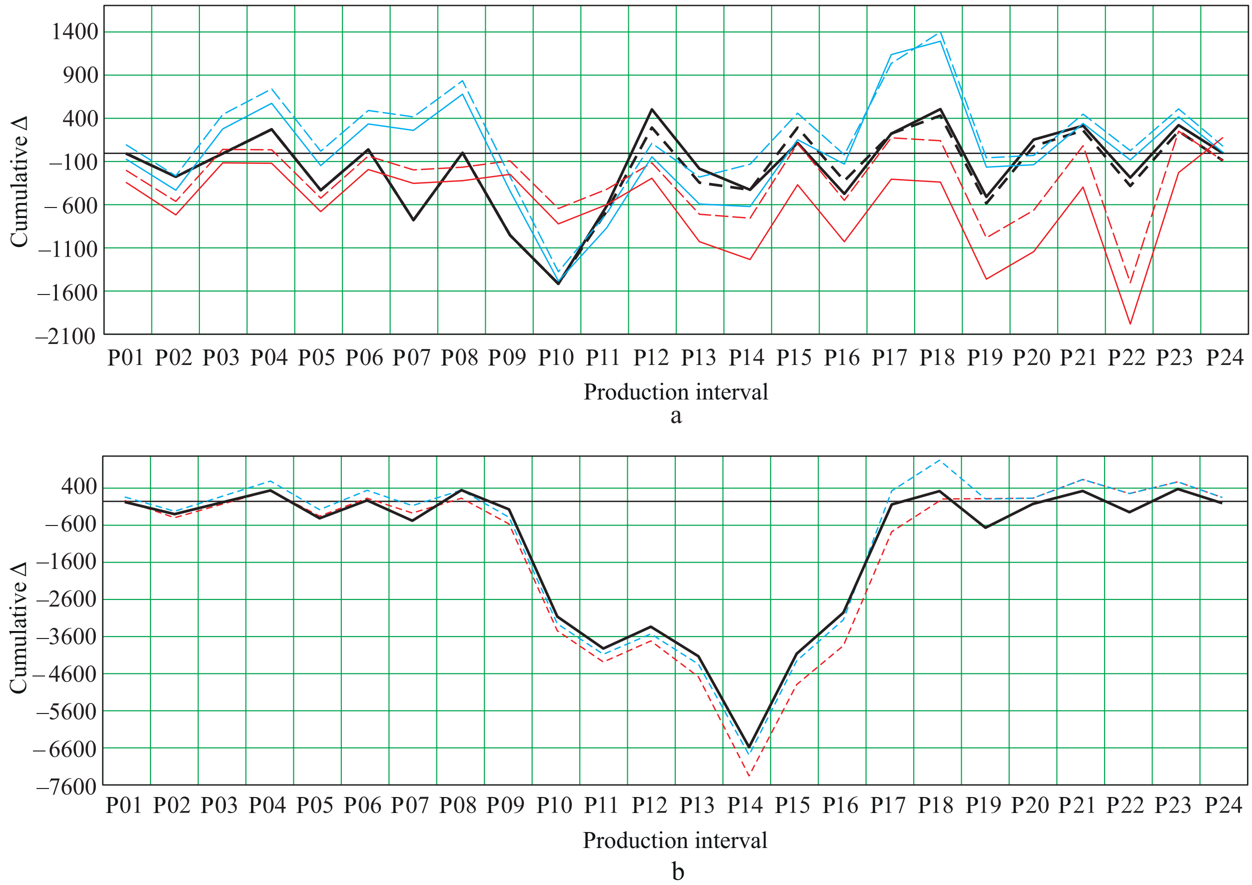

Fig. 5. Experiment results: a – cumulative ∅ of the plans plotted for fulfilment of O1; —— – only TT (MPP); —— – only TT (A1); —— – only TT (A2); ----- – TT + weekend work (MPP); ----- – TT + weekend work (A1); – – – TT + weekend work (A2); b – cumulative ∅ of the plans plotted for fulfilment of O2; ----- – MPP; ----- – A1; —— – A2

Taking into account order volumes and limitations T_{shift} and CT_{max}, it can be noted that reaching zero ∅ for each production interval is impossible. Hence, the best algorithm is selected based on the following:

- number of intervals with cumulative ∅ close to zero (cumulative ∅ = ±50);
- minimum value of cumulative ∅;
- maximum value of cumulative ∅.

Values of all criteria for the plans shown in Fig. 5 are given in the Table.

Virtually in all cases of plan plotting, as a result of A2, the minimum cumulative ∅ is achieved more often than in the case of manual plan plotting

Analysis of plotted plans

Criterion	Order 1						Order 2		
	Only TT			TT + weekend work			TT + weekend work + additional shifts		
	MPP	A1	A2	MPP	A1	A2	MPP	A1	A2
Number of intervals with cumulative ∅ = ±50	2	0	5	4	3	4	1	4	5
Minimum value of cumulative ∅	–1518	–2017	–1521	–1358	–1525	–1521	–6778	–7335	–6607
Maximum value of cumulative ∅	1347	195	528	1449	259	463	1107	566	334

and A1 (see the Table). The criteria for the minimum and maximum values of cumulative ∅ were assessed in the aggregate, and for the two cases out of three, A2 has the best combination thereof. In case of the plan for O1, plotted as per A1 using TT and weekend work, it should be pointed out that a rather long interval was obtained, which is characterized by a negative value of cumulative ∅ (see Fig. 5, a) and which indicates a long-term non-fulfilment of the order, thus, this plan cannot be selected as the best one. Taking into account the analysis of plotted plans, A2 was selected as the optimal one.

The developed algorithm for plotting a production plan is the basis for an automated production planning system implemented in the form of a website. This implementation option allows system operation only with Internet access and has no specific system requirements. It should be pointed out that the software was engineered based on the original task defined by the planners. Each element was tested and modified at all engineering stages, taking into account the specifics of the studied process. The research has shown enhanced efficiency of the production planning process due to automated system implementation, which consists in full compliance with the deadlines for collecting information for the production plan plotting by virtue of automatically sent notifications, reduction of the production plan plotting time from 30 to 1 min., elimination of errors in the production plan, and reduction of option assessment time by 80 % on average [8]. The research results were implemented at JSC "Laser Systems" instrument-making enterprise.

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Методы алгоритмизации планирования высокопроизводительного сборочного производства

Проведен анализ наиболее популярных систем планирования производства. К основному их недостатку относится отсутствие инструментов бережливого производства. Существует потребность в создании систем, ориентированных на клиента и учитывающих бережливые принципы. Описан уникальный алгоритм расчета оптимального времени такта, заложенный в основу разработанной системы планирования. Приведены методы алгоритмизации процесса планирования и результаты создания плана с использованием нескольких алгоритмов.

Ключевые слова: производственное планирование, время такта, алгоритмизация планирования, бережливое производство, высокопроизводительное предприятие.

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