Machinery & Energetics
Vol. 16, No. 2. 2025

Journal homepage:
https://technicalscience.com.ua/en

UDC 004.65:681.5
DOI: 10.31548/machinery/2.2025.20

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Hardware and software complex for operational management of a flexible site of highly efficient assembly production

Abstract. The work was devoted to the urgent issues of increasing productivity, efficiency and reducing the cost of assembly plants of multi-series productions. The goal of the work was to create an effective hardware and software complex for modelling the process of assembling objects and their components (using the example of power cells), which took into account the structure and parameters of production modules, transport and warehouse systems, allowed generation of initial plans and used Petri nets to determine scenarios for operational management of the specified production process. The distribution of autonomous transport modules by sections of the production site according to a certain structure and number was proposed. The execution time of each operation was calculated, after which a matrix of the duration of detailed operations was created. An initial schedule was drawn up and the decision rules were investigated, and a custom rule was proposed that prioritises details going to the most distant modules. The behaviour of the production system with the resulting schedule was simulated when autonomous transport modules were introduced. The created hardware and software complex, based on a script written in the Python3 language, combined the functionality necessary for the flexible production modules transport service algorithm study, the analysis of the network model for flexible automated production site functioning equipment, and organisation of flexible automated production site operational management subsystems. The obtained modelling results made it possible to adjust site's structural filling and organisation of the

Article's History: Received: 14.01.2025; Revised: 09.04.2025; Accepted: 22.05.2025.

Suggested Citation:
Smolij, V., Smolij, N., Shvydenko, M., & Voloshyn, S. (2025). Hardware and software complex for operational management of a flexible site of highly efficient assembly production. *Machinery & Energetics,* 16(2), 20-35. doi: 10.31548/machinery/2.2025.20.

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production, transport and warehouse components, eliminating overloading of modules and ensuring a reduction of the industrial cycle while maintaining the volume of work. The Petri net modelling method in the created hardware and software complex made it possible to compare several options for the operational management organisation and to obtain a living grid of a non-accumulating system in which all transitions were activated at least once, and so, obtaining a working option for the effective production process organisation

Keywords: assembly station; robotic production; flexible production modules; technological equipment; automated warehouse; automated transport module

INTRODUCTION

Manufacturing, tuning (stitching), testing, flight tests, sub-tuning of a specific sample for a specific battery to ensure compliance of electrical and tactical-technical parameters with the appropriate values is a very difficult and urgent problem. Solving this challenge ensures accurate, prompt, and effective mission execution and the achievement of the planned results. During a full-scale war in Ukraine, the need for the production of drones is undoubtedly relevant, but equally important are the organisation of flexible robotic production studies, adjusted to ensure the appropriate communication quality parameters, the finished products carrying capacity, reliability, and most importantly, establishing the production rhythm and continuity. At the beginning of the war, the production was voluntary and non-professional, which allowed to gain invaluable experience (although some time and material resources were lost), which confirmed the need of only high-quality components use, unified structural and technological solutions, ensuring quality parameters reproducibility.

According to V. Yakymets *et al.* (2022) the enemy was actively considering the main problems and areas of training highly qualified organisation and production personnel for flexible production and unmanned aircraft and aerial vehicles complexes operations, which will allow him (the enemy) to apply the accumulated knowledge and skills against Ukraine on the battlefield. It was impossible to allow this, so it was necessary to systematise, acquire and introduce new knowledge into development and production technologies for obtaining the highest quality, most effective and optimal UAV samples in terms of tactical, technical and design and technological features.

B. Sopha *et al.* (2024) investigated the problem of staff shortages in the context of the need to increase production through the use of advanced technologies, among other things, the increase in interest in advanced technologies in agriculture and processing, such as IoT, sensors, robots, unmanned aerial vehicles, digitisation and artificial intelligence, which in turn would lead to radical changes in the organisation of production technologies. Considering the subjective component, one should highlight the heuristic nature of each person's decision-making, different financial capabilities and access to commercially available components, different degrees of awareness and skills regarding technological manufacturing processes and their regulatory values, different degrees of ownership for firmware, etc.

Scientists K. Li *et al.* (2022) considered the problems of creating, piloting and organising the operation and use of unmanned systems and complexes. The practice of introducing unmanned aerial vehicles into production and operation was analysed. Problems related to the creation, experimental implementation and organisation of operation and use of unmanned systems and complexes were considered. Organisational and management measures for the sustainable development of the field of unmanned systems for 2023-2030 were proposed.

The option of manually assembling devices from the cheapest components is unacceptable, since there is an extremely low probability of successful, correct and safe performance of the task. Automated production ensured the quality and reliability of finished products while preserving the variation of the required actual nomenclature, the rhythm of production and the required number of finished products.

D. Hawashin *et al.* (2024a) proposed the application of blockchain technology in the industry of unmanned aerial vehicles. Blockchain could provide key solutions to several challenges related to security, data integrity, and operational efficiency in UAV systems. An in-depth study of the transformative role of blockchain in the field of UAVs was conducted. The potential influence and application of blockchain technology for solving problems at the stages of production, planning and operation of UAV systems had been studied.

The proposed hardware and software complex for operational management of the production site provided customisation of product parameters, in particular power elements, for use at certain distances, for work on stationary or moving objects, ensured reproducibility of tactical, technical and operational characteristics. The conjuncture of finished products, coordination of the needs of specific consumers and consideration of feedback on the results of use were taken into account (Perkumienė & Vienažindienė, 2024)

Similar problems were solved by K. Raoufi *et al.* (2024). A scheme of a flexible production cell with placement of mechanical equipment for the manufacture of mechatronic elements of innovative projects was proposed. When creating a flexible production cell in the industrial park of the university, the authors performed scientific research on the planning of technological processes. For functional modelling based on the theory of Petri net graphs, the actions of this object were investigated and a graph-scheme of functional modelling of the machine tool module was constructed. The addressing parameters in the structure for the implementation of joint management of the network of the researched technological process were defined.

Researchers K. Aghaee *et al*. (2024) developed the most acceptable production methods, covering biological technologies and topology optimisation. The preferred materials and their characteristics for ground, air, and extraterrestrial construction were discussed. In addition, relevant testing methods were presented, and construction-related challenges and limitations were elucidated.

The goal of the work was to create an effective hardware and software complex for modelling the process of assembling objects and their components (for example, power cells), which took into account the structure and parameters of production modules, transport and warehouse systems, allowed generating initial plans and usage of Petri nets to determine scenarios operational management of the specified production process.

MATERIALS AND METHODS

The creation and testing of a hardware and software UAVs components production modelling and operational management complex was an urgent and difficult task, the decomposition of this task involved systematic study of the technological process of assembly and testing of the obtained results. It was impossible to immediately cover all stages and nomenclature of production, therefore, the production of batteries for unmanned aerial vehicles was studied deeply compared to other parts of technological process. To ensure the products supply to the flexible production module and the interaction organisation with the automated system in the flexible automated section, an automated transport system was used as part of transport modules or stacker robots that had transport routes of movement. These routes were circular (closed one-way traffic), linear (bidirectional open traffic) or mixed (combination of linear and circular routes). With high loading of the flexible production module, the use of input and output drives was mandatory. The choice of the specified layout solution for the scheme of the production area allowed to divide and speed up the transport process service by replacing the first operation of transporting with the next part for processing, and then the transportation of the previous one, which was already expected for further processing already on another flexible production module.

The load estimate of a flexible production module was considered to be the ratio of the number of parts processed by the specified module to the nomenclature number of parts. If the value was no more than 0.3, then one drive was enough. There were also some restrictions imposed on the operation of storage devices and the operation of the flexible production module, which were related to ensuring the requirements for the procedure for initiating a technological operation on the equipment. In particular, the following was considered: the automatic transport module couldn't bring the next part to the flexible production module for processing while its input storage was loaded; the flexible production module couldn't start processing the loaded part from the input drive while its output drive was occupied; after completion of processing on the flexible production module, the part immediately arrived at its output storage.

For the construction of the specified hardware and software complex, a number of initial conditions were considered, in particular, that 14 parts were processed with the following nomenclature of operations performed on each of them. Groups of operations for the manufacture of parts are presented in Table 1.

Table 1. Nomenclature of parts and list of operations

№	Marking	Order of operations
1	0	T1,T2,C1,F2,F3
2	1	T5,T4,T1,C2,T3
3	2	T2,C1,C2,F1,F2,P2
4	3	T1,T2,C1,T3,C2,T4,F1
5	4	T3,T4,C2,F1,P1,T3,T5
6	5	T2,C3,F1,T3
7	6	T1,T2,C1,P2,F1,T3,T4
8	7	T4, T2, C3, C2, F1, F2, T5
9	8	T1, T4, T2, C3, T5
10	9	T1, C1, T4, T2, C1, F2, T5, F1
11	10	T4, T2, C3, F2, T5
12	11	T3, T4, T2, C3, C2, F1
13	12	T3, C1, T4, T2, C3, T5
14	13	T4, T2, C3, T1, C1, T5

Note: Ti, Ci, Fi, Pi – varieties of types of investigated operations
Source: compiled by the authors

The time components and the average speed of movement of components in a flexible automated section, which was used for the calculation of design problems, are given in Table 2.

Table 2. The main parameters of the functioning of a flexible automated precinct

Parameter	Marking	Unit of measurement	Value
The average processing time of one detail installation	t_{OB}	hour	0.3
The loading time of the flexible manufacturing module	t_Z	minute	6
The unloading time of the flexible production module	t_P	minute	6
The average length of movement of the stacker robot	l_{CP}	meter	40
The average speed of movement of the stacker robot	v_{CP}	meter / minute	30
Time for the take/put operation	$t_{VZ/POC}$	minute	0.21

Note: there is a very large range of parameter values
Source: compiled by the authors

The Figure 1 shows parts movement graph between working equipment. GBM1 and GBM2 served the largest number of product nomenclature, GBM6 served the smallest number, which was due to the specialisation of performed functions, transformations and operations and features of the blank processing process.

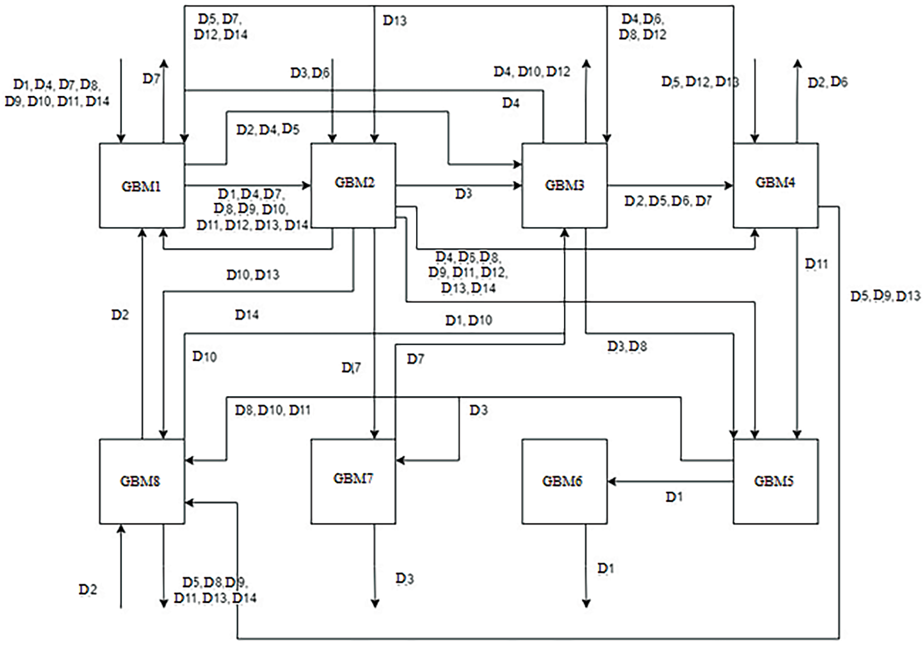

Figure 1. Graph of technological operations
Note: GBM1...8 – flexible production modules, D1...14 – details
Source: compiled by the authors

The flexible automated site included eight flexible production modules, for each of them the following module specialisation was involved: M0: {T1, T4}; M1: {T2, C1}; M2: {C2, F1, P1}; M3: {C3, T3}; M4: {F2}; M5: {F3}; M6: {P2}; M7: {T5}. Petri nets were used as a modelling method in the created hardware and software complex of the experimental production site, which allowed comparison between several options for their organisation and operational management. The proposed hardware and software modelling complex was written in the Python programming language version 3.10.4 with the usage of the following libraries: Numpy – for organising large volumes of calculations; Matplotlib – for visualisation of Gantt charts; Xlwt – for recording data about transitions in an Excel file; Pygame – for visualisation of the constructed Petri net.

RESULTS AND DISCUSSION

The creation of highly efficient assembly production was particularly acutely dependent on the assembly unit's manufacturability. The assembly itself was the main criterion that determined the quality of design developments for specific production conditions. The indisputable trend of modern production is the formation of certain flexible production systems, which includes automated departments, designed for appropriate productivity and assembly volumes. The research carried out in the work is relevant, in particular, when launching, debugging and testing such productions as battery accumulators for unmanned aerial vehicles. The specified complex included relevant technological equipment, in particular, a battery life cycle tester, battery and cell testing equipment, a battery marking machine, a battery cell sorting machine, a cylindrical battery visual inspection machine, battery spot welding machine, test equipment, integrated battery tester, battery aging machine, battery assembly equipment, battery module stacking and pressing machine, etc.(Fig. 2).

The specified production should be integrated with the production of drones of a certain type and variety, which in turn includes equipment for the manufacture of cases, large-node assembly of electronic components, corresponding varieties and types of batteries, etc. Special attention was required for the so-called "software component" in setting up the device. It was necessary to agree with the manual execution of certain technological processes, and the quality control system with rejection and to ensure the possibility of prompt replacement of the nomenclature of products depending on the available ones, replacement of components, variation of manufacturing parameters, etc.

Figure 2. Technological equipment for battery production
Note: numbers indicate the sequence of actions in accordance with route maps of technological routes
Source: stage of assembling a power element from open sources of information

The structural and technological diagram of a flexible automated station equipped with the appropriate number of production modules and operations performed on each module, is shown in Figure 2. Separately marked streams of parts that were processed by the corresponding technological module.

After calculating the load factors of each module to determine the number of drives, 11 pieces of autonomous transport modules were obtained that were needed to move production objects between the warehouse and production modules. As a result, the structural and composition scheme of the flexible automated section was taken on the form shown in Figure 3. Here was defined transport schemes (routes) of transportation of processed parts on flexible production modules and between them, and schemes of their interaction with the automated warehouse. The type of chosen transport system of the flexible automated section was a combined circular-linear type.

In the proposed structural and composition scheme of the flexible automated section, an automated warehouse with five transshipment points (overloading) was provided, which acted as a central warehouse for intermediate storage of production facilities before switching to flexible production modules or for final storage of finished products. The functions of overload points were not divided into input and output. To draw up a schedule for the technological equipment operations while solving the problem of operational planning for a flexible automated station, it was necessary to determine a technological route for each part, which included the order of its passage through the technological equipment of a flexible automated station and the processing time of each unit of equipment. To calculate the technological route, it was necessary to determine the nomenclature of parts, the sequence of the processing stages and the processing equipment. The technological route included the order of passage of parts through the technological equipment (part installations) and the time of processing the part on a unit of technological equipment. The order of passage of parts through the technological equipment was determined according to the list of operations (detail operations) that had been carried out for the production of parts, and based on the operational module's specialisation (Fig. 3). The corresponding matrix of detailed operations is given in Table 3.

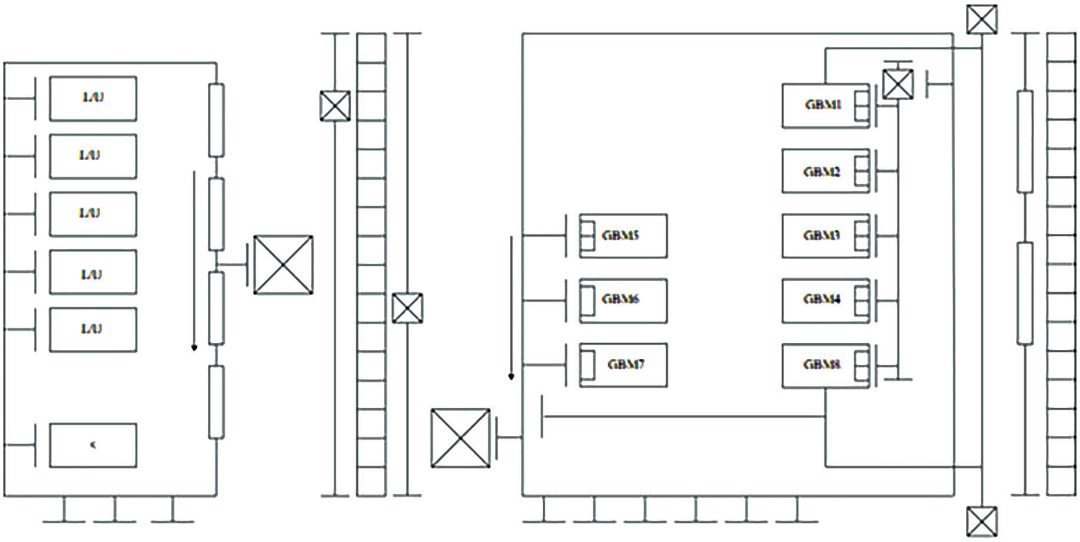

Figure 3. Structural and composition scheme of a flexible automated section
Note: L/U – loading/unloading, K - compiler, GBM1...8 – flexible production modules
Source: compiled by the authors

Table 3. Matrix of detailed operations

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
DO1	T1 M1	T5 M8	T2 M2	T1 M1	T3 M4	T2 M2	T1 M1	T4 M1	T1 M1	T1 M1	T4 M1	T3 M4	T3 M4	T4 M1
DO2	T2 M2	T4 M1	C1 M2	T2 M2	T4 M1	C3 M4	T2 M2	T2 M2	T4 M1	C1 M2	T2 M2	T4 M1	C1 M2	T2 M2
DO3	C1 M2	T1 M1	C2 M3	C1 M2	C2 M3	F1 M3	C1 M2	C3 M4	T2 M2	T4 M1	C3 M4	T2 M2	T4 M1	C3 M4
DO4	F2 M5	C2 M3	F1 M3	T3 M4	F1 M3	T3 M4	P2 M7	C2 M3	C3 M4	T2 M2	F2 M5	C3 M4	T2 M2	T1 M1
DO5	F3 M6	T3 M4	F2 M5	C2 M3	P1 M3		F1 M3	F1 M3	T5 M8	C1 M2	T5 M8	C2 M3	C3 M4	C1 M2
DO6			P2 M7	T4 M1	T3 M4		T3 M4	F2 M5		F2 M5		F1 M3	T5 M8	T5 M8
DO7				F1 M3	T5 M8		T4 M1	T5 M8		T5 M8				
DO8										F1 M3				

Note: parts passage order through technological equipment is taken into account
Source: compiled by the authors

After transforming the matrix of detail operations by combining related operations into one stage of detail processing on one flexible production module, a corresponding matrix of technological routes was obtained as an execution sequence of detail installations. The execution time of each operation depended on its complexity, which determined a part of the total duration of all operations. The complexity of the operation was established according to the order of their application in the matrix of detailed operations, based on the following: the closer the operation application was to the beginning of the technological process (sequence), the more difficult it was considered to be in terms of time spent; the preferred place (position) of the application of the operation was considered to be the place where it occurred for most part routes.

From the matrix of detailed operations, a technological process operations use matrix was obtained, with the calculation of the number of uses of operations at each of the positions where they occurred. The time for each operation was calculated based on the following formula:

$$t_i = k_i * t^{max}, \quad (1)$$

where k_i – operation complexity factor.

Value t^{max} defined as:

$$t^{max} = \frac{m_{ds} * t_{pt}}{\sum_i k_i * m_i}, \quad (2)$$

where m_{ds} – number of detail settings; t_{pt} – processing time (0.3 h); k_i – the complexity factor of the i-th operation; m_i – number of applications of the i-th operation, $\sum_i k_i * m_i$ = 6.61482683982684. In accordance: $t^{max} = 8 * 0.3/6.615 = 0.362811$ h $= 21.769$ min.

Hence, the complexity and time of the corresponding operation form the matrix of the durations of processing parts, which is given in Table 4.

Table 1. Matrix of durations of processing parts

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
DU1	8.708	15.238	34.83	8.708	17.415	21.769	8.708	19.592	28.3	8.708	19.592	17.415	17.415	19.592
DU 2	34.83	28.3	16.327	34.83	19.592	6.531	34.83	21.769	21.769	13.061	21.769	19.592	13.061	21.769
DU 3	4.354	5.442	4.354	17.415	17.415	10.885	3.265	6.531	6.531	19.592	6.531	21.769	19.592	6.531
DU 4	2.177	17.415	3.265	5.422	17.415	17.415	10.885	16.327	15.238	34.83	4.354	6.531	21.769	8.708
DU 5				19.592	15.236		17.415	4.354		4.354	15.238	16.327	6.531	13.061
DU 6				10.885			19.592	15.238		15.238			15.238	15.238
DU 7										10.885				
DU 8														
Sum	50.069	66.395	58.776	96.872	87.075	56.6	94.965	83.811	71.838	106.668	67.484	81.634	93.606	84.899

Note: duration is measured in minutes
Source: compiled by the authors

Possible movements with distances in conventional units were studied, movement time was calculated without taking into account additional operations, allowances for transportation time were calculated, based on the formulas for movement maintenance:
for transition PP – GBM:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post} + t_z, \quad (3)$$

for transition GBM – PP:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post}, \quad (4)$$

for transition AC – PP:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post}, \quad (5)$$

for transition PP- AC:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post}. \quad (6)$$

for transition AC-GBM:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post} + t_z, \quad (7)$$

for transition GBM-AC:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post}, \quad (8)$$

for transition GBM-GBM:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post} + t_z, \quad (9)$$

where t_{obsl} – service time, t_{vz} – time to take (capture) the detail, t_{tp} – moving time, t_{post} – time to place (drop) the detail, t_z – loading time, t_p – unloading time.

The planning process included jobs, which were technological operations performed on batches of parts. The main purpose of planning was to determine the order and time of passage of parts through the equipment, taking into account fixed technological processing routes. The technological route provided for the sequence of technological operations on the equipment, but did not determine the specific terms of receipt of parts. Technological routes could be both sequential and cyclical or different for all processed parts or have partial similarity.

Nomenclature list of products produced on m groups of equipment $(k = 1, \overline{\overline{m}})$, consisted of n names of details $(j = 1, \overline{\overline{n}})$. The production of a batch of parts of each denomination was determined in advance by the sequence of passage of parts through groups of equipment, which was called a technological route:

$$G\overline{j} = (Lij | i = 1, M\overline{\overline{j}}), \quad (10)$$

where Lij – technological operation, which is performed i-th in the order of production of the j-th part; Mj – number of operations performed on the j-th part. Technological operations were on the route $Lij = (Qij, Tij)$ had the following characteristics: $Qij = k$ – the number of the equipment group configured to perform the operation Lij; Tij – regulatory duration of the operation Lij.

It was necessary to make a schedule $P = (Tij\Pi | i = 1, Mj, j = 1, n)$, which determined the start of operations Lij (starting moments of a batch of parts on equipment units) and satisfied the system of constraints: the condition of execution of the technological sequence $Tij\Pi \geqslant Ti - 1, jK$; under the conditions of execution of technological routes Gj; provided operations were performed without interruptions $TijK = Tij\Pi + Tij$; provided that only one operation per unit of equipment was performed at each moment of time $\forall Li1j1, Li2j2 : (Qi1j1 = Qi2j2) \rightarrow (Ti1j1K \leqslant Ti2j2\Pi) \cup (Ti2j2K \leqslant Ti1j1\Pi)$, where $TijK$ – operation completion moment Lij.

In operational and dispatch management, important indicators of the quality of implementation of the formed schedule were the reliability of execution under external influences. These metrics included factors such as equipment downtime, waiting time for parts to be processed, and local time reserves.

For decision rules in simulation modelling algorithms, different preference rules were used. Obviously, there was a possibility of situations where the use of only one rule did not provide an unambiguous sequence of starting parts. To achieve unambiguity, an additional rule was used that allowed to choose one alternative from the set of options that were selected according to the first rule. One of the possible additional rules was determining the order by part number. For example, if the part number was the smallest, then it was processed first, which ensured an unambiguous start sequence. The following rules were chosen to schedule the technological equipment work: maximising residual labour intensity, prioritising spare parts that travelled the furthest distance from the automated warehouse (a rule proposed by the authors), and the longest-operation rule. Having determined the order of passage of modules for the manufacture of each part, the corresponding time matrix of the duration of detail operations was formed (Table 5).

Table 5. Matrix of durations of processing parts

	Manufacture path of every detail	Detail operations duration matrices
D0	[0, 1, 4, 5]	[8.708, 34.83, 4.354, 2.177]
D1	[7, 0, 2, 3]	[15.238, 28.299999999999997, 5.442, 17.415]
D2	[1, 2, 4, 6]	[34.83, 16.326999999999998, 4.354, 3.265]
D3	[0, 1, 3, 2, 0, 2]	[8.708, 34.83, 17.415, 5.442, 19.592, 10.885]
D4	[3, 0, 2, 3, 7]	[17.415, 19.592, 17.415, 17.415, 15.238]
D5	[1, 3, 2, 3]	[21.769, 6.531, 10.885, 17.415]
D6	[0, 1, 6, 2, 3, 0]	[8.708, 34.83, 3.265, 10.885, 17.415, 19.592]
D7	[0, 1, 3, 2, 4, 7]	[19.592, 21.769, 6.531, 16.326999999999998, 4.354, 15.238]
D8	[0, 1, 3, 7]	[28.299999999999997, 21.769, 6.531, 15.238]
D9	[0, 1, 0, 1, 4, 7, 2]	[8.708, 13.061, 19.592, 34.83, 4.354, 15.238, 10.885]
D10	[0, 1, 3, 4, 7]	[19.592, 21.769, 6.531, 4.354, 15.238]
D11	[3, 0, 1, 3, 2]	[17.415, 19.592, 21.769, 6.531, 16.326999999999998]
D12	[3, 1, 0, 1, 3, 7]	[17.415, 13.061, 19.592, 21.769, 6.531, 15.238]
D13	[0, 1, 3, 0, 1, 7]	[19.592, 21.769, 6.531, 8.708, 13.061, 15.238]

Note: duration is measured in minutes
Source: compiled by the authors

As it was mentioned above, the main rule of preference was the rule of maximum residual labour intensity, since the average production time of each part was 78.602 min. Below this value, 6 details and for 8 – above. Accordingly, the rule of maximum residual labour intensity was considered as the one to reduce the production time of a larger number of parts.

The use of an auxiliary rule reduced the load on the first modules, since a higher priority during processing gave to parts whose next operation was performed on a machine with a higher serial number.

Also, in order to solve all possible conflicts that could arise when applying these rules, it was advisable to use the LPT priority rule, as this would help to advance the parts to the most distant machines, since there were mainly short-time operations. Simulation results were given for a combined rule with a sequence of application MWKR – FPD – LPT. The class diagram is shown in Figure 4.

File main.py consists of 4 main components:

1. Class task_manager that constructed an initial ideal schedule based on given rules with prioritisation according to the submission sequence. The resulting sequence of detail processing was transferred to the time_table_extender class using the form_periods() method. The class constructor accepted the following arguments: a matrix of transitions through part modules, a matrix of part processing time at each stage, the number of parts for processing, the number of processing modules, all possible priority rules were implemented.

2. Class time_table_extender that performed schedule extension and data generation for the Petri Net construction phase. The class constructor accepted the following arguments in the appropriate sequence: the matrix of transitions through modules of parts, the matrix of the cost of transitions between modules, the matrix of the time of processing parts at each of the stages, the sequence of processing parts for each flexible production module, the number in which the automated warehouse stands in the matrix of movements (starting with 0), the number in which there was an overload point in the movement matrix (if there wasn't, it was necessary to provide the total number of fWlexible production modules + 1), an array characterising the number of modules in each part of the flexible automated site, an array characterising storage units (input storage capacity, output storage capacity, or the total capacity if the drive works in both input and output mode).

3. The field of entering input data included: Ops – a list of operations that can be performed, Input_array – encrypted with elements from the previous array of the technological process of processing parts, timings – the duration of each operation, modules – a description of the modules with the operations they perform, moves_price – a matrix characterising the cost movements in the system of a flexible automated precinct (0 means there was no movement). Customising the script to work with each individual system was done by changing the values of these data arrays.

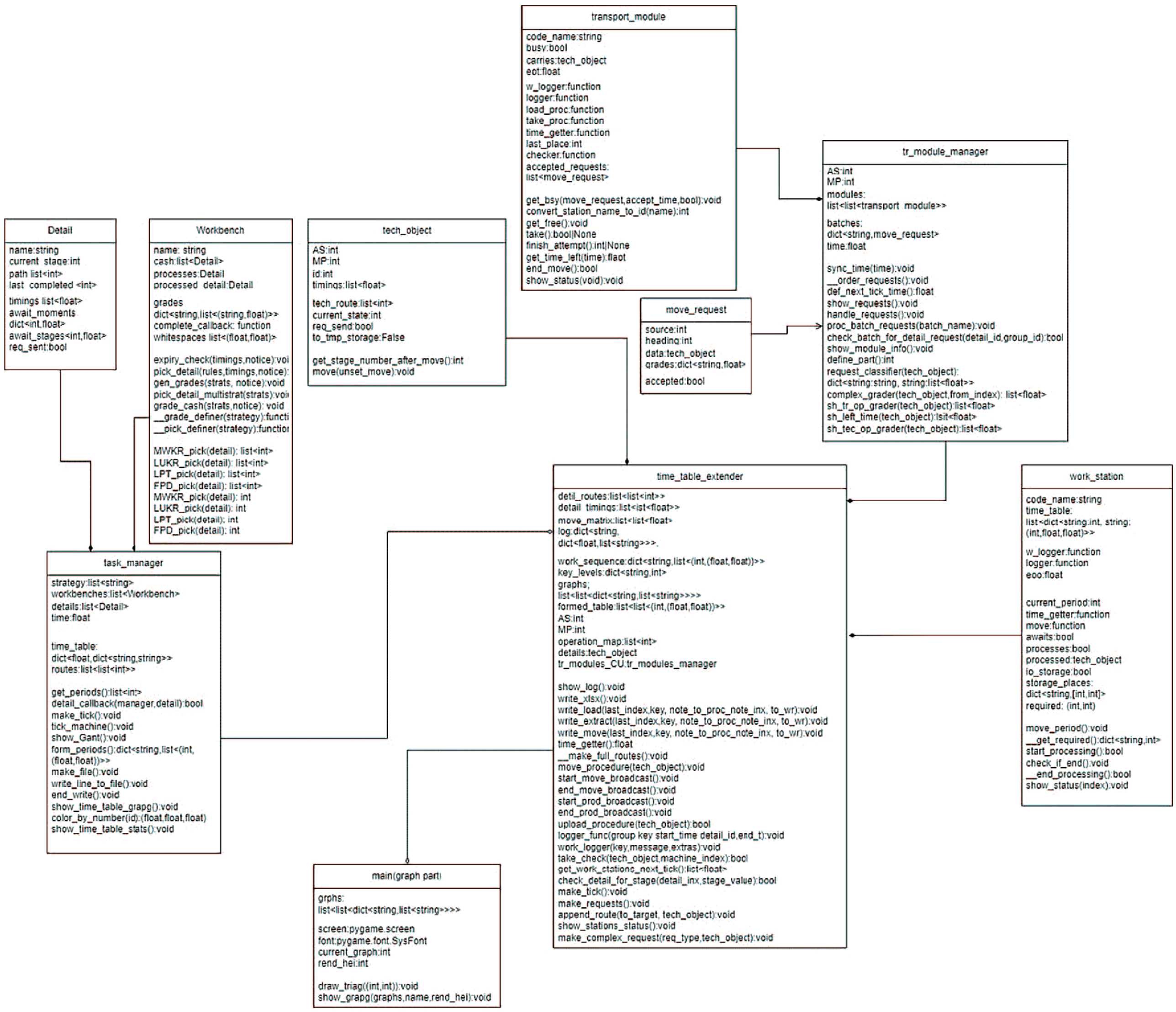

Figure 4. Class diagram

Note: all components of the automated production process are presented

Source: compiled by the authors

4. Petri net visualisation was implemented with pygame tools, when the nets were built for each module separately. The module displayed was selected by keys 1 and 2, the scheme was scrolled by the up and down arrow keys.

The created hardware and software complex sequentially outputted a Gantt chart for the primary schedule, then a similar chart for the extended schedule. After analysing and closing the contents of these windows, a window appeared with the results of modelling the specified production process using Petri nets. Also, in the process of generating the schedule, logs appeared in the console for each important moment in time (screening), in which it was possible see the description of the system in this time period, active requests and their evaluations according to various criteria. After the extended schedule was generated, the petry.xls file containing descriptions of transitions in the Petri net appeared in the file folder. The simulation results are shown in Figure 5. The analysis of the structural and compositional scheme showed that the application of a ring unidirectional transport service scheme of all flexible production modules and an automated warehouse with the help of two automated transport modules was the most rational and effective. This proved a concept that if there was an application from flexible production modules or an automated warehouse, it must be served by the nearest free transport module. This principle appeared to be the most optimal, because the least possible time would be spent on transportation at the moment. The result of the dispatch control algorithm based on the transport service strategy was an extended Gantt chart (Fig. 6), in which all units of technological and transport equipment were reproduced, all processing and maintenance operations were coordinated.

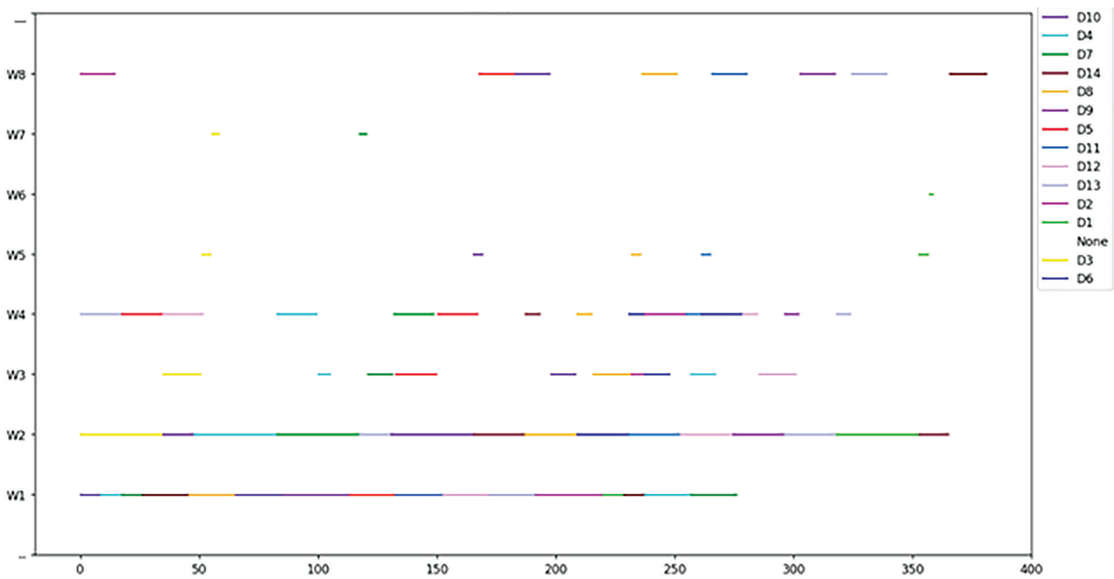

Figure 5. Simulation results
Note: corresponding colors indicate the Gantt Charts for the corresponding details
Source: compiled by the authors

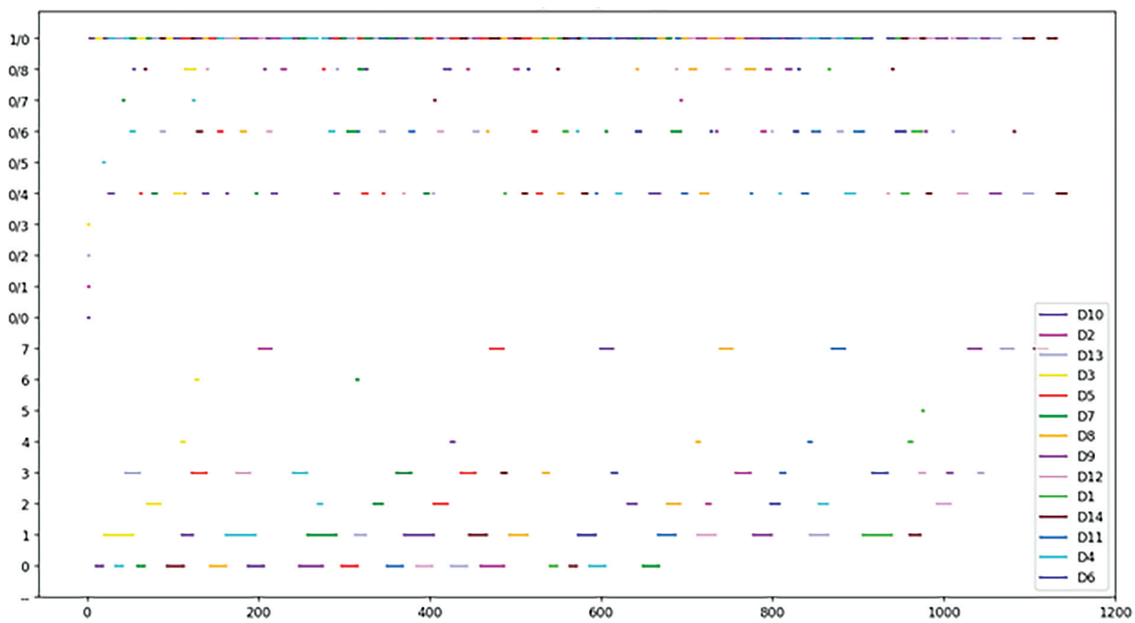

Figure 6. Extended schedule of operation of technological equipment (system simulation results based on input data)
Note: in the diagram, the machine tools have a name with a single number starting with 0
Source: compiled by the authors

As a result of the simulation, a certain sequence of processing parts was obtained that satisfied the conditions of the assembly technological process. An effective tool for analysing the state of loading of automated production components was obtained. In particular, in Figure 5 shows an extended schedule of the technological equipment, the obtained sequence of processing parts by autonomous transport modules such as:

0/0:[9]

0/1:[1]

0/2:[12]

0/3:[2]

0/4:[3]

0/5:[9, 6, 13, 7, 12, 4, 2, 9, 2, 2, 8, 11, 11, 6, 7, 11, 11, 5, 7, 5, 4, 4, 1, 7, 3, 9, 9, 13, 1, 5, 10, 8] ...

The sequence of processing parts by flexible production modules looks like this:

0:[9, 3, 6, 13, 7, 9, 8, 4, 10, 11, 12, 1, 0, 13, 3, 6]

1:[2, 9, 3, 6, 12, 9, 13, 7, 5, 10, 11, 8, 12, 0, 13]

2:[2, 3, 6, 4, 9, 7, 1, 5, 3, 11]

3:[12, 4, 11, 3, 6, 4, 13, 7, 5, 1, 10, 5, 11, 8, 12]
4:[2, 9, 7, 10, 0]
5:[0]
6:[2, 6]
7:[1, 4, 9, 7, 10, 8, 12, 13]

According to the simulation results, the total order processing time increased from 380,954 min to 1143.228 min. Since the modelling process considered modules that have an input drive, a work area, and an output drive of variable capacity, the production processes were described as follows. For each part there were following positions:

D{№}_{stage}_A – detail in the automated warehouse before the stage.

D{№}_{stage}_P – in the overload device to the stage (if there were 4 stages in the processing of the part, such as in part 0, then after the completion of 4 stages, the 5th stage of transfer to GBM).

For each stage of detail processing:

D{№}_{stage}_I – in the input drive for stage processing stage.

D{№}_{stage}_W – undergoing stage processing stage.

D{№}_{stage}_O – in the source drive is ready for further processing at the stage.

The following positions were introduced for flexible production modules:

P{№}_{iteration} – module needs details from an iteration of its workflow №iteration.

There was a number of positions for iterating through the stages of ATM operation:

A{№}_{iteration} – module needs details from an iteration of its workflow №iteration.

Also, for convenience, the position T0_F was entered, that marked the presence of the part in the overload point. Next, the transitions for each process were described in detail, in particular, the process of loading into the workspace from the input drive had the form given in Table 6.

Table 6. Formalisation of the process of loading into the workspace from the input drive

Position	Description	Entry/Exit	Inhibitor
D{№}_{stage}_I	Detail in the input drive	Entry	
P{№}_{iteration}	The flexible production module is in a stage that allows you to accept this part	Entry	
D{№}_{stage}_W	Detail in the workspace of the flexible production module	Exit	
D{№}_{stage}_W	The part from the previous iteration is in processing state		Inhibitor

Note: proposed notation of equipment states for working automata: Entry, Exit, Inhibitor
Source: compiled by the authors

The formalisations specified in Table 6 were carried out for the processes of loading into the output storage from the work area, for transportation from the automated warehouse, from the transshipment point, from flexible production modules, input positions for transportation from flexible production modules to the automated warehouse, to the transshipment point, to flexible production modules.

Each of the elements of the experimental structure of the manufacturing process was simulated by the developed hardware and software complex. In particular, the Petri net for flexible production module 0 has the form shown in Figure 7.

Initial markings (listed positions in which markers were present) followed next naming rules:

- all parts are in an automated warehouse: D0_A, D0_A, D1_A, D2_A, D3_A, D4_A, D5_A, D6_A, D7_A, D8_A, D9_A, D10_A, D11_A, D12_A, D13_A;
- all flexible manufacturing modules on the 1st iteration of the work cycle: P0_1, P1_1, P2_1, P3_1, P4_1, P5_1, P6_1, P7_1;
- all automated transport modules are on the 1st iteration of the work cycle: A0/0_0, A0/1_0, A0/2_0, A0/3_0, A0/4_0, A0/5_0, A0/6_0, A0/7_0, A0/8_0, A1/0_0.

An oriented view of the corresponding set of transitions for the modeled system is given in Table 7.

Table 7. Multiple transitions

Module	Transition	Position	Description of the performance condition	Condition type	Note
				Entry/Exit	Inhibitor
GBM 0	T0|9|1P	D9_1_I	Detail 9 in the input storage of GBM 0 before stage 1	Entry	
		P0_1	GBM 0 waiting for detail 9 before stage 1	Entry	
		D9_1_W	Detail 9 in the work area undergoes processing at the stage 1	exit	
		D6_6_W	Detail 6 GBM before step 6 in the input drive 0		Inhibitor
...	...	...	...	...	...

Note: simulation results of the specified type were obtained using the proposed hardware and software complex for all production components
Source: compiled by the authors

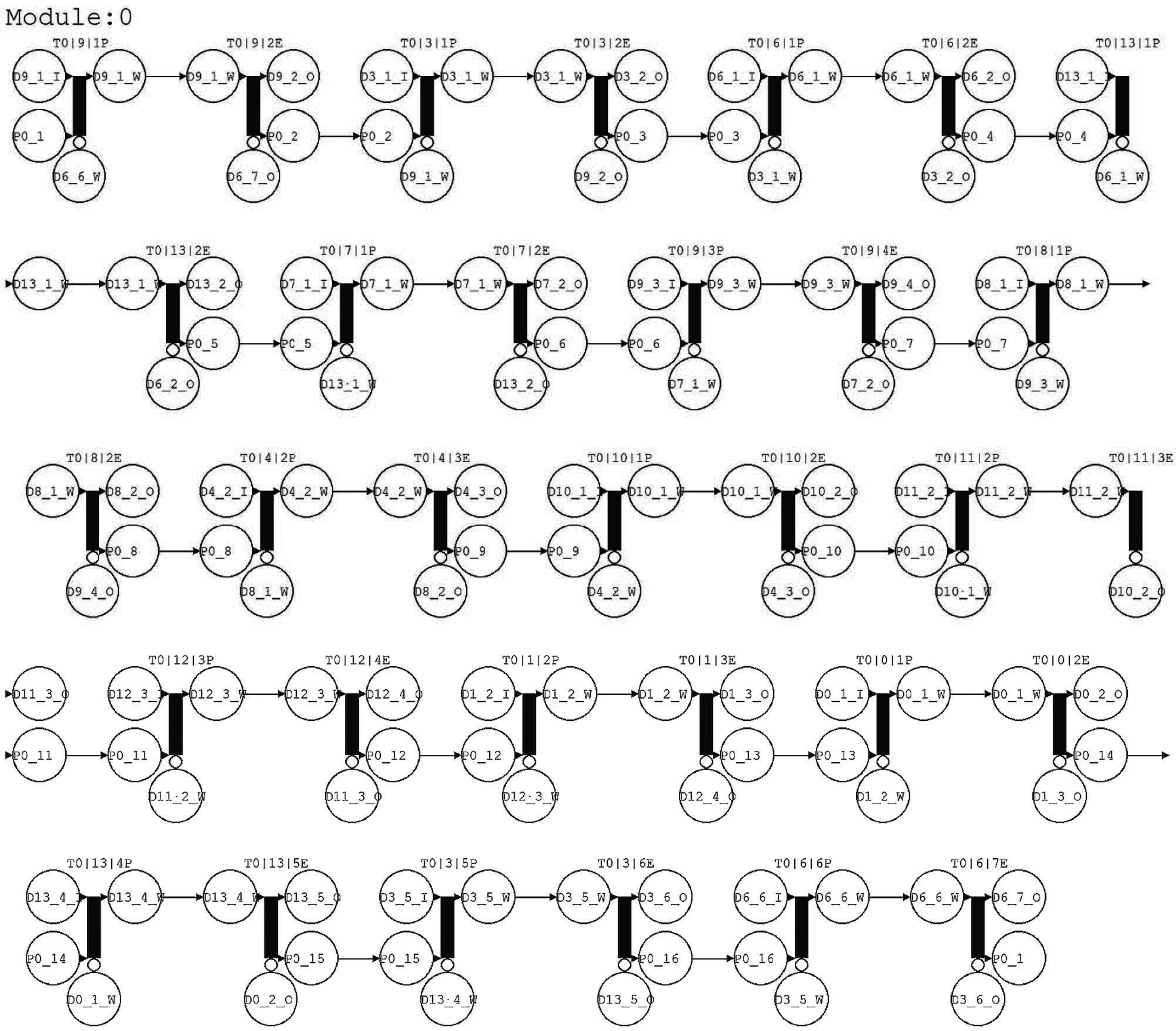

Figure 7. Multiple transitions
Note: D – details, T – time, P – stage in the operation of the equipment
Source: compiled by the authors

There were no loops in the work of this model, all transitions worked. Flexible production modules and automated transport modules, after completing the assigned tasks, were again in a state of readiness to work with the first parts according to their schedule, but the Petri net was not alive because the part after processing at the last stage was into the state of the finished part.

The obtained grid was limited because there were no accumulative markings, thanks to which the finiteness of the processes was ensured. N. Feng *et al.* (2024) demonstrated the effectiveness and usability of the proposed software design approach for the analysis and debugging of 233 N-NFRs related to 62 software-related problems in robotic systems, including robot aids and drones used in the production of robots and their subsystems. R. Ghimire *et al.* (2024) proposed a new approach for using machine learning in the design, development, and testing of multifunctional composites for aircraft, unmanned aerial systems, and spacecraft. The architecture of an artificial neural network was proposed in this work. The approach integrates the complete life cycle of devices. The proposed method uses the power of ANNs on metadata to characterise multifunctional properties of materials and processes, as well as display failure modes against predicted models and history.

The work of A. Koganti *et al.* (2024) was devoted to the improvement of electronic devices. By analogy with this work, in the research carried out by the authors, the emphasis was on creating a simulation model for the manufacture of drone components in software, where the performance of each technological module was determined and the continuity of the entire production was ensured. The issue of layout of technological areas was systematically solved for the reproducibility of technological parameters and ensuring the efficiency of drone production.

P. Raj *et al*. (2024) analysed digitisation and digitisation technologies. All industrial artifacts were digitised, connected, and able to be cognitive in their operations, offerings, and products. Through smart use of an amazing array of digital technologies and tools, interaction and collaboration with human experts. Such cognitive industrial machines, equipment, devices, assembly lines, robots, vehicles, drones and other assets together provide an intelligent environment for the development and implementation of cutting-edge industry 4.0 and 5.0 applications. Every industrial process was optimised and automated to produce next-generation products to satisfy consumers, explore new ways to increase revenue and improve productivity. In addition, there were chapters that illustrate industrial use cases, infrastructure optimisation, technology adoption, and AI-powered data analytics for industrial automation. The specified approaches and trends were generalised and adapted to solve the specific task of building a hardware and software complex for operational management of an operational production site. The technologies of using artificial intelligence have not yet been considered due to the limited time requirements for solving the given task, which may be eliminated in future research.

E. Karadag *et al*. (2024) the design process was studied with load options at each point of the motor, so that the result of the drone has an optimal design, light and strong. Combined with 3D printing, complex geometries can be created and material waste can be reduced. Variants of the design of the device with minimal production costs were analysed, which was aimed at effective use of materials and ensuring the best tactical and technical indicators for unit production. The problem of optimisation of large-scale multi-item production was only mentioned in the future.

B. Zhou *et al*. (2024) analysed the production of aviation equipment (e.g., ballistic missiles, missiles, unmanned aerial vehicles (UAVs) and aircraft) and concluded that traditional assembly quality inspection methods mainly rely on manual control of laser trackers with one or more stations, but they were unable to measure and evaluate complex components of aviation equipment. This document presents a method of automatic detection and assessment of assembly accuracy, where at each measuring station the robot controls the movement of the scanning arm; after the completion of all measurement processes, data from several measuring stations were integrated into one coordinate system for calculation and analysis of assembly quality.

J. Ren & Q. Quan (2024) solved the problem of managing the docking station during the refuelling stage, which requires a high level of safety, accuracy and efficiency. As a result, the modelling and control problems that arise in the refuelling phase were typical and complex. First, the article presents the fundamental idea of management, after which the characteristics and requirements for management were outlined. Advances in modelling and control techniques were then systematically reviewed.

By the authors D. Hawashin *et al*. (2024b) proposed a blockchain and non-fungible token (NFT) based solution that manages, certifies and tracks the origin, history and ownership of UAVs and their production components. The solution provides decentralisation, transparency, visibility and reliability. Complex NFTs were used that collect and store UAV data in a hierarchical structure where parent NFTs represent collected UAV data and child NFTs represent individual parts of the UAV. This approach ensures traceability in the system and facilitates the smooth exchange of ownership rights.

Q. Wang (2024) described the surge in attempts to build homemade UAVs and the challenges in implementing control systems that can effectively control multidimensional UAV operations, especially in the context of proportional-integral-derivative (PID) control. Investigated the choice of PID control configuration to achieve optimal UAV performance. Summarised the most acceptable management model. Using tools such as MATLAB, the various roles and effects of each parameter in the field of PID control were explored, thus providing valuable perspectives for hobbyists and professionals involved in the field of UAV design and control mechanisms.

G.P. Badea *et al*. (2024) created an innovative unmanned aerial vehicle designed for a specific mission. The main objective of this research was to develop an innovative hybrid UAV concept with key features including a fixed-wing design and integrated vertical take-off and landing capability in an experimental model. This document details the entire drone manufacturing and assembly process, covering both the structural framework and associated electrical installations.

M. Battaglia *et al*. (2024) proposed innovative approach to design and manufacture the UAV tail using additive manufacturing completely changes the concept of designing and manufacturing products using traditional methods. AM-based processes can reduce costs, lead times, and increase design freedom by allowing parts to be tailored to specific needs. A key advantage of AM processes was the ability to create optimised structures with reduced mass and without compromising structural efficiency. This was made possible by the combination of high-performance AM materials and the extraordinary manufacturing capabilities of AM technologies, combined with an appropriate design approach for additive manufacturing that overcomes traditional manufacturing techniques.

In the works V. Smolij *et al*. (2023) the general issues of management of complex technological objects with the provision of optimal parameters of the course of technological processes were investigated, and in works V. Smolij *et al*. (2024) directly robotic links of production sites were investigated, software tools for modelling components and processes were tested, connections between the parameters of finished products and the organisation of the production process were analysed in detail.

In current research a distribution of autonomous transport modules across sections of the production site according to a specific structure and quantity was proposed with an example for the technological assembly process (using the example of battery production for unmanned aerial vehicles). As a result of the processing data for technological processes through math computations and variety of simulations, the execution time for each operation was determined, which allowed for the creation of a matrix of the duration of individual operations. Based on this data, an initial schedule was drawn up, where decision-making rules were investigated, including a custom rule prioritising parts destined for the most distant modules.

CONCLUSIONS

For the technological assembly process (using the example of battery production for unmanned aerial vehicles), a distribution of autonomous transport modules across sections of the production site according to a specific structure and quantity was proposed. The execution time for each operation was calculated, after which a matrix of the duration of detailed operations was created. An initial schedule was drawn up, and decision rules were investigated, including a custom rule prioritising parts destined for the most distant modules. The behaviour of the production system with the resulting schedule was simulated considering the introduction of autonomous transport modules. The created hardware and software complex, based on a Python3 script, combined the necessary functionality for studying the transport service algorithm of flexible production modules, analysing functioning of the flexible automated production site equipment network model, and operational management of the entire site. The modelling results allowed for adjustments in the structural composition and organisation of the production, transport, and warehouse components, eliminating module overloading and reducing the industrial cycle time while maintaining the workload. Modelling in the created hardware and software complex of the experimental production area using the Petri net method allowed comparison of several operational management approaches, resulting in a live net of a non-accumulating system where all transitions were activated at least once, thus providing an effective option for organising the production process.

Prospects for further research includes tests for the created hardware and software complex to achieve the management organisation effectiveness and ensure the operational management effectiveness for production and assembly areas for other products and models of unmanned aerial vehicles and comparing the obtained results of modelling and organisation of discovery processes with the results of modelling obtained using blockchain and artificial intelligence technologies.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Апаратно-програмний комплекс оперативного управління гнучкою дільницею високоефективного складального виробництва

Анотація. Робота присвячена актуальним питанням підвищення продуктивності, ефективності та зниження собівартості складальних дільниць багатосерійних виробництв. Мета роботи полягала в створенні ефективного апаратно-програмного комплексу моделювання процесу складання об’єктів та їх компонентів (на прикладі елементів живлення), що враховувала структуру і параметри виробничих модулів, транспортної та складської системи, дозволяла генерувати початкові плани та задіяти сітки Петрі для визначення сценаріїв оперативного управління перебігом зазначеного процесу виробництва. Запропоновано розподілення автономних транспортних модулів по розділах виробничої дільниці за певною структурою і кількістю. Було обраховано час виконання кожної операції після чого створено матрицю тривалості деталеоперацій. Складено первинний розклад та досліджені вирішальні правила, запропоновано власне правило, яке ставить в пріоритет деталі, що прямують до найбільш віддалених модулів. Симульовано поведінку системи виробництва з отриманим розкладом при введені автономних транспортних модулів. Створений апаратно-програмний комплекс базувався на скрипті, написаному мовою Python3, поєднував в собі функціонал, необхідний для дослідження алгоритму транспортного обслуговування гнучких виробничих модулів, аналізу сіткової моделі функціонування устаткування гнучкої автоматизованої дільниці виробництва, організації функціонування підсистем оперативного управління всією гнучкою автоматизованою дільницею виробництва. Отримані результати моделювання дозволили скорегувати структурне наповнення і організацію виробничих, транспортних і складських компонент дільниці, усунувши перевантаження модулів і забезпечивши зменшення промислового циклу при збереженні об’єму робіт. Моделювання в створеному апаратно-програмному комплексі дослідної ділянки виробництва методом сіток Петрі дозволило порівняти декілька варіантів організації оперативного управління і отримати живу сітку не накопичуючої системи в якій спрацьовують всі переходи хоч раз, тобто отримати працюючий варіант ефективної організації виробничого процесу

Ключові слова: складальна станція; роботизоване виробництво; гнучкі виробничі модулі; технологічне обладнання; автоматизований склад; автоматизований транспортний модуль