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ORIGINAL ARTICLE

On the aspect of implementing solutions for information support of industrial plant control systems

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Abstract The authors of this paper look at the aspect of engineering information systems for planning and scheduling operations of an industrial plant. The authors propose to introduce new steps to the engineering process which include functional modelling, elaboration of an initial request for proposal (or RFP) for a functional model, development of functional models and algorithms, and elaboration of a software specification. The engineering step-by-step process is presented as an entity set model. The authors introduce a system functionality design formula which includes business rules, business logic, project roles, and visualization. An example of a machining shop with repeated machining operations is used to demonstrate the effect of introduction of new design stages. The simulation software AnyLogic was chosen as a visualization tool to demonstrate all the functionalities of the new system. AnyLogic enabled to implement all the roles of the information system. Elaboration of the functional model took place along with development of an RFP for implementation of an information system as part of an automation package of an industrial plant. As a result of the functional model demonstration, certain drawbacks were identified in the project, and recommendations were provided on how to eliminate them.

Keywords Information systems · Engineering/design · Initial study · Production plant · MES · Simulation modeling

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1 Introduction

Nowadays in order to create new or improve the existing production lines, a scientifically substantiated design approach is required, which is true for any industry. In relation to this, when preparing design solutions, several areas are taken into consideration such as identifying potential resources to manufacture products, justifying the choice of equipment and the production area requirements, conducting the target market research, training the personnel, etc.

All the above-mentioned areas are specified in an RFP, which has a formalized structure and formalized contents. With all the thoroughness involved in the process of drafting an RFP, the customer does not have a clear insight into the adaptability of a new plant or the problems related to break-downs, risks, and bottlenecks, all of which can be minimized during the engineering phase.

Simulation algorithms and simulation modeling systems are developed for visual representation of a production line. A great number of scientific works and practical studies are known that are used to create simulation algorithms and modeling systems. This paper [1] considers the application of integer linear programming (ILP) for planning a job of chemical treatment of items in discrete and continuous time. The paper [2] also looks at the issues of scheduling that would allow for energy and environmental factors with two lines operated at maximum power while producing various parts. As a separate subject, classification and application of mathematical methods in the scheduling theory [3, 4] are considered. The authors of the papers [3, 4] present an up-to-date classification of simulation techniques when producing one type of product, multiple products, or to simulate a particular plant or a cluster of plants. The papers describe a possibility to apply heuristic methods, simulation modeling techniques, and genetic algorithms.

The Russian Federation currently witnesses intensive scientific studies aimed at creating model studies that take place before designing a production line. Scientific schools have been established which act in cooperation with existing plants and have created unique products [5, 6]. Many of the authors' papers [5, 6] present the results of a long-term systematic study of flexible production systems. They are models, algorithms, and software packages. The papers [7, 8] look at the possibilities of scheduled operation of a large-scale multistage steel making facility comprising interrelated process stages. The interrelated nature of different process stages leads to the establishment of smart decision-making and support systems [9]. Transfer of control in such systems determines the production rate, the product quality, and if the scope of works will be completed to the deadlines set by the customer.

The best management practice in case of large-scale systems comprising interrelated components implies that initial studies are conducted at the design stage. Recently, there has been established a traditional approach to the information structure of a management system, as well as to what its design stages should be. It is traditionally understood that a modern management system consists of seven constituent parts. They are data, technical information, software, process information, linguistic support, mathematical support, and legal support. All the components of an information system are designed to perform the functions of acquiring, processing, storing, transferring, and visualizing data based on the functional requirements of a particular site.

The process of designing information systems for industrial applications has to date acquired some specific features:

1. There is a methodological basis, which includes a description of an object and multiple subjects, a description of the operational structure of the object, principles and norms of the subjects, models of the object and multiple subjects, as well as design methods and procedures;
2. The scale of the system under development is taken into account, which includes a certain number of participants who are the potential system users; a certain number of divisions and companies who are to use the system in view; a set of functions to be automated with the help of the designed sys-tem; and a list of interfacing information systems that the designed system will communicate with.

According to the basic methodologies set out in [10], the period of the initial and the design stages is when the need for a system analysis is most evident. In the course of the system analysis, a concept and a structure of the system design process are shaped along with sequential and parallel implementation of tasks relevant to the goal set (Fig. 1).

Tasks identified in the course of a system analysis are standard tasks and are determined as a result of the system analysis of an object and multiple subjects. Even with a great number of theoretical and practical studies available on engineering the information layer of a management system, the following problems stay relevant:

– To identify a set of tasks to be completed during the initial study and design stages and to identify the order such tasks are to be addressed in.
– To identify the tools and notation required for the system analysis of an object and multiple system subjects.
– To define and present a functional model of the area under consideration. The above named problems defined the purpose of the study, which is to improve the initial study and design stages when creating the information- and soft-ware of a MES.

The defined purpose is achievable when the below tasks are fulfilled:

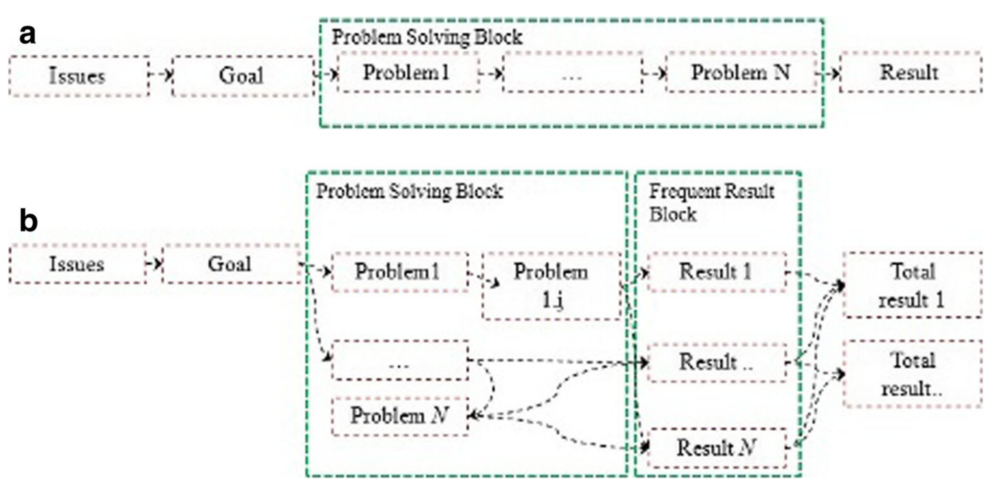


Fig. 1 Structure of system design process: **a** Linear design; **b** sequential and parallel design

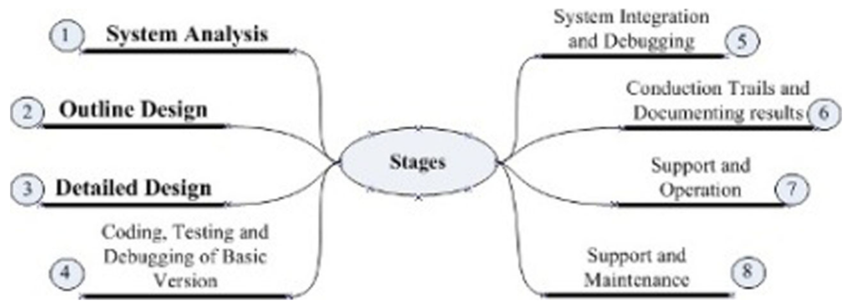


Fig. 2 Standard stages of design process

- To identify a complete array of tasks to be completed during the initial study of a given object and multiple subjects.
- To elaborate a decision-making procedure for the order of the chosen task completion with a serial or parallel implementation.
- To select a notation for the functional model of an object and multiple subjects.

2 Methodology

2.1 Entity set model of the initial study of an object and multiple subjects

Norms and standards regulating how information systems should be designed, i.e., ISO 12207-95, IDEF0-2000, ISO/IEC 15288-02, 34.602-89, IDEFIX, define a variety of tasks, including system analysis of the subject field, outline (or preliminary) design, coding (or programming), testing, debugging and documenting the components of the basic version, integration (the use of modules together) and the system debugging, trials and documenting the results, support during the operation, and maintenance of the system. The practical experience of building information systems showed that the standard guidelines are not complete in the areas of the system analysis and outline and detailed design, and therefore more tasks should be added to them. Figure 2 highlights the components that help expand the array of tasks of the stages mentioned above.

If we believe that Ph stands for multiple phases that constitute the engineering of an information system, and St stands for multiple stages that constitute the engineering of an information system, we come up with a simple semantic equation defining the order in which an information system is designed:

$$Ph = \{St_1, St_2, St_3, St_4, St_5, St_6, St_7, St_8\},$$

where the number of each stage corresponds to a number in Fig. 2.

Actions mentioned in Fig. 3 are added to each of the stages 1 to 3. Note that the straight lines used in Fig. 3 stand

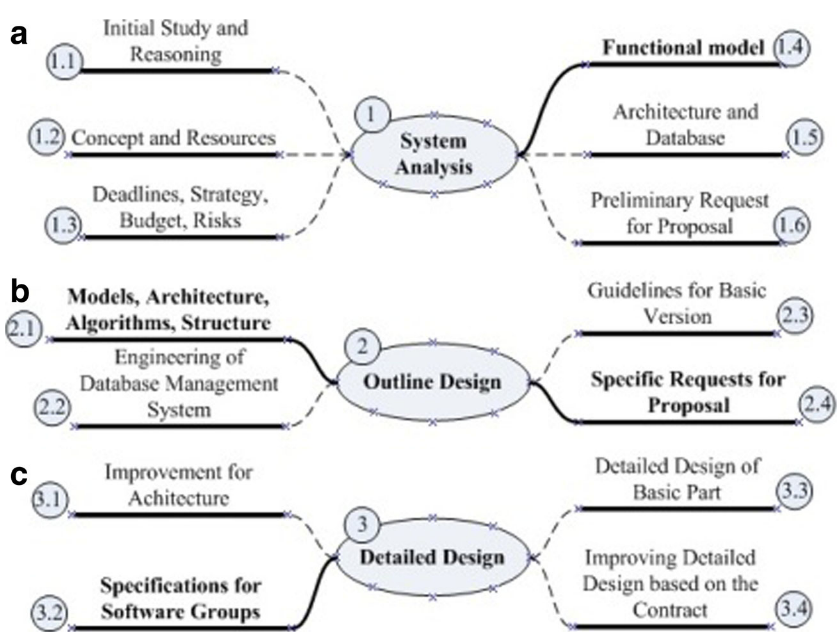


Fig. 3 Standard phases and stages of the engineering process: **a** System analysis stage; **b** outline design stage; **c** detailed design stage

for new added activities, whereas the dotted lines stand for standard activities.

If we believe that stands for a task of a selected engineering stage, we come up with an extended base set that defines the order in which an information system is designed

$$Ph = \{St_1\left(Ts_{1,1}, Ts_{1,2}, Ts_{1,3}, Ts_{1,4}, Ts_{1,5}, Ts_{1,6}\right), St_2\left(Ts_{2,1}, Ts_{2,2}, Ts_{2,3}, Ts_{2,4}\right), St_3\left(Ts_{3,1}, Ts_{3,2}, Ts_{3,3}, Ts_{3,4}\right), St_4(\ldots), St_5(\ldots), St_6(\ldots), St_7(\ldots), St_8(\ldots)\},$$

where the first index stands for a stage number and the second index stands for a task number, both being in exact correspondence with Fig. 3.

The elements $Ts_{1,4}$, $Ts_{2,1}$, $Ts_{2,4}$, and $Ts_{3,2}$ define the functionality of an engineered system. Having different degrees of detail, these functions should be implemented with the help of the engineered system. As more details are added to the system in the course of engineering, the gap is increasing between the business logic of the customer and the logic of the IT person responsible for design and development of the system.

The increasing integration between various information systems requires that the customer and the IT person in charge had a common view on the purpose of the system. That is how a formula forms of how to build an integrated information system, as shown in Fig. 4.

Figure 4 introduces a number of terms: Business Logic stands for the process laws; Business Rules stand for the limitations of the business process; Roles are objects and multiple subjects within a business process; and Form of Presentation stands for visualization of a functional model.

Business logic along with business rules define the way the business processes will be implemented at the algorithm level.

A subject field is a combination of business processes designed to achieve the result, i.e., the output of a product, document, semi-finished product, etc. Business logic should be formalized and described during the initial study and the design stages. Business logic of an information system may not cover all the business processes of the subject field, in which case the application of the system should undoubtedly be defined by business rules. Business rules set limitations when realizing automated functions of a subject field. A separate business rule applies to a separate business process or a combination of processes. Business rules lay the basis of the system functionality specification and define the base behavior of a role within an information system.

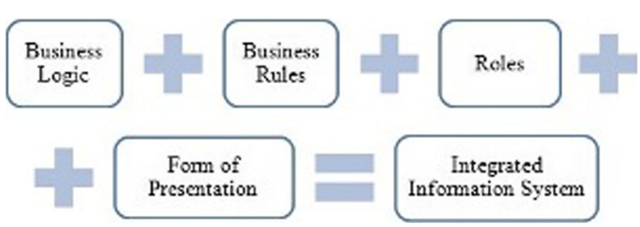


Fig. 4 Formula of engineering the functionality of integrated information system

Roles are objects and subjects within an information system. Objects and multiple subjects are defined as a part of the business rules and business logic definition process. Each role receives its definition, while its attributes and characteristics are highlighted. The list of roles defines the architecture of the system database. Presentation of information system elements in the system architecture includes a graphic user interface (dialog windows, buttons, modal windows, etc.); system objects presented as maps, schemes, graphs, etc.; report forms (tables, charts); and reference tables (directories, classifiers, rules).

The elements shown in Fig. 4 are used as long as it takes to build an information system enabling to establish a connection between the functional and the information models of the subject field under consideration. They also enable to get a general understanding about the system requirements from both the business process side and the information technologies side. A great amount of time is spent on discussions between the business users and the system developers about how the objects should look.

Definition of the system objects, understanding of their interaction, and the object hierarchy play a key role when designing and developing an information system. A system analysis of the subject filed, an RFP and project documentation are all essential in the implementation of automated information systems at major plants. Albums of screen and print forms, a list of automatic functions, testing scenarios, a method of the system handover and acceptance, definition of business processes are all elements of the structured system analysis of a subject field and serve as a basis for building the functional model of an information system.

Today's information technologies enable to create functional models that are most true to life.

2.2 Notation of the functional model of an object and multiple subjects

The functional model of a system object represents the processes that take place in the object and shows both incoming and outgoing data streams while overlooking calculation or conversion algorithms. Basically, the functional model demonstrates a list of simulated (described) operations, actions, and limitations of a business process.

The method of building a functional model of an object and multiple subjects allows the use of several approaches to creating diagrams (eEPC, BPM). However, all of them are based on the structured analysis and design technique

(SADT). SADT enables to manage the object presentation process independently of approaches or tools selected. The process of building a system comprises the following phases: analysis, i.e., what the system does; design, i.e., description of how the subsystems interact; implementation, i.e., development of subsystems and interfaces; testing, i.e., function check of the system and its subsystems; installation, i.e., commissioning of the system; operation, i.e., utilization of the system.

Data flow diagram (DFD) is one of the structured analysis methods which represents the results of the analysis phase. Any information system first receives data through the front-end interfaces (external entities). Based on the algorithms set, new data flows are generated as a result of the system internal processes. They can either be incoming data for the subsystems inside the mother system or they can be outgoing data flows transferred through the front-end interfaces (external entities).

The DFD model has its hierarchy. Every process needs to be decomposed down to ultimate one-to-one relations. The depth of decomposition depends on complexity of the information system and the qualification of the developers and analytics. The final model of the data flows and the description of the business processes of an information system serve as a specification for the software.

Currently, the following description techniques are used to describe the subject field after the system analysis has been completed (see Table 1).

At this time, one cannot give preference to just one of the techniques. When designing an information system, analytics and developers have to use elements of all of them.

3 Results

The multiple models and functional model presentation techniques discussed above were used to elaborate an RFP for an information support system for the management systems of two plants. The system should consist of the following subsystems: operations planning; dispatching and management; monitoring; process flow monitoring and optimization; equipment diagnostics. The pending issues described below encouraged the project:

- Insufficiently developed techniques which help demonstrate to the customer the functional capabilities of the engineered information system.
- Inadequate optimization of the production management based on the data received from the information system.

The following goal is defined to eliminate the mentioned drawbacks: to create and implement a monitoring and operations management system for the machine fleet of the plant, which is aimed at improved management practices and more reliable and cost-efficient operations.

The authors implemented one of the subsystems, which is an operations planning model. The activities took place following the scheme given in Fig. 1a. When implementing the module, the main tasks under Scheme 4 included:

- To describe the project roles including levels of planning, system and production resources, a data unit of the system.
- To describe the project business logic which determines the structure of each element of the production system.

Table 1 System analysis results description techniques

Technique	Description	Application
IDEF0	Functional Modeling Technique which presents a system as a combination of interacting processes/jobs/functions	Used for documenting production processes and displaying the data and resources utilized at each step
IDEF3	Graphical Modeling Technique which is designed to describe and document data flows in a system with a given process sequence	Used for creating and displaying processes, as well as for capturing and structurizing system functions multi -level systems with support of the IT system
ARIS	A set of techniques used to analyze and simulate plant's activities and to develop automated information systems	Used as a development and description tool for life cycle theory
Archi	General Mnemonic Presentation used for the functional and information models description so that a business analytic and IT experts had a uniform way to present the system processes	Used to describe a work process at the level of businesspeople, engineers, scientists etc.; at the program level (calculations, formal data transformations etc.); at the equipment level (servers, system software etc.)
DED	This technique offers to introduce an additional object which indicates where within a business process data or resources are stored	Used to describe processes as a flow of data and resources

- To describe the project business rules which include limitations for the whole module or particular parts of the module.
- To implement visualization of the project functionalities using the AnyLogic simulation software.

3.1 Objects, subjects, and hierarchies

The initial analysis of cooperation between the planning divisions of the company showed a low automation level of the planning process undertaken by the site departments. The authors distinguished four levels of planning (see Fig. 5). Level 1 is for general plant planning for a calendar year, level 2 is for scheduling for each site of the plant, level 3 is for month-long operations planning for site departments, and level 4 is for shift-long planning for site departments. Therefore, the functional planning module should comprise two parts: plant-scale planning (levels 1–3) and planning for a site or a site department (levels 3 and 4).

When implementing the operations planning module at level 3, the site production plans are duplicated the first plan is drafted by Production Planning Department as the basic plan, and a copy plan is calculated by the operations planning module for verification. Once the system has been commissioned, i.e., upon implementation, site operations plans will be calculated by the module based on the schedule obtained from level 2. When the plans are being generated at level 2, the module can, on request, send to the next level the information about workpiece requirements for the calculated site operations plan to be fulfilled.

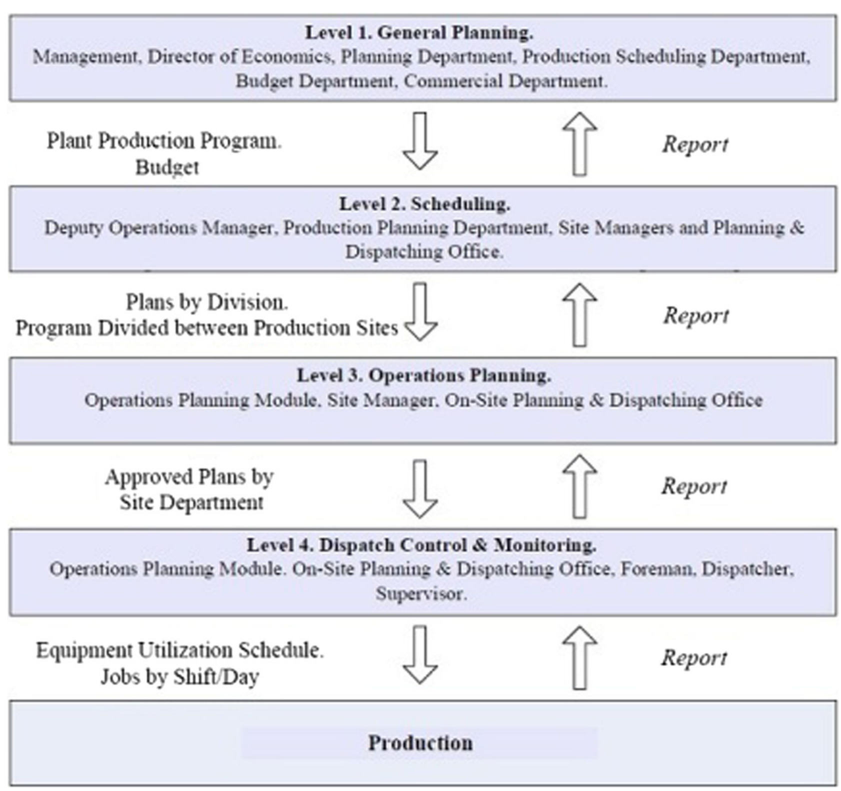
The module is designed to change the way monthly site operations plans are calculated (calculations by Production Planning Department are replaced with the Module calculations) and to make the generation of jobs by shift/day an automated process.

This structure has three layers of detail: layer 1 (levels 0–1) current production status for the absolute (world) time with discreteness of up to 1 min; layer 2 (levels 2–4) machine status of each machine at the current moment of time; layer 3 (levels 5–9) ingredient and semi-finished product status for each ingredient and each semi-finished product for the current machine at the current moment of time. Multiple subjects are defined at all levels of planning: operations plan, world time, production, machines, product, ingredient, order. The characteristics hierarchy of each subject is given in Fig. 6.

Production order statuses are defined by a group with a certain order number for machines and their semi-finished products. Workpiece (material) statuses are defined by a group assigned to a certain primary machine and their ingredients. Finished product statuses are defined by a group assigned to certain final machines and their semi-finished products.

Figure 6 introduces the following designations: Plan stands for a data unit; World time stands for an array of continuous production order execution time; An array of

Fig. 5 Production planning levels



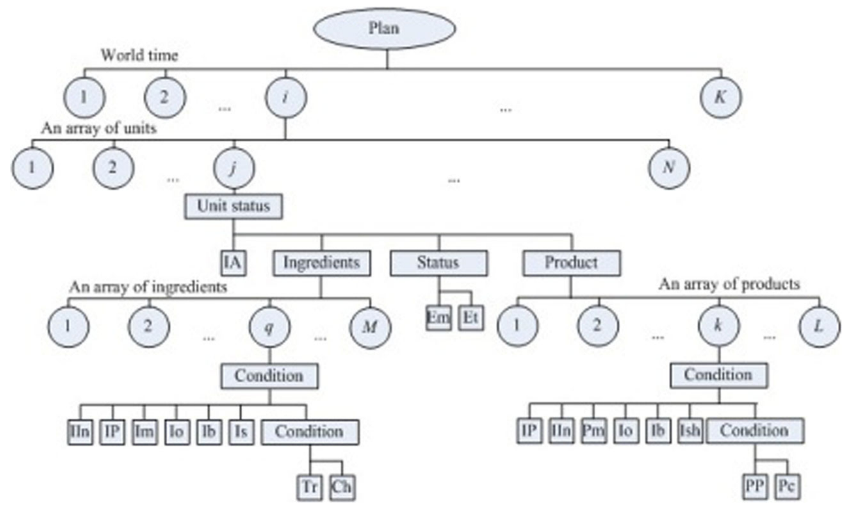


Fig. 6 Hierarchy of the model subjects' characteristics

units is an array containing the site equipment (machines) details; Units status contains characteristics of each element of the equipment (machines) array; IA stands for the artificial code of a machine; Ingredients is an array each element of which serves as a machine that describes the properties of the ingredients required to create a product; Status stands for equipment (machine) utilization status; Product is an array each element of which serves as a machine to describe the properties of a product; Em means that the equipment is used; Et describes how the equipment is used; IIn stands for an ingredient identifier; IP stands for a product identifier; Im stands for the weight of an ingredient; Io is an order identifier; Ib is a workpiece identifier; Is indicates if the ingredient has arrived; Condition can stand for either an ingredient or a product status (defined by the structure); Tr stands for the processing state; Ch is a type of change; PP stands for execution status (percent); Pc is a type of product change; K, M, L, N stand for the dimensions of corresponding arrays.

The analytical formula of a data unit looks as shown below:

$$Plan(1;k).(Units\ \ status(IA, Ingradients(1;m)$$

$$(IIn, IP, Im, Io, Ib, Is, Condition(Tr, Ch))),$$

$$Status(Em, Et), Product(1;L)(IP, IIn, Pm, Io, I, \\ Ish, Condition(PP, Pc))).$$

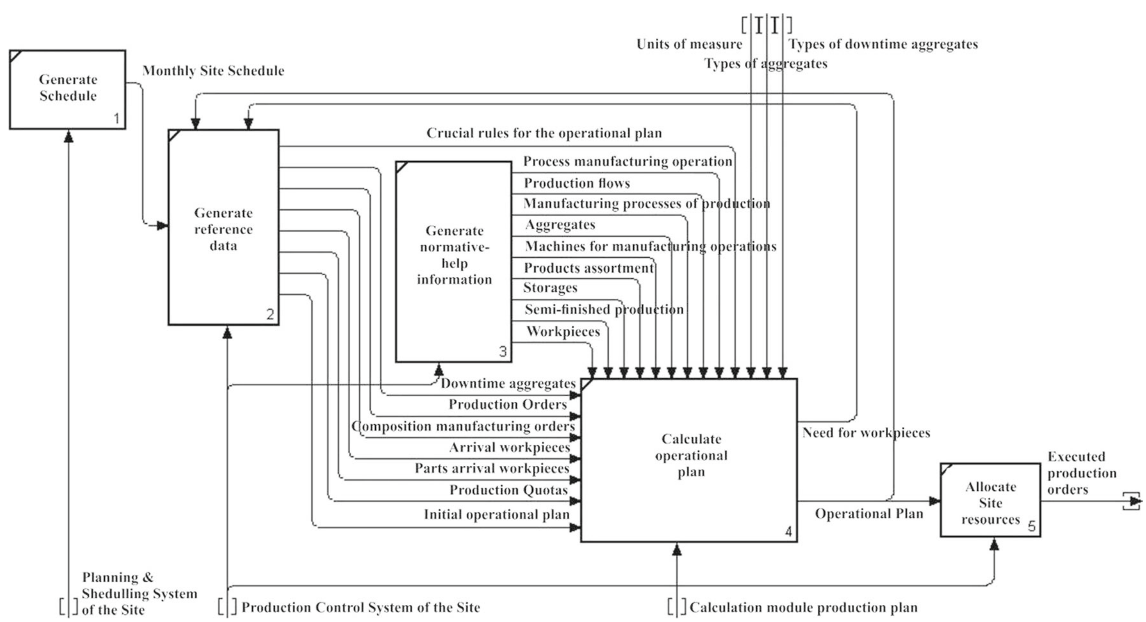
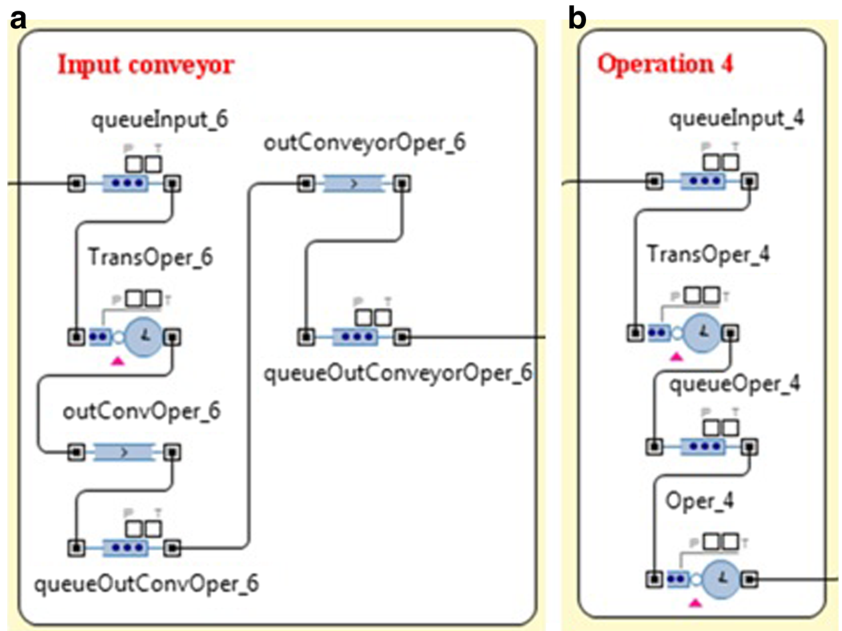


Fig. 7 Interaction between scheduling module and external environment

Fig. 8 Interaction between scheduling module and external environment



3.2 Business logic of the process

The business logic of the operations planning process contains two functional parts: business logic of how the module interacts with the external environment, which is typically realized in the IDEF3 notation; functionality logic of each separate system element, the description of which only takes the basic simulation.

Figure 7 shows business logic behind the operations planning module's interaction with the external environment. The elements of the job site function in a standard way which can be compared to three complex logic blocks: blocks responsible for delivering resources to or transporting a workpiece away from the job site a conveyor (see Fig. 8a); a block responsible for processing a workpiece at one of the process stages an operation (Fig. 8b).

Figure 8 contains the following designations: queueInput is an object for simulating an incoming job order queue; TransOper stands for capture elements for a set amount of resources for holding an order/part for the handling period; OutConvOper, outConveyorOper stand for elements, like a conveyor, that are used to handle orders/parts; queueOutOper, queueOutConveyorOper, queueOper stand for the elements from the order/part queue that are waiting to be received by the objects following the order element in the flow chart; Oper stands for capture elements for a set amount of resources for holding an order/part for the process period.

Incoming orders/parts join the queue following a certain order either under the FIFO rule or by priority. The priority status may either be stored in an order/part, or it may be calculated based on the properties of an order/part and on predefined external processing conditions. The model is capable of buffering orders/parts between any processing or handling objects, i.e., before an order/part has been handled (queueInput), between the input and output conveyors (queueOutConvOper), after the conveyor (queueOutConveyorOper), before an order/part goes into the machine (queueOper); OutConvOper and outConveyorOper stand for elements, such as a conveyor, used to handle orders/parts. The model contains two conveyors an input conveyor and an output conveyor, both are used at the processing area. Each of the two conveyors consists of two parts (inConvOper, inConveyorOper, OutConvOper, outConveyorOper) that are at 90° to each other. When implementing the simulation

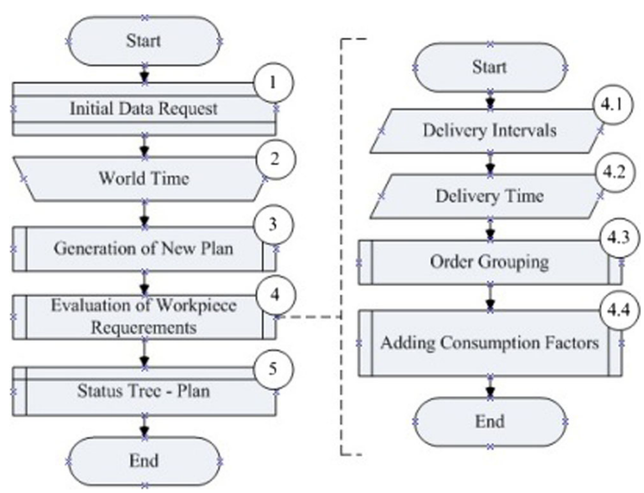


Fig. 9 Operations plan generation algorithm

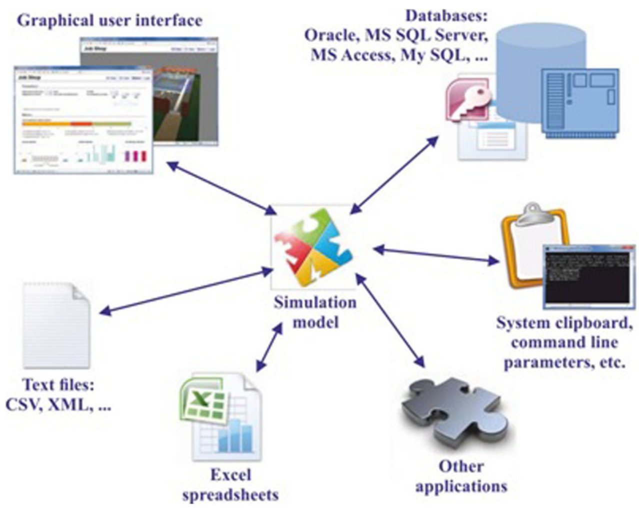


Fig. 10 Operations plan generation algorithm

model, a job site was created for demonstration purposes that contained 28 blocks implemented under Pic. 8b and 8 blocks implemented following the logic in Fig. 8a.

The operations planning module has the following business functions:

1. Import of the initial data for the current session based on the structure in Fig. 6.
2. Import of the initial operations plan with the changes from the original positions under the structure in Fig. 6.
3. Verification of the check values to make sure there occurred no distortions during the data transfer.
4. For an external information system, to determine, transfer and update the upper time estimate for an operations plan to be built.
5. To build a new operations plan.
6. To identify the workpiece requirements for the new operations plan.
7. To write the operations plan and the workpiece requirements in the database.

The module is based on the algorithm shown in Fig. 9.

Figure 9 contains the following designations: Block 1 is a request for initial values necessary to build a plan, the initial values cover all initial statuses of all the machines, ingredients and products at every moment of the previous (initial) planning period per the structure in Fig. 6.; Block 2 is for identifying the start point of the planning period for a new operations plan (the world time when the planning started for the current session plus the longest estimated processing time); Block 3 is for implementation of the resource distribution algorithm with regard to the world time stamp; Block 4 is for calculating the amount of workpieces required to realize the newly built plan; Block 5 is for preparation of a new status tree of the resulting plan based on the structure given in Fig. 6. The point when the planning period ended becomes available once the calculations are over.

The procedure for Block 4 comprises the action of assigning intervals of materials at a given site (Block 4.1), the action of determining an acceptable materials delivery time with regard to early deadlines (Block 4.2), the task of grouping orders by materials and by standard machine procedure (Block 4.3), as well as the action of determining the amount of materials required for each unit of the job site allowing for the consumption factor.

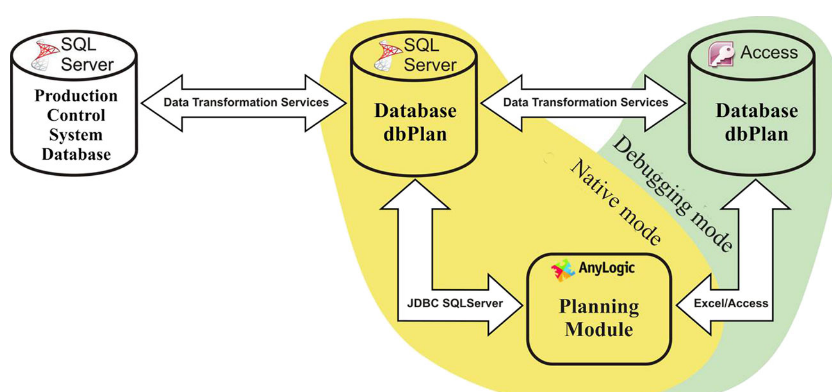
3.3 Business rules of the object

The module is controlled by an external information system (the external system is an initiator). The following conditions rule every session when the external system interacts with the module:

The module is waiting to receive data from the external system.

1. The external system prepares necessary initial data of the module.
2. The external system activates the module and transfers the data to it.
3. The module receives the data from the external system.
4. The module sends back temporary data on the calculation completion time.

Fig. 11 Interaction between planning module and database



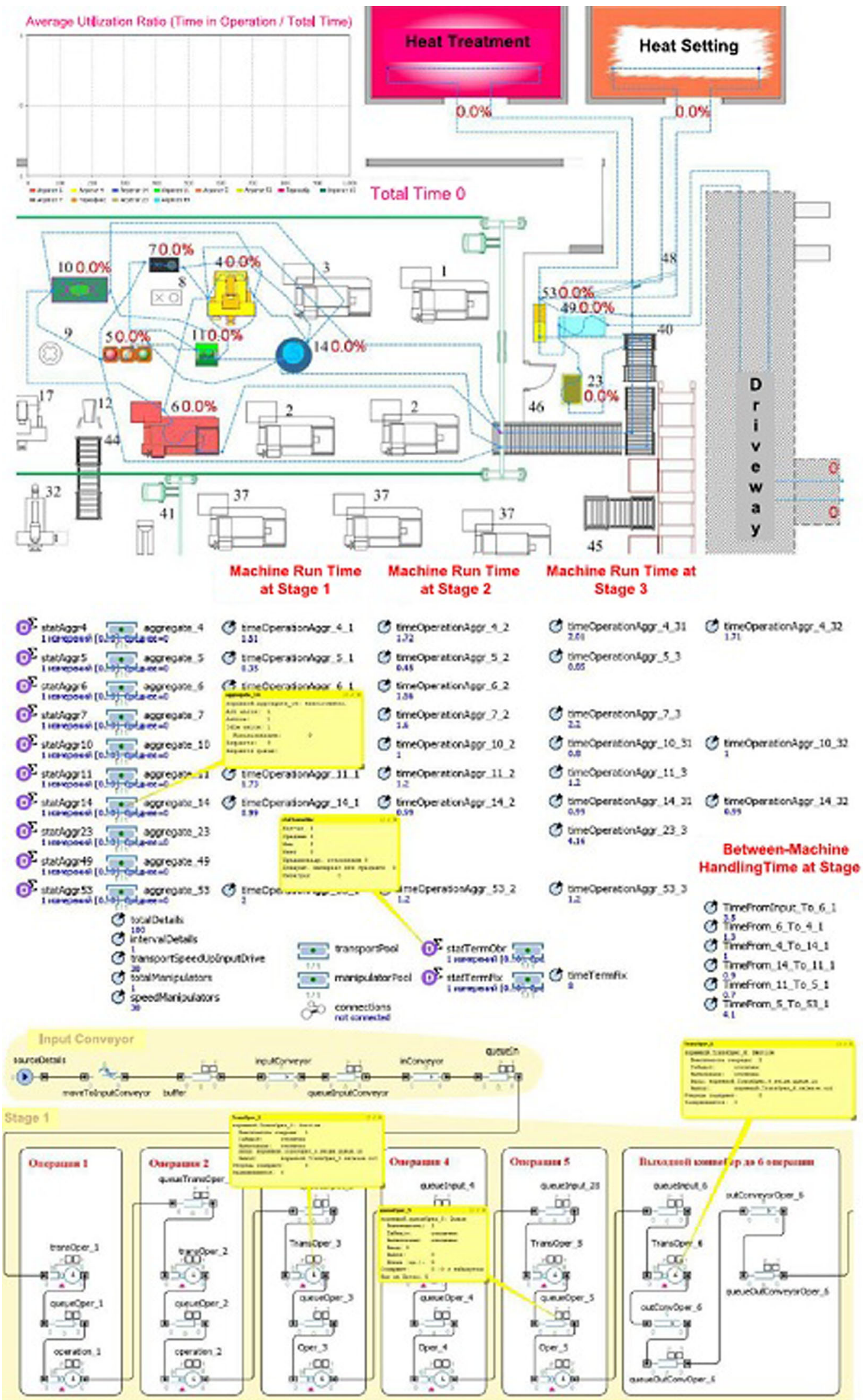


Fig. 12 How the job site looks in designer

5. The module calculates an operations plan within a set time.
6. If the calculation time did not exceed the set time, the module sends back the resulting data.
7. Otherwise, the module sends back an update on the calculation completion time.
8. The external system receives the data from the module.
9. The module switches to the waiting mode for data receipt from the external system.

The planning module is realized with the help of the simulation software AnyLogic. Possible interactions between the module and the external environment are shown in Fig. 10.

An option of interacting with databases is used for the module. The database object—an element of the AnyLogic simulation model which has a real database prototype and which ensures interaction with the latter—is used to connect the Module to the database.

Every module session is assigned a unique number, or a session key defined by the external system.

Data required by the module are transferred by the external system as data arrays containing the following details: a list of running equipment; a production rate of each unit; scheduled downtime; warehouse capacity; semi-finished product temporary storage time; specific limitations of the warehouse areas and the machines; product assortment; an order and duration of process operations for each product item; monthly production quotas by machine and by product; a workpiece arrival schedule (register); a portfolio of sales and site orders; critical planning rules.

A server is designed as a part of the production control system with data processed by the database management system. The planning module receives data from the external database and sends the result following the scheme in Fig. 7. Data required for plan calculation and the module calculation results are arranged in a stand-alone database referred to as dbPlan. Figure 11 shows how the external database, dbPlan and the planning module interact with each other. The interaction takes place in two modes. There is a stand-alone mode used to debug the module, and the main mode of remote interaction between the Module and SQL of the database server.

The data exchange between the Production Control System database, dbPlan and Access (DBMS) is performed by SQL Server DTS (Data Transformation Services).

3.4 Visualization of the project functionalities based on the anylogic simulation software

Visualization of the designed system functionalities was done with the help of an object-oriented model which was created using the AnyLogic tools. The project visualization included building a site map, introducing objects for the machines, defining the production flow, and assigning properties and methods to each object (Fig. 12).

The model parameters are set up in an interactive mode. The dialog window for defining initial parameters is given in Fig. 13.

The parameters include setting of the project execution rate, the number of manufactured parts, the workpiece arrival time, the transportation arrival rate, the number of

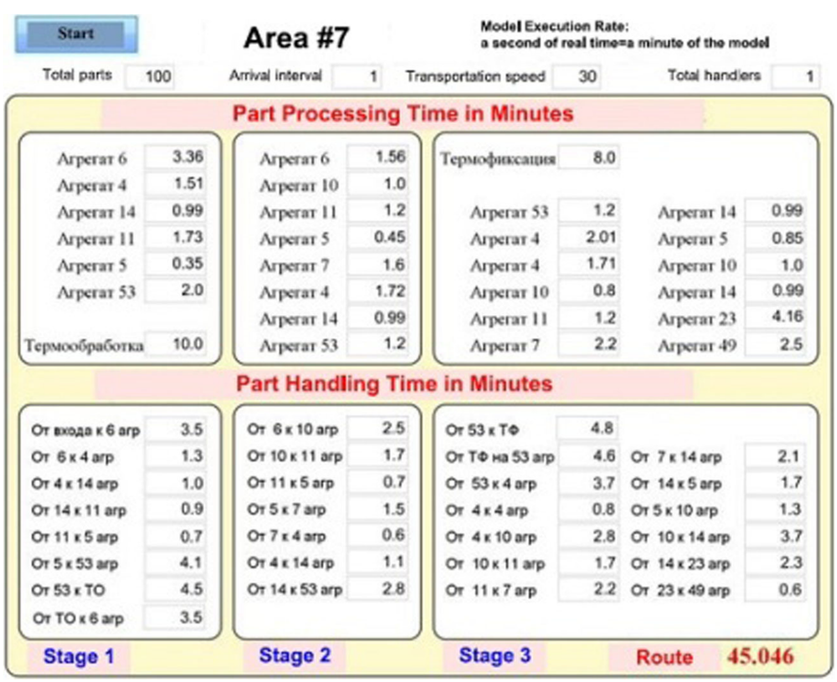


Fig. 13 Dialog view for setting the simulation model parameters

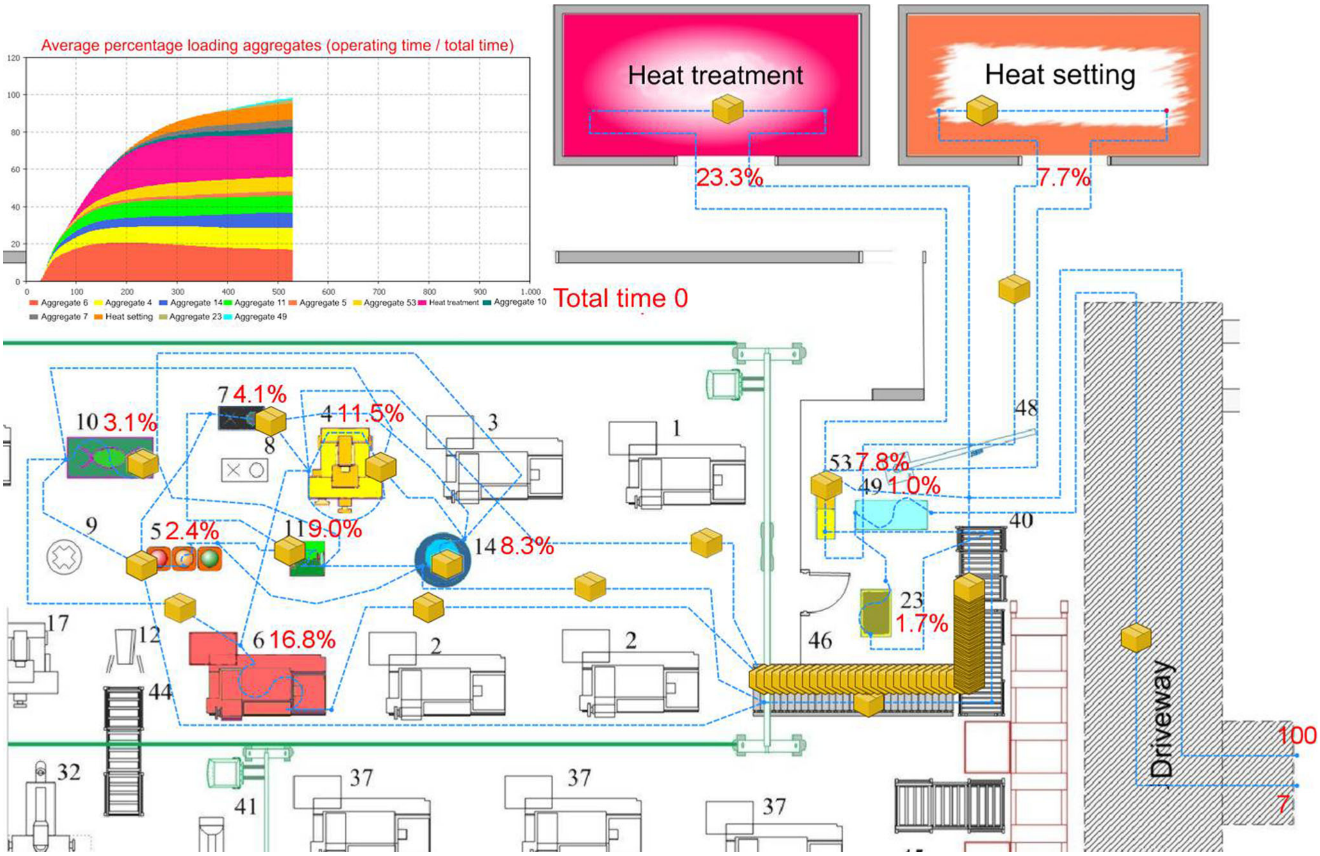


Fig. 14 Visualization of the job site

part handlers, an array of semi-finished product process time for each machine, and an array of workpiece handling time. Default parameters are set for the model start that are specified in Fig. 13.

Boxes are added in the job site work area to display statuses of each machine and indicate the percent of the task execution. There is also a graph showing execution of the overall task and individual machine tasks.

Figure 14 presents a final visualization picture of the job site in the order execution mode with default parameters which are taken close to the real values. Pic. 14 demonstrates how a queue is being formed at the input conveyor. There are no queues formed before the machines. Machine 6 (Fig. 14) has downtime intervals. Conveyor 46 is the only bottleneck of the site that determines the overall production rate. This bottleneck can only be eliminated by introduction of the second conveyor that would enable to separate new workpieces from the workpieces returning to the machines after the heat treatment and the heat setting operations.

4 Conclusion

Thus the authors of the paper:

1. Offer a sequence in which a production control system can be engineered, where new design stages are added which offer a better presentation of the project functionalities.
2. Built a simulation model of the process to demonstrate the project functionalities using the well-known software AnyLogic which allowed to offer to the customer a full graphic visualization of the process.
3. Identified bottlenecks of the new production site, which allowed to improve the detailed design of the job site.
4. Were implementing decisions and, at the same time, they were elaborating an RFP for an information system for an industrial plant.

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