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Implementation of Simulation Modeling of Single and High-Volume Machine-Building Productions

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Abstract: The authors of this article analyze the existing methods and models of technological preparation of machine-building industries. The structure of a three-level simulation model with network-centric control, the structures of individual elements of the simulation model, and the process of simulation modeling are described. The criteria for choosing a rational option for the processing technological route have been determined. During this research, a simulation program was implemented in C++. It allows you to select the optimal scenario for the operation of a production site based on two criteria: time and cost. The volume of implementation is about 2×10^3 lines of code. A diagram of the modeling algorithm for the implemented program and a description of the classes and their interactions are given in the article. The developed simulation model was tested at a machine-building enterprise using the example of the "Pusher" part, manufactured under single-unit production conditions. The technological equipment used for the manufacture of this part was formed in the form of input data of the simulation model. The results of simulation modeling for the selected part are described. For each variant of the technological processing route, the values of variable costs and the duration of the production cycle were determined.

Keywords: technological preparation of production; automation of production processes; small-scale production; single production; machine-building enterprises

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Citation: Savelyeva, N.; Nikonova, T.; Zhetessova, G.; Irina, K.; Yurchenko, V.; Černašėjus, O.; Zharkevich, O.; Dandybaev, E.; Berg, A.; Vassenkin, S.; et al. Implementation of Simulation Modeling of Single and High-Volume Machine-Building Productions. *Designs* **2024**, *8*, 24. https://doi.org/10.3390/designs8020024

Academic Editor: Min-Hwi Kim

Received: 15 November 2023
Revised: 28 February 2024
Accepted: 29 February 2024
Published: 8 March 2024

1. Introduction

The prevailing trend in modern production organization involves shifting towards sophisticated digital, intelligent production technologies, and robotic systems. Embedded within this trend is the defining direction for the future of material goods and service production, which revolves around employing production networks featuring network-centric control [1]. Examples of modern production sites are complexes of multifunctional computer numerical control (CNC) machines, 3D printers, and robots, which are integrated into a network to create conditions for effective planning and optimal implementation of parallel technological processes [2–5].

One characteristic of technological processes is their ability to adapt to small-scale or custom production in various fields such as mechanical engineering, raw material processing, assembly of multi-component products, and so forth [6,7].

Technological preparation of production (hereinafter referred to as TPP) is one of the most important stages of the process for the production of parts. The Chamber of

Commerce and Industry provides options for solving problems in many areas: for instance, guaranteeing the feasibility of product design; planning technological processes and crafting technological documentation; designing and producing technological equipment; and the organization and management of the process of technological preparation of production [8]. Typically, production automation and manufacturing processes involve standardizing design elements and technological procedures [9], although in situations of individual or small-scale production, this strategy might not be efficient due to the significant preparatory expenses [10].

The objective of this endeavor is to construct a simulation model aimed at diminishing the duration and labor intensity involved in the technological preparation of individual and small-scale production, thereby enhancing the efficiency of production processes.

To build a new simulation model, it is necessary to use an analysis of various technological processing routes and the corresponding technological machinery used. One of the most effective methods for assessing the many options for technological processes and selecting the most suitable one is simulation modeling of production processes and multi-criteria analysis based on a selected set of criteria [11,12]. When speaking about the technological preparation of production, the authors will further refer to its model.

One of the factors for increasing the efficiency of an enterprise and its competitiveness is the automation of production processes [13]. Production processes also include technological preparation of production, the automation of which through digitalization ensures not only a reduction in production preparation time, but also optimizes the overall costs of manufacturing products. In addition, such automation ensures and allows you to adapt the technological process to changes in external conditions and quickly recalculate the technological process [14].

The main approaches of modern TPP models include the theory of computational complexity, analysis of design and technological elements, analysis of the similarity of design solutions, and a scheduling system.

Complexity theory, as the basis of TPP, allows one to calculate the complexity of a system based on the complexity of the elements included in the system [14–18]. The complexity of the system (S) can be represented as the sum of the products of the complexity of an element of a certain type (S_i) and the number of such typical elements (k_i):

$$S = \sum_{i=1}^{n} S_i \cdot k_i \quad (1)$$

Along with the complexity of individual elements of the system, an assessment is made of the complexity of the relationships between them and the load on the system with connections.

This theory was used as the basis for a number of techniques aimed at increasing the efficiency of the TPP. These methods allow for, based on the analysis of time indicators, the duration of the production cycle and the frequency of inter-operational pauses, while facilitating the design of numerous technological processing routes for a product batch do not enable the estimation of production costs for manufacturing the batch [19].

The theory, based on the analysis of design and technological elements (hereinafter referred to as DTE), makes it possible to increase the efficiency of TPP through various strategies and selection of equipment [20–22]. If we imagine the final product as a set of DTEs, i.e., an elementary surface or a set of elementary surfaces that have a common design purpose and are characterized by a common manufacturing route, then the DTE can be described by characteristic parameters. These include the diameter of the DTE, the ratio of the length of the DTE to the total axial length of the part, the location of the material for cylindrical surfaces (inside/outside), the shape of the generatrix for surfaces obtained by rotating the generatrix around the axis of rotation of the part or other features of the shape of the DTE, and the location of the DTE in detail. Assessing the degree of compliance of a cutting tool with a number of criteria allows one to set an algorithm for selecting the optimal set of tools [23].

Different strategies for using a selected set of tools allow you to construct a set of possible outcomes, that is, the order in which these tools are used. Strategies take into account machine processing time and tool change time, its cost, and other costs (for example, the cost of processing an elementary surface).

Using a mathematical apparatus, a multi-criteria optimization problem was formulated, setting the significance of the criteria described above by weighting coefficients (a_i) [24]:

$$J(x) = \sum_{i=1}^{m} a_i \cdot f_i(x); a > 0,\ \sum_{i=1}^{m} a_i = 1, \tag{2}$$

where $f_i(x)$—one of the criteria for the processing strategies under consideration.

This technique makes it possible to construct instrumental strategies for processing DTEs and determine the parameters of the tools used in them. However, this technique does not take into account an important parameter—the accuracy of DTE processing.

The methodology for analyzing the similarity of design solutions during the technological preparation of production is based on the formalization and comparison of design and technological solutions [25–27]. The basic concept of this technique includes a technological complex (hereinafter referred to as the T-complex), which is a set of various standard surfaces for which there is a trajectory in which these surfaces can be processed together. Such complexes correspond to certain technological methods, used separately or in combination, depending on the expected production conditions and workmanship. T-complexes are characterized by types of incoming surfaces; indicators of production and operational quality; and external attributes of the connection of this complex with the others. These connections can be represented in the form of a model—a graph, the nodes of which are the identifiers of the selected T-complexes, and the edges are the corresponding connections between them. The connection graph makes it possible to estimate constructive similarity in two ways, including by the composition of T-complex models and the structure of connections of T-complexes [28,29]:

$$S = \frac{2m}{b+c} \tag{3}$$

where S—the value of the selected assessment of the design similarity of the part models.

Depending on the selected method, different values are associated with the parameters.

The disadvantages of this approach include incomplete consideration of the design of the part and its technical parameters and the inability to evaluate many alternative pathways for technological processing. As a result, the length of time for completing the production cycle and the amount of production costs are not determined accurately.

The TPP scheduling system is based on the calculation of time intervals between already planned operations for a given set of parts planned for production in the time period under consideration [30–32]. In the process of scheduling, the complexity of performing each operation on specific equipment is assessed: processing time for individual technological operations, as well as the total processing time for a given technological route, and equipment downtime during the processing of technological routes. Thus, based on the results of successfully implemented technological routes, it is possible to determine the most suitable equipment that has the best performance for still unprocessed routes. The criterion of minimizing service time is a solution to the problem of optimizing the production process [33]:

$$k_{1(i)} = \min\left(\sum_{I \in I_S} W_{ij}\right) \tag{4}$$

where W_{ij}—time interval between the end of the ($j-1$)-th and the beginning of the j-th operation of the i-th part;

I_s—many order details S.

Planning is carried out taking into account the loading of technological equipment for processing the ith part.

Minimization of the time required to complete all work on a given set of parts is carried out using the following formula [20]:

$$k_3 = \min(\sum_{I \in I_S} R_{ik} - \sum_{I \epsilon I_S} F_i), \quad (5)$$

where R_{ik}—the amount of work that needs to be performed on the i-th order detail S.

With this theory, the planning of technological processes is conducted utilizing the foundation of available data on successful implementations of similar or identical technological processes. Single and small-scale production involves the production of complex products in a small series or single copy, which makes it impossible to use this model. The use of equipment with the highest productivity for all identical technological routes does not allow for optimizing the overall duration of the production cycle, as well as the loading of all available equipment. In addition, this model does not take into account production costs.

Thus, methods based on complexity theory make it possible to design many technological processing routes, but do not allow for estimating production costs for the manufacture of a given batch of products. The methodology for analyzing design and technological elements makes it possible to determine strategies for processing DTE and the necessary parameters and tools used in them. Unfortunately, the parameters used do not take into account the accuracy of DTE processing. Methods based on the method of similarity of design solutions do not allow taking into account the design features and technical parameters of the product. In addition, the methodology does not allow us to evaluate many options for technological processing routes, as well as determine the precise length of the production cycle. The scheduling method does not allow for the correction of the start time of already existing technological routes. This constraint results in a notable limitation on the overall number of potential production scenarios and prevents the selection of the most optimal production process variant.

Therefore, the scientific novelty of this work is the construction of a simulation model that describes the method for selecting the best option for the production process of technological preparation of single and small-scale production based on multi-criteria analysis. The purpose of the article is to enhance the effectiveness of preparing technology for single and small-scale production based on simulation modeling of technological processes. The objectives of the study are to identify the main criteria for choosing a rational variant of the technological process, implement a simulation program for individual and limited-scale production with the possibility of multi-criteria analysis based on selected criteria, and test the implemented program for simulating the manufacture of the "Pusher" part.

2. Materials and Methods

The main task of creating a model is to choose the most suitable scenario for the operation of a production site using the provided information.

It must be taken into account that, depending on the equipment used and processing methods, the same product may have many solutions [34,35].

As part of the work, a generator of implementations of technological processes for the production of a given range of products on a given equipment (hereinafter referred to as ITTP) was built. The main task of the ITTP is to generate the largest possible number of possible implementation options at both the structural and parametric levels.

The generation of various implementations occurs by searching through all possible priorities of processing operations for given technological processes. Each technological process, as well as equipment, is given priority in the form of positive integers. Moreover, as the number increases, the priority increases. The given preferences within the technological process influence the choice of application, while the preferences regarding the equipment determine the sequence in which equipment is selected for executing the technological route. If a request with higher priority arrives while servicing an application, the current application is not interrupted, and the incoming application awaits its turn.

Likewise, priorities establish the order for choosing applications from sources, representing parts associated with specific technological processes, and dictate the sequence for their processing on designated technological equipment.

Upon completing these procedures, the ITPP yields a comprehensive array of implementations, from which suitable options must be chosen to satisfy the relevant decision-maker.

Hence, we encounter a multi-criteria problem with m objective functions delineated on a finite set D [36].

Problems of multi-criteria optimization of technological processes arise at different stages of modeling. Within the framework of a given specific structural implementation of a technological process, "continuous" problems may arise related to the multi-criteria choice in the space of such continuous variables as the processing time of parts on various machines, processing costs, cost of machine downtime, etc. Similar problems can be solved for all possible (generated) structural implementations. At the next level of modeling, when all particular implementations have been optimized according to their controllable parameters, we have a finite set of implementations and each element of this set has a vector estimate—the duration required for executing the technological process, the cost of implementation, the downtime of machines, etc. The number of structural implementations generated can be quite significant.

Thus, the task arises of automating the decision-making process for choosing a rational option for implementing a technological process in accordance with the system of preferences of the decision maker. Such problems belong to "discrete" multi-criteria selection problems.

When designing appropriate decision support systems, one can focus on existing methods of multi-criteria selection [36–39].

2.1. Structure of the Simulation Model and Description of the Simulation Process

The research methodology and multi-criteria solution are based on the application of Pareto principles and the associated concepts of effective (Pareto optimal) and suboptimal solutions [40–42]. We examine a multi-objective optimization issue of the form:

$$f_i(x) \to \max,\ \ npu\ x \in D \tag{6}$$

$$f_i : D \to R,\ i = 1, \ldots,\ m; \tag{7}$$

$$D \subseteq R^m \tag{8}$$

Hence, m functions or functionals f_i are provided, which map the set of Dn-dimensional vectors $x = (x_1, \ldots,)$ to real numbers R. The selection of optimal values for the controlled parameters (x) is not performed across the entire n-dimensional space Rn, but solely within its subset D.

Equation (8) can be depicted as the optimal parameter selection problem $(x_1, \ldots, x_n)$ for a system, evaluated based on quality metrics $(f_1, \ldots, f_m)$. In this context, the constraint $x \in D$ signifies our technological and other constraints that determine the feasible values for x_i. In particular, the processing times for parts on machines and other equipment are obviously non-negative. Certain limitations can be established based on the existing information, which makes it possible to exclude obviously unsuccessful option x from consideration.

To address the outlined multi-criteria problem in this research, we will employ the linear convolution approach.

This technique of "scalarization" (convolution) of Equation (8) enables us to substitute the vector optimality criterion $f = (f_1, \ldots,)$ with a scalar criterion J: $D \to R$. It relies on the linear amalgamation of all partial objective functionals $f_1, \ldots,$ into one [43]:

$$J(x) = \sum_{i=1}^{m} \alpha_i f_i(x) \to \max;\ \text{at } x \in D;\ \alpha_i > 0,\ \sum_{i=1}^{m} \alpha_i \tag{9}$$

In this case, the weighting coefficients α_i can be viewed as indicators of the relative significance of individual criterion functionals f_i. Giving more weight to a criterion f_j implies it should contribute more to the overall sum, hence requiring a higher value for α_j. When dealing with significantly disparate criteria, determining the final set of coefficients αi is often challenging and typically relies on informal considerations, typically stemming from the outcomes of expert analysis.

The method outlined above for tackling the posed multi-criteria problem does not pinpoint a single optimal solution. Solutions associated with different sets of weighting coefficients are equally valid elements within sets of effective and suboptimal solutions. These solutions, as per the general framework of the decision problem, represent the cores of the respective binary relations (Pareto's principle and Slater's condition), thus fulfilling the requisite criteria. However, from a practical standpoint, such as in problems involving the selection of rational options for organizing technological processes, additional insights into the decision maker's preferences should be factored in. In this context, the Pareto principle merely serves to refine the pool of potential solution candidates, eliminating clearly inferior options from consideration.

Methods for selecting a single solution to a multi-criteria problem exist and are associated with the use of models and procedures designed to structure and quantitatively describe the subjective opinion of the decision maker (technologist). These methods are not discussed in this paper.

2.2. Description of the Methodology for the Simulation Modeling Process and Development of the Structure of the Simulation Model

The main task is to analyze the maximum possible number of options for processing technological routes for given products, in order to select the optimal work scenario according to two criteria: time and cost of processing.

A simulation model of technological preparation of production can be presented as a model structured into three tiers with network-centric management [43–45]:

Level 1: Management of technological macro-operations (hereinafter referred to as MO—these are sequences of messages exchanged between the built-in controllers of first-level objects and second-level computers that control the implementation of the technology) of machine tools and robots. Every component of the production system is supervised, involving evaluating the present condition of each system component, verifying the accurate implementation of ongoing tasks for each component, and transmitting data indicating the beginning or completion of any actions of elements of the production system, as well as errors in their operation. At the first level, control of each element of the production system is carried out.

Level 2: Management and control of technological processes, described in the form of sequences of macro-operations: the interaction of elements of the production system is monitored, as well as the transmission of data on the state of network objects and their environment to the third level. At the second level, the interaction of elements of the production system is monitored, as well as the transmission of data on the state of network objects and their environment to the third level.

Level 3: Hierarchical optimization and planning involving multiple criteria of production processes. At the third level, the "data lake" is analyzed, on the basis of which dynamic planning of the workshop is carried out. When planning, the execution of MO by production network objects is optimized, which takes into account the possibilities of parallel execution of MO, their synchronization, areas of acceptable values of state parameters, conditions for reliable execution of the plan, etc. Since specific success criteria are defined for each operating mode of each network object, the third level must solve the problems of multi-criteria planning, as well as deriving new or changing existing control rules or assessing the state parameters of network objects.

Within the framework of this study, the third level of the model is considered, at which the modeling and analysis of various options for the process of determining the technological processing paths and the corresponding technological equipment utilized for each batch of components is conducted. The model being discussed will be realized in the form of a queuing system, abbreviated as QS [46].

QS are models of systems into which applications (requirements) are received at random times from outside or inside. Each application received into the system must be serviced by the system. The service system is a set of maintenance equipment and personnel with the appropriate organization of the maintenance process. The basic concepts of QS include [47]:

1. A source that generates applications, and a set of sources create the input flow of applications into the system. As a rule, sources can be of two types, finite and infinite, which differ in the methods of generating requests.
2. Buffer memory (storage location of the request queue). As a rule, it is divided into two types: general and zone. The shared memory stores requests from various sources, and the order in which they are recorded is determined only by the buffering discipline. Zone memory is a buffer divided into zones, each of which records requests only from a specific source. Thus, the quantity of zones aligns with the number of sources.
3. Devices that service requests and create an output stream of requests after servicing.
4. Arrangement manager: sends a request for service or to buffer memory if there are no free devices and organizes the refusal or knocking out of an application from the buffer memory if there are no free places left in the buffer.
5. Selection manager: selects the device on which applications will be processed and selects a request from the memory buffer, if it exists there.

Figure 1 shows the standard structure of the QS:

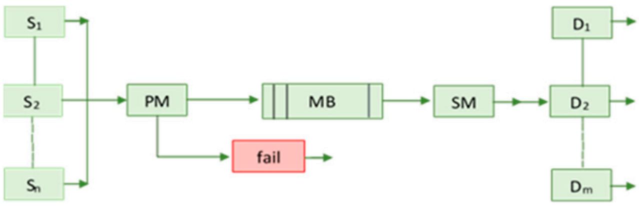

Figure 1. An example of the structure of a queuing system, where И_i (i = 1 … n)—sources, PM—production manager, MB—memory buffer, SM—selection manager, Π_i (i = 1 … m)—device.

Unlike the standard structure, the following changes were made to the implemented model:

1. In the model, the sources are represented by technological processes (referred to as TP). TP denotes a precise sequence of tasks, starting from the delivery of raw materials and tools from the warehouse to the machines, and concluding with the storage of finished products of specific types at the warehouse. Moreover, the durations of all tasks are explicitly defined.
2. No buffer memory.
3. The system operates seamlessly as it cannot bypass any stages of the process.
4. The quantity of devices in the system is contingent upon the designated technological equipment required for executing the specified technological processes.
5. During the modeling process, applications are generated—a separate stage of the technological process. Simultaneously, the system handles one occurrence of each technological process. Consequently, the quantity of applications within the system does not surpass the overall count of technological processes.

3. Result

Algorithmization of Simulation Modeling

To analyze the widest range of potential technological processing routes for designated products and subsequently select the optimal operational scenario based on processing time and cost criteria, the simulation algorithm can be delineated into four primary phases: user input processing, preparatory phase, generation of implementation options, and selection of the optimal operational scenario (refer to Figures 2 and 3).

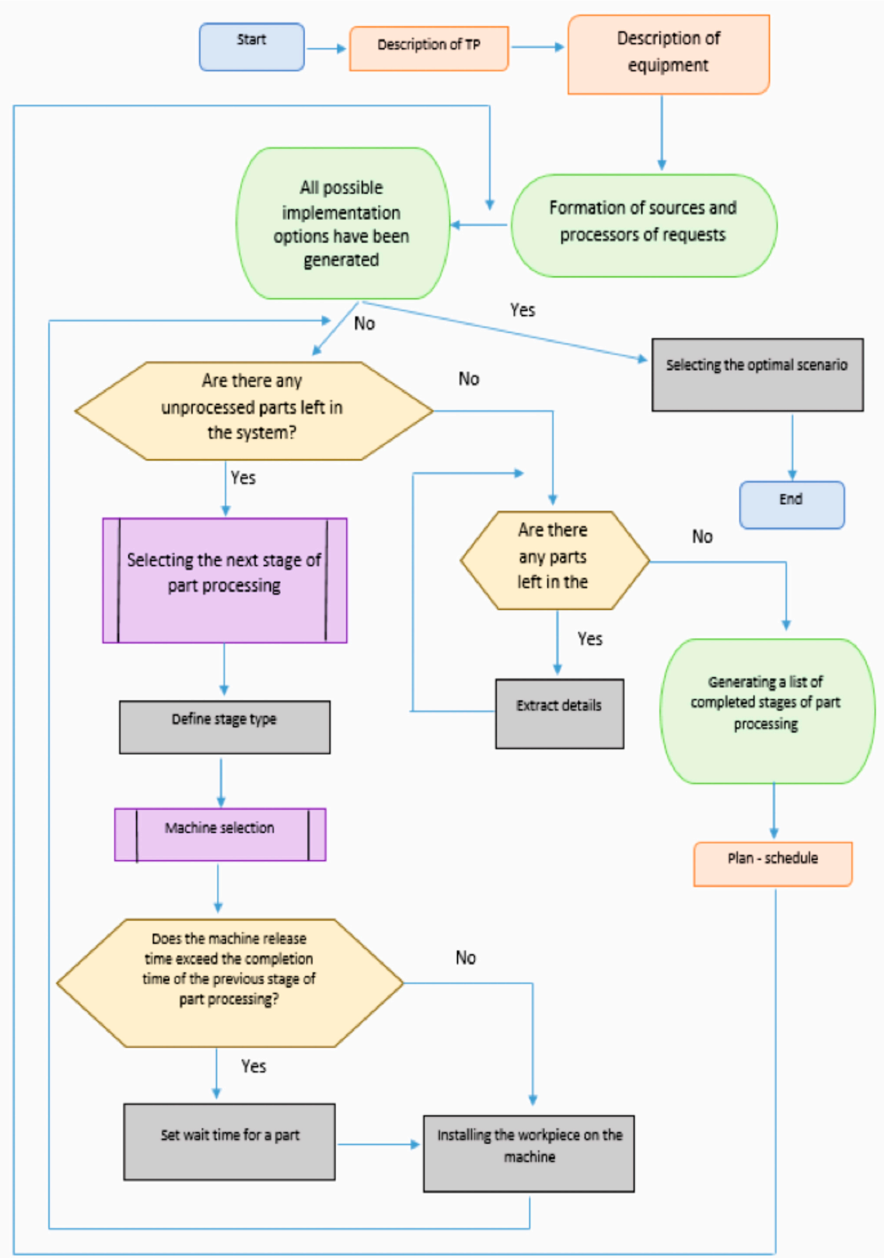

Figure 2. Simulation model algorithm diagram.

User Input: Input data are provided to the simulation model to ensure its proper functioning:

1. A compilation of TPs along with the number of implementations for each, comprising the operation type, time required, and implementation cost.
2. A collection of technological equipment—where one unit of a specified piece of equipment corresponds to one or more types of operations conducted.

Preparatory Stage: this involves the creation of processors and request sources, considering the user-provided information.

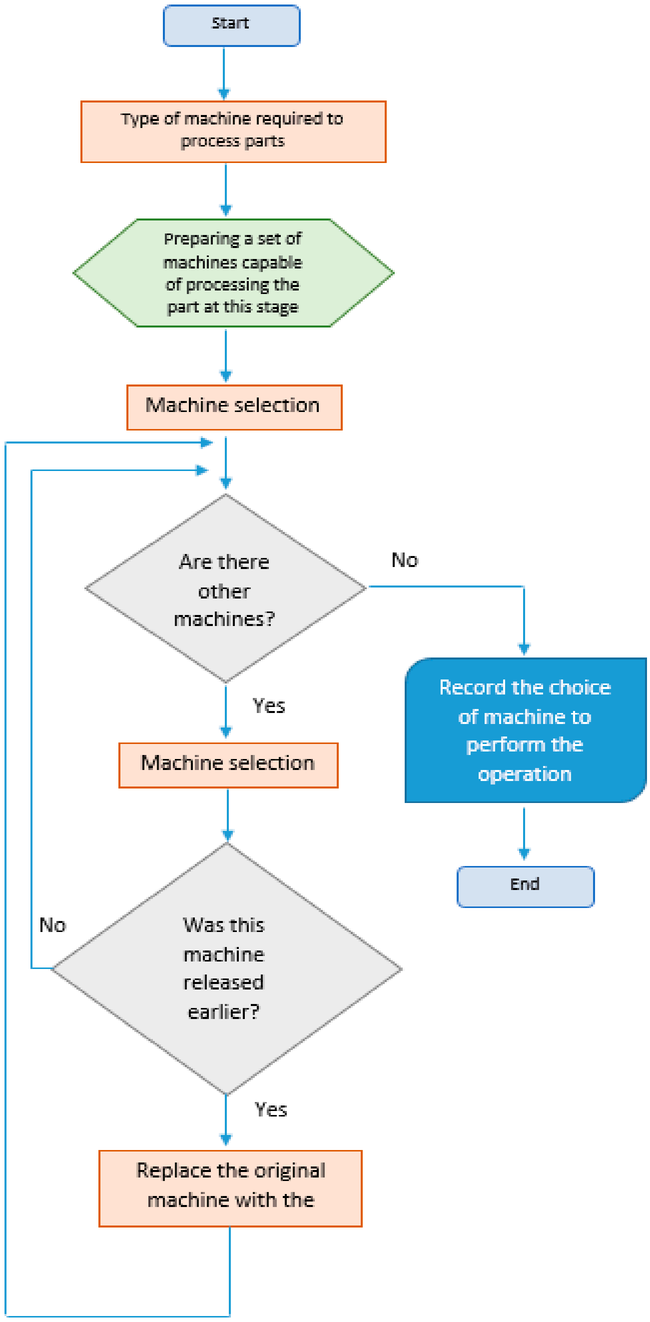

Figure 3. Scheme of the technology process description algorithm (TP).

Main Stage: This stage encompasses the operation of the ITTP. The process of generating implementation options allows you to generate the largest number of possible implementation scenarios by enumerating the priorities of operations for processing given data. Priorities allow you to set the sequence of selecting applications from sources, that is, parts corresponding to certain technological processes, as well as the sequence of their processing on specified equipment (machines) [48,49].

The optimal operational scenario is determined utilizing the linear convolution technique [50,51].

A simulation model consists of a set of simple elements, designed as basic abstractions. Based on these concepts, it is possible to formulate a basic algorithm for the implemented component of the simulation model.

To implement the TP, it is necessary to consistently perform all its stages. Each such stage can be represented in the form of a simulation model application. The application must contain the following information:

1. The TP's identification number implemented within the system (indicated by the id_ field);
2. The sequence number of the operation within this TP (id_);
3. The implementation number of the TP (id_);
4. The time when the application enters the system (birth_time_).

Fresh requests within the system await the availability of technological equipment capable of executing the relevant technological operation. Upon submitting a service request, the waiting duration (wait_time_) and the contractor's identifier (exec_id_) are logged. Consequently, for each implementation of a technological process, it becomes feasible to compute the delay time for executing technological operations. A comprehensive diagram of the Request class is depicted in Figure 4.

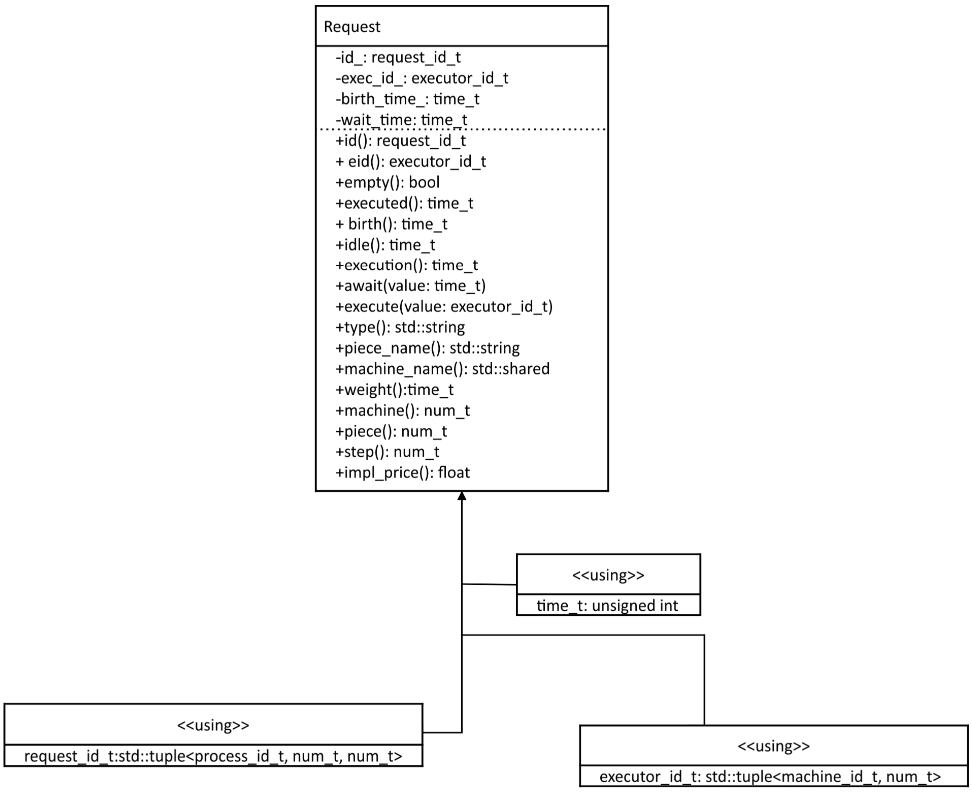

Figure 4. UML diagram of the Request class.

TPs are portrayed in the system as application sources, which monitor the number of implementations of a particular TP and generate a unique application identifier. The execution of the TP process is reiterated until the designated number of implementations is accomplished. As the TP stages unfold sequentially, each source furnishes only one application at a time. Consequently, the quantity of requests within the system corresponds to the number of concurrent processing operations. This pool of orders can be managed: for example, you can select orders of a certain type of operation.

The management of the application pool is overseen by the Device_union class. Order sources are depicted through the Device class, while TPs are portrayed by the Process class. Figure 5 presents a comprehensive UML diagram illustrating the detailed relationships among these classes and their interactions with the Request class.

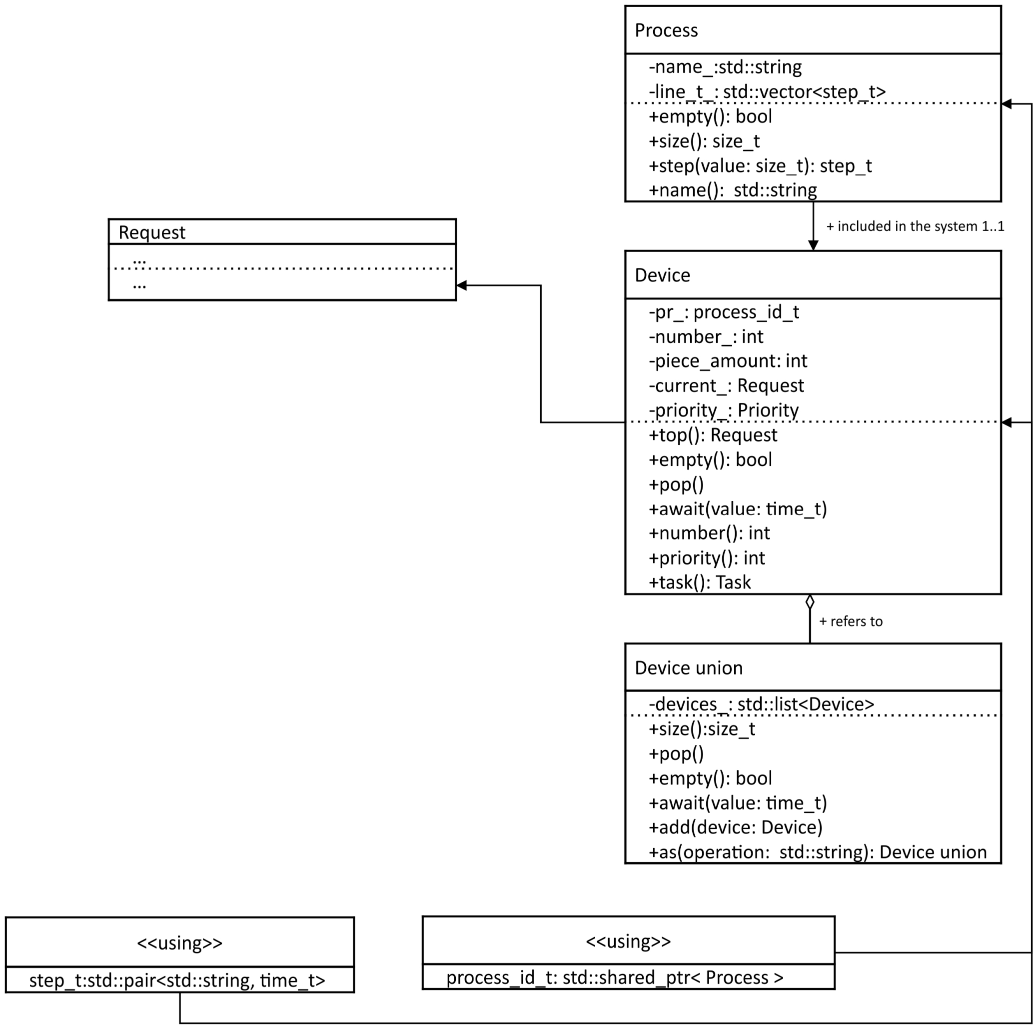

Figure 5. UML diagram of technological processes and sources of requests.

The technological equipment is embodied by the Machine class, encompassing the following details:

1. The designation of the process equipment (captured by the name_attribute);
2. The categories of operations it can execute (line_).

The resources associated with a specific piece of technological equipment are overseen by the Consumer class, which retains data regarding the most recent completed request. The information contained within the application is sufficient for determining the readiness of a particular piece of technological equipment to handle the subsequent application.

Throughout the modeling procedure, the Consumer_union class facilitates the allocation of the requisite unit of technological equipment based on the chosen request, considering the priorities and availability status of the units of technological equipment.

Below is a detailed UML diagram of technological equipment and application processors (Figure 6).

The complete class diagram is shown in Figure 7.

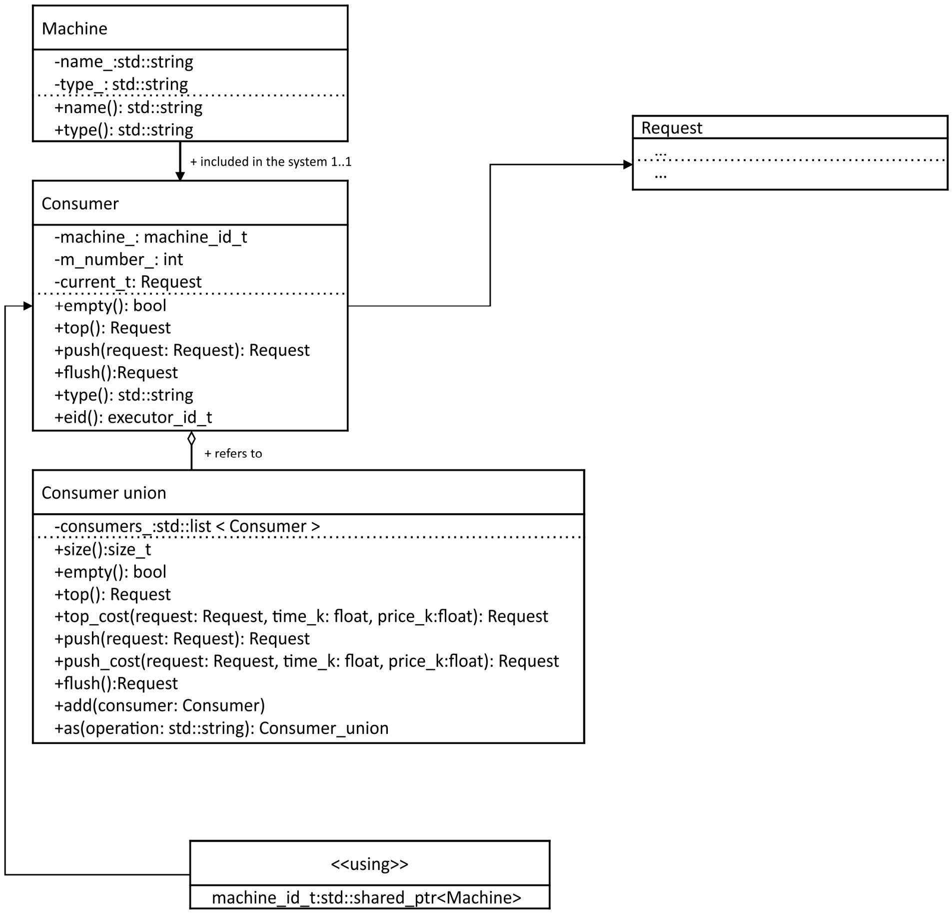

Figure 6. UML diagram of technological equipment and application processors.

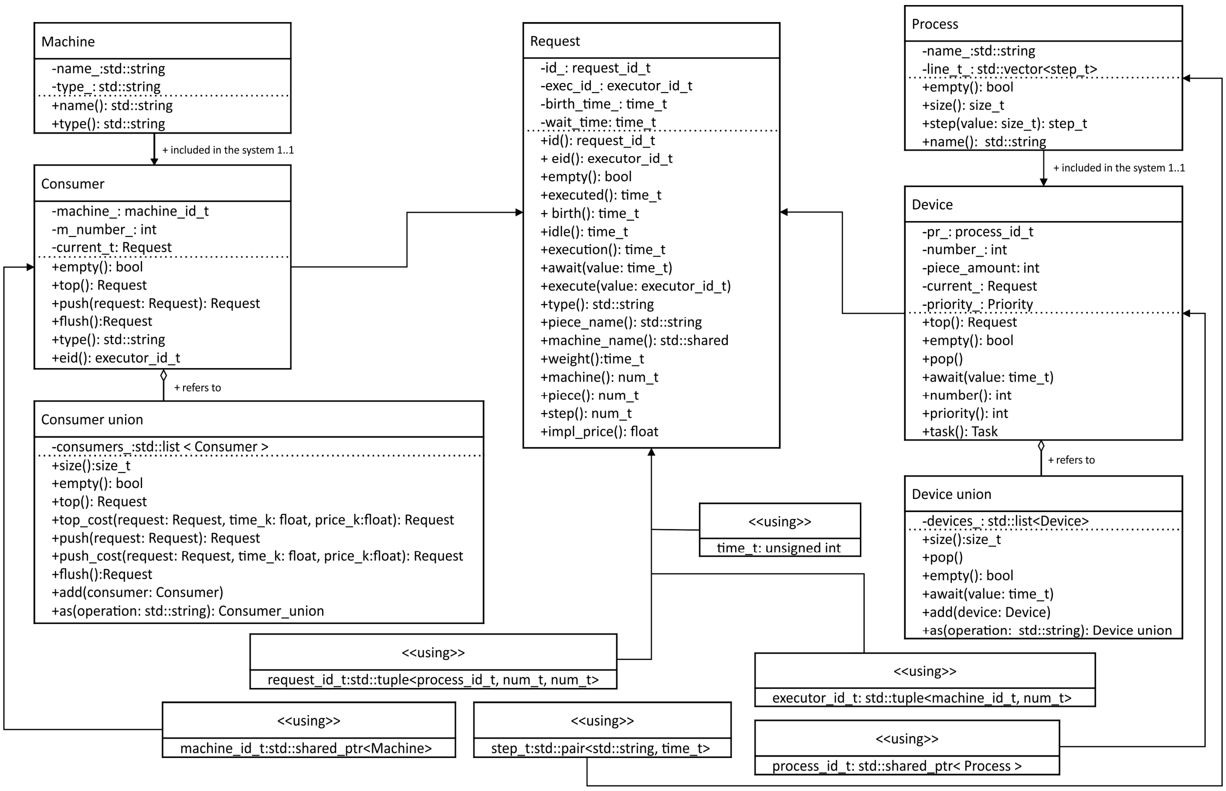

Figure 7. UML diagram of the complete simulation model.

4. Discussion

In existing models based on queuing systems, the production manager sends requests either directly for service or to buffer memory. If there are no free devices, the dispatcher organizes a refusal or the request from the buffer memory. If there are no free places left in the buffer the selection manager selects the device on which the requests will be processed, selects the request from the memory buffer if it is there. This whole process, in turn, makes it difficult to parameterize the state of the network according to specific success criteria for each operating mode of a certain model object. In the model proposed, the quantity of devices within the system is contingent upon the specified technological equipment essential for executing the designated technological processes. Consequently, in this model, there exists no buffer memory, thereby preventing the system from bypassing individual stages of the technological process and ensuring flawless operation. Throughout the modeling phase, applications are generated as a distinct step of the technological process. Concurrently, the system handles a singular instance of each technological process. Hence, the generation of applications within the system is managed in such a manner as to not exceed the overall count of technological processes. The developed simulation model was utilized in simulating the technological preparation of production for mimicking the production of the "Pusher" component.

The manufactured part "Pusher" (Figure 8) has the following technical parameters:

1. Dimensions: maximum diameter 24 mm, length 26 mm;
2. Exact dimensions:
   - outer diameter ϕ 24h6 with roughness Ra 0.8;
   - internal diameter ϕ 11H8 with roughness Ra 1.6;
   - internal threaded surface M8-7H, roughness Ra 3.2.
3. General tolerances for other dimensions: H14, h14, $\pm$IT14/2.

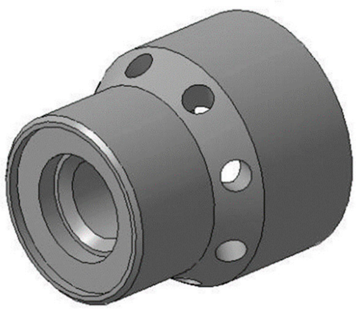

Figure 8. Solid model of the "Pusher" part.

Four types of machines are involved in the processing route:

- Thun—universal lathes;
- Tchpu—lathes with numerical control;
- TFNC—turning and milling machines with numerical control;
- KSh—cylindrical grinding machines.

Table 1 describes the types of machines and their method for processing technological units.

Table 1. Varieties of machine tools utilized and their machining techniques.

№	Machine Type	Type of Machinery Designation	Machining Technique	Designation of Processing Method
1	Tun	mach1	tapping threads	op1
			drilling	op2
			semi-finish turning	op3
			rough turning	op4
			finishing turning	op5

Table 1. *Cont.*

№	Machine Type	Type of Machinery Designation	Machining Technique	Designation of Processing Method
2	T_{CNC}	mach2	tapping threads	op1
			drilling	op2
			semi-finish turning	op3
			rough turning	op4
			finishing turning	op5
3	TF_{CNC}	mach3	tapping threads	op1
			drilling	op2
			semi-finish turning	op3
			rough turning	op4
			finishing turning	op5
			pre-grinding	op6
4	KS	mach4	tapping threads	op1

In accordance with Table 1, the input data for the simulation model for the given equipment were formulated:

4.1. Equipment

(:consumer 0:worker (:machine "mach1":line ("op1" "op2" "op3" "op4" "op5"):factor 1.0:):)
(:consumer 1:worker (:machine "mach2":line ("op1" "op2" "op3" "op4" "op5"):factor 1.2:):)
(:consumer 2:worker (:machine "mach3":line ("op1" "op2" "op3" "op4" "op5"):factor 1.3:):)
(:consumer 3:worker (:machine "mach4":line ("op6"):factor 1.0:):)
Explanation:

- Consumer ID—unique identifier for the designated equipment;
- Operator—details regarding the designated equipment;
- Machinery—designation of the specified equipment;
- Operation list—roster of operation types feasible on this equipment;
- Factor—cost factor (greater values correspond to higher part processing costs on this equipment).

For each block of surfaces, the following sequence of processing of the design and technological elements included in their composition was determined:

- MB(1/1): DTE(1H-1)1 → DTE(2H/2-1)2 → DTE(2H/1-1)2 → DTE(2H/2-1)1;
- MB(1/2): DTE(1H-1)2 → DTE(2H/1-4)1;
- MB(2/1): DTE(2B/1-2)1 → DTE(2B/1-1)2 → DTE(2B/2-1)1 → DTE(1B-1)1;
- MB(2/2): DTE(2B/1-2)3 → DTE(2B/1-3)4 → DTE(2B/2-2)2 → DTE(1B-1)2 → DTE(1B-2)3;
- MB(4/1): DTE(4B/1-2)1.

For the "Pusher" part, the following sequence of processing of surface blocks was defined: MB(1/2) → MB(2/1) → MB(1/1) → MB(2/2) → MB(4/1).

Technological elements are included in the design and technological elements are processed sequentially.

The given surface blocks were divided into final operations (Table 2):

Table 3 shows the relationship between processing methods and their cost and execution time:

In accordance with relation (7) and Tables 2 and 3, the TP input data for the simulation model were formulated, and the input data of the simulation model for a given technological process are as follows:

Table 2. Analysis of surface blocks for final operations.

№	Block of Surfaces	DTE		Processing Method	Machining Process Identification
1	MB(1/2)	1	DTE(1H-1)2	rough turning	op4
		2	DTE(2H/1-4)1	re-grinding	op6
				rough turning	op4
				semi-finish turning	op3
				finishing turning	op5
2	MB(2/1)	1	DTE(2B/1-2)1	drilling	op2
				semi-finish turning	op3
		2	DTE(2B/1-1)2	drilling	op2
		3	DTE(2B/2-1)1	drilling	op2
		4	DTE(1B-1)1	rough turning	op4
3	MB(1/1)	1	DTE(1H-1)1	rough turning	op4
		2	DTE(2H/2-1)2	rough turning	op4
		3	DTE(2H/1-1)2	rough turning	op4
		4	DTE(2H/2-1)1	rough turning	op4
4	MB(2/2)	1	DTE(2B/1-2)3	drilling	op2
				semi-finish turning	op3
		2	DTE(2B/1-3)4	drilling	op2
				semi-finish turning	op3
				rough turning	op5
		3	DTE(2B/2-2)2	drilling	op2
				semi-finish turning	op3
		4	DTE(1B-1)2	rough turning	op4
		5	DTE(1B-2)3	rough turning	op4
				semi-finish turning	op3
5	MB(4/1)	1	DTE(4B/1-2)1	drilling	op2
				thread cutting	op1

Table 3. Correlation of processing methods with cost and execution time.

№	Designation of Processing Method	Processing Method	Processing Time (Working Hours)	Amount of Costs (Conventional Units)
1	op1	tapping threads	32	4800
2	op2	drilling	18	5600
3	op3	semi-finish turning	12	8200
4	op4	rough turning	20	6800
5	op5	finishing turning	16	7400
6	op6	re-grinding	29	5800

4.2. Technological Process

(:device 0:task ((:process "TP-T":line (("op4" (:time 40:price 13,600:)) ("op3" (:time 12:price 8200:)) ("op5" (:time 16:price 7400:)) ("op6" (:time 29:price 5800:)) ("op2" (:time 18:price 5600:)) ("op3" (:time 12:price 8200:)) ("op2" (:time 36:price 11,200:)) ("op4" (:time 100:price 34,000:)) ("op2" (:time 18:price 5600:)) "op3" (:time 12:price 8200:)) ("op2" (:time 18:price 5600:)) ("op3" (:time 12:price 8200:)) ("op5" (:time 16:price 7400:)) ("op2" (:time 18:price 5600:)) ("op3" (:time 12:price 8200:)) ("op4" (:time 40:price 13,600:)) ("op3" (:time 12:price 8200:)) ("op2" (:time 18:price 5600:)) ("op1" (:time 32:price 4800:))):) 1):)

Explanation:

- Device №—identification number of the specified TP;
- Tsk—information about a given TP;
- Process—name of the specified TP;
- Line—list of operations that make up the given TP:
  (1) time—processing time of a given operation;
  (2) price—the cost of processing a given operation.
- No.—number of implementations of a given TP.

The output of the simulation model is presented in MRD (Machine-readable Data) format, where:

id: details concerning the ongoing application;
name: TP name;
num: current TP part number;
step: operation number in progress;
type: type of ongoing operation;
birth: timestamp of when the current request entered the system;
price: cost of the ongoing operation;
wait: start time of processing the current request;
executor: details regarding the equipment processing the application:
name: name of the equipment processing the current request;
num: equipment number processing the current request;
execution: completion time of application processing;
impl_price: cost after the application is processed.

A listing of the final schedule of the simulation model with the main set of cutting tools:

4.3. Part of the Simulation Listing Is Shown Below

(:id (:name TP-T:num 0:step 0:type op4:):birth 0:price 13,600:wait 0:executor (:name mach1:num 0:execution 40:impl_price 13,600:):)

(:id (:name TP-T:num 0:step 1:type op3:):birth 40:price 8200:wait 40:executor (:name mach1:num 0:execution 52:impl_price 8200:):)

(:id ():birth 0:price 0:wait 0:executor ():) (:id (:name TP-T:num 0:step 2:type op5:):birth 52:price 7400:wait 52:executor (:name mach1:num 0:execution 68:impl_price 7400:):)

(:id (:name TP-T:num 0:step 4:type op2:):birth 97:price 5600:wait 97:executor (:name mach1:num 0:execution 115:impl_price 5600:):)

(:id (:name TP-T:num 0:step 5:type op3:):birth 115:price 8200:wait 115:executor (:name mach1:num 0:execution 127:impl_price 8200:):)

(:id (:name TP-T:num 0:step 3:type op6:):birth 68:price 5800:wait 68:executor (:name mach4:num 3:execution 97:impl_price 5800:):)

Res_price:175,000 Res_time: 471

The full listing is provided in Appendix A.

As a result of simulating the production of the "Pusher" part, the optimal scenario for the operation of the production site was selected according to the two criteria of time and cost. The final duration of the production cycle was 471 working hours, and the final value of variable costs was 175,000 conventional units, which confirms that the created algorithm and simulation model are adequate under the conditions of a single production. In the future, it is planned to develop a simulation model with an alternative set of cutting tools. Typically, the choice of cutting tool affects the processing time of the part and its cost.

5. Conclusions

In this article, the authors solved the problem of automating the decision-making process of choosing a rational option for implementing a technological process in accordance with the system of preferences of the decision maker. Such problems belong to "discrete" multi-criteria selection problems.

1. The manuscript scrutinized technological production preparation models outlined in both Russian and international literature. In delving into the scientific literature, models focusing on complexity theory, scrutiny of individual design and technological facets, examination of design solution similarities, and scheduling were analyzed.

Through the examination of various methods and models aimed at enhancing the efficiency of production technological preparation, the following observations emerged:

Multi-criteria analysis is notably absent in the majority of production technological preparation models. The selection of optimal technological processing routes and processing strategies for individual part elements is not elaborated upon; rather, decisions are predominantly based on analyzing production cycle duration or production cost assessments.

2. Methods for estimating the value of inter-operational breaks, based on the method of mathematical statistics, do not allow an accurate assessment of the duration of the production cycle and a highly accurate prediction of the production time of the product.
3. Approaches relying on the similarity of design solutions during the design of a technological process fail to consider all the design intricacies of the component and its technical specifications. Moreover, they do not facilitate the assessment of numerous processing route options or the determination of production duration with high precision.
4. A number of the described methods use a production process planning method based on the analysis of identical operations that have already been implemented in the conditions of a particular enterprise. This method does not provide high accuracy in single and small-scale production types due to the wide variety of design and technological solutions.
5. In the model of technological production preparation, based on the scheduling method, when forming a production schedule, adjustments to the start time of already existing technological operations are not allowed, which significantly limits the number of simulated production scenarios. Consequently, this does not allow for choosing the most rational option for the production process.

To build a new simulation model, the authors used an analysis of various technological processing routes and the technological equipment used. One of the most effective methods for assessing multiple options for technological processes and selecting the most suitable one is simulation modeling of production processes and multi-criteria analysis based on a selected set of criteria.

Unlike the standard structure, the following changes were made to the implemented model:

1. In the model, the sources are represented by technological processes (referred to as TP). TP embodies a strict sequence of operations, encompassing the delivery of raw materials and tools from the warehouse to the machines, culminating in the retrieval of finished products of specified types at the warehouse. Additionally, the durations of all operations are precisely defined.
2. There is no provision for buffer memory.
3. The system operates flawlessly as it cannot bypass individual stages of the process.
4. The quantity of devices within the system is contingent upon the designated technological equipment essential for executing the specified technological processes.
5. Throughout the modeling process, applications are generated as a distinct step of the technological process. Concurrently, the system handles a singular instance of each technological process. Consequently, the number of applications within the system does not exceed the overall count of technological processes. Following the analysis, a simulation model algorithm was devised, and UML diagrams were crafted to delineate the system structure, classes, attributes, methods, and object relationships.

6. A simulation program was developed in C++ specifically tailored for single and small-scale production, with the objective of automating the technological processing process by automatically generating a plethora of work scenarios and subsequently selecting the optimal scenario for the production site based on two criteria: time and cost.
7. Upon simulating the production of the "Pusher" component, the resultant production cycle lasted 471 working hours, with variable costs totaling 175,000 conventional units.

In the future, based on the obtained structures and algorithms of the network-centered simulation model, and created UML diagrams, it is planned to develop a new software product that will combine the functions of production preparation systems (technical processes, equipment preparation, route development, preparation of operational maps) and MES (production control, schedule tracking, planning, and optimization). The peculiarity of this development will be that it will not be a direct competitor to large narrowly focused products that have a significant cost and in most cases are not available to small and medium-sized businesses, this software product offers a private solution to a number of mechanical engineering problems with low labor intensity of use.

In the following works, the purpose of rational cutting modes will be considered, based on the calculation of the total processing error and the quality loss function according to the Taguchi theory. The issues of assembly production will also be covered. It is planned to develop a methodology for selecting a rational option for the assembly technological route, and the variables that wield the most substantial influence on them, to implement the developed simulation model: mathematical dependencies for determining the production cycle, mathematical dependencies for determining the duration of the production cycle, and mathematical dependencies for determining the amount of costs.

Author Contributions: Acquisition of the financial support for the project leading to this publication; conducting the research and investigation process, specifically performing the experiments, or data/evidence collection, N.S.; application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data; verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs, T.N.; development or design of methodology; provision of study materials, G.Z.; scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use; preparation, creation, and/or presentation of the published work, specifically visualization/data presentation, K.I.; oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team and creation of models, V.Y.; conducting the research and investigation process, specifically performing the experiments, or data/evidence collection, O.Č.; management and coordination responsibility for the research activity planning and execution; preparation, creation, and/or presentation of the published work by those from the original research group, specifically critical review, commentary, or revision, including pre- or post-publication stages, O.Z.; programming and software development, E.D.; designing computer programs and implementation of the computer code and supporting algorithms, E.D.; designing computer programs; implementation of the computer code and supporting algorithms, A.B.; testing of existing code components, S.V.; preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation), M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14972804) "Development of Software for Technological Preparation of Production on the Basis of the Formalized Design Methodology" (Head N.A. Savelyeva).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

(:id (:name TP-T:num 0:step 6:type op2:):birth 127:price 11,200:wait 127:executor (:name mach1:num 0:execution 163:impl_price 11,200:):)

(:id (:name TP-T:num 0:step 7:type op4:):birth 163:price 34,000:wait 163:executor (:name mach1:num 0:execution 263:impl_price 34,000:):)

(:id (:name TP-T:num 0:step 8:type op2:):birth 263:price 5600:wait 263:executor (:name mach1:num 0:execution 281:impl_price 5600:):)

(:id (:name TP-T:num 0:step 9:type op3:):birth 281:price 8200:wait 281:executor (:name mach1:num 0:execution 293:impl_price 8200:):)

(:id (:name TP-T:num 0:step 10:type op2:):birth 293:price 5600:wait 293:executor (:name mach1:num 0:execution 311:impl_price 5600:):)

(:id (:name TP-T:num 0:step 11:type op3:):birth 311:price 8200:wait 311:executor (:name mach1:num 0:execution 323:impl_price 8200:):)

(:id (:name TP-T:num 0:step 12:type op5:):birth 323:price 7400:wait 323:executor (:name mach1:num 0:execution 339:impl_price 7400:):)

(:id (:name TP-T:num 0:step 13:type op2:):birth 339:price 5600:wait 339:executor (:name mach1:num 0:execution 357:impl_price 5600:):)

(:id (:name TP-T:num 0:step 14:type op3:):birth 357:price 8200:wait 357:executor (:name mach1:num 0:execution 369:impl_price 8200:):)

(:id (:name TP-T:num 0:step 15:type op4:):birth 369:price 13,600:wait 369:executor (:name mach1:num 0:execution 409:impl_price 13,600:):)

(:id (:name TP-T:num 0:step 16:type op3:):birth 409:price 8200:wait 409:executor (:name mach1:num 0:execution 421:impl_price 8200:):)

(:id (:name TP-T:num 0:step 17:type op2:):birth 421:price 5600:wait 421:executor (:name mach1:num 0:execution 439:impl_price 5600:):)

(:id (:name TP-T:num 0:step 18:type op1:):birth 439:price 4800:wait 439:executor (:name mach1:num 0:execution 471:impl_price 4800:):)

(:id (:name TP-T:num 0:step 3:type op6:):birth 68:price 5800:wait 68:executor (:name mach4:num 3:execution 97:impl_price 5800:):)

(:id (:name TP-T:num 0:step 0:type op4:):birth 0:price 13,600:wait 0:executor (:name mach1:num 0:execution 40:impl_price 13,600:):)

(:id (:name TP-T:num 0:step 1:type op3:):birth 40:price 8200:wait 40:executor (:name mach1:num 0:execution 52:impl_price 8200:):)

(:id (:name TP-T:num 0:step 2:type op5:):birth 52:price 7400:wait 52:executor (:name mach1:num 0:execution 68:impl_price 7400:):)

(:id (:name TP-T:num 0:step 4:type op2:):birth 97:price 5600:wait 97:executor (:name mach1:num 0:execution 115:impl_price 5600:):)

(:id (:name TP-T:num 0:step 5:type op3:):birth 115:price 8200:wait 115:executor (:name mach1:num 0:execution 127:impl_price 8200:):)

(:id (:name TP-T:num 0:step 6:type op2:):birth 127:price 11,200:wait 127:executor (:name mach1:num 0:execution 163:impl_price 11,200:):)

(:id (:name TP-T:num 0:step 7:type op4:):birth 163:price 34,000:wait 163:executor (:name mach1:num 0:execution 263:impl_price 34,000:):)

(:id (:name TP-T:num 0:step 8:type op2:):birth 263:price 5600:wait 263:executor (:name mach1:num 0:execution 281:impl_price 5600:):)

(:id (:name TP-T:num 0:step 9:type op3:):birth 281:price 8200:wait 281:executor (:name mach1:num 0:execution 293:impl_price 8200:):)

(:id (:name TP-T:num 0:step 10:type op2:):birth 293:price 5600:wait 293:executor (:name mach1:num 0:execution 311:impl_price 5600:):)

(:id (:name TP-T:num 0:step 11:type op3:):birth 311:price 8200:wait 311:executor (:name mach1:num 0:execution 323:impl_price 8200:):)

(:id (:name TP-T:num 0:step 12:type op5:):birth 323:price 7400:wait 323:executor (:name mach1:num 0:execution 339:impl_price 7400:):)

(:id (:name TP-T:num 0:step 13:type op2:):birth 339:price 5600:wait 339:executor (:name mach1:num 0:execution 357:impl_price 5600:):)

(:id (:name TP-T:num 0:step 14:type op3:):birth 357:price 8200:wait 357:executor (:name mach1:num 0:execution 369:impl_price 8200:):)

(:id (:name TP-T:num 0:step 15:type op4:):birth 369:price 13,600:wait 369:executor (:name mach1:num 0:execution 409:impl_price 136,00:):)

(:id (:name TP-T:num 0:step 16:type op3:):birth 409:price 8200:wait 409:executor (:name mach1:num 0:execution 421:impl_price 8200:):)

(:id (:name TP-T:num 0:step 17:type op2:):birth 421:price 5600:wait 421:executor (:name mach1:num 0:execution 439:impl_price 5600:):)

(:id (:name TP-T:num 0:step 18:type op1:):birth 439:price 4800:wait 439:executor (:name mach1:num 0:execution 471:impl_price 4800:):)

(:id (:name TP-T:num 0:step 3:type op6:):birth 68:price 5800:wait 68:executor (:name mach4:num 3:execution 97:impl_price 5800:):)

Res_price:175,000 Res_time: 471

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