DOI: https://doi.org/10.30932/1992-3252-2020-18-06-23

Verifiable Structure of Technological Processes in Dynamic 3D Models of Railway Stations

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ABSTRACT

The article is devoted to the study of technological processes at railway stations reproduced in a three-dimensional model from the standpoint of assessing reliability of the development of those processes. The identifiable simulated and virtual processes are matched against specific comparative positions. The benchmark is a fixed set of technological series of operations for processing wagon flows of all categories at a particular railway station.

To provide adequacy of model reconstruction to the prototype, the emerging waiting time and downtime of rolling stock are considered, which are introduced into the model as special split states of main spatial locations of rolling stock. The concept of «paraphysical structures» is introduced into the developed model of the station, which comprises any conditions impossible according to physical canons and irrational according to technological requirements regarding the objects of track development and rolling stock. The logic of program control over similar states of modelled structures is based on the analysis of the allowed positions of station objects when performing reference technological operations. Slowdown in station operations can be a forerunner to waiting or downtime.

An important methodological basis for the technique for developing a dynamic model of a station includes formation of a system of internal program analysis of the current situation, recognition of the moment of occurrence of a paraphysical situation and its anticipation by transforming it into normally developing standard situation. The adapting module of the information prototyping environment should be an intelligent agent with developed ability of generating exceptional situations based on comparative tests conducted by it, of developing an appropriate knowledge base and of using it in the process of further operations without any external users' participation.

The objective of the study, described in the article, is associated with development of general requirements for a dynamic model of a railway station, functioning adequately to a real technical system due to assessment of reliability of reproduced station technological processes.

Keywords: railway, 3D modelling, railway station, model validity criteria.

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Article received 09.04.2020, accepted 25.09.2020.

For the original Russian text of the article please see p. 6.

Background. Modelling the processes of processing wagon flows at a railway station with three-dimensional visualization of the technological operations performed is an effective direction of digitalization of traffic management. The implementation of algorithms for functioning of model objects, adequate to the physics of the processes of interaction between the track and rolling stock, as well as to the technology requirements not only in terms of external form, but also regarding internal properties, will allow creating a physical data model of a station [1; 2]. Since the reconstruction processes of changing the states of model objects are based on correct interpretation of the physical interactions of bodies, the entire modelling process results in consistent consequences that are adequate to real station events. However, the degree of reliability of the simulated states will depend on accuracy of simulation of influencing external forces, stresses, pressures, and efforts generated by them. With incorrect algorithms for replicating the operating conditions of existing objects, the model forms a world of interacting simulated images, somewhat different from the effects of action of real physical laws and technological requirements for the routine operation of a technical system. Such a simulation of reality is capable to dynamically develop and function under certain equilibrium modes of simulated processes [3]. However, incompleteness and inaccuracy of algorithmic replication of real processes will lead to simulation results that differ from the referenced ones. Therefore, it is important to determine the conditions for deployment of a model interpretation of processes, leading to consistent from the point of view of physics and technologically correct prototyping of station operations. The self-sufficiency of the model in this regard should be based on information procedures for self-testing of the states of objects that determine reliability of simulation processes based on appropriate comparative procedures.

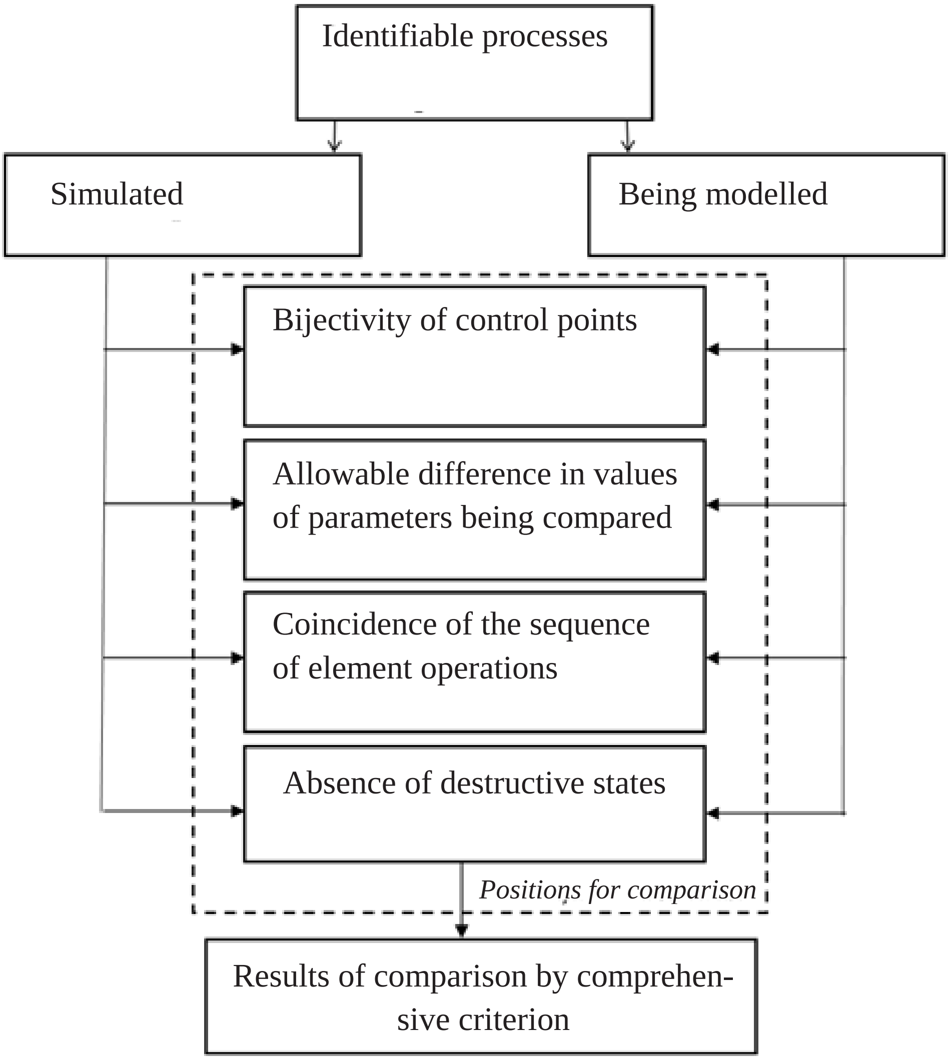
The *objective* of the research, described in the article, is to set positions for comparing model and prototype technological processes of railway station operations, determining the level of permissible deviations from the declared template and of updating data simulation when it goes beyond normal functioning of the station. The *method* of system analysis allows achieving this objective due to application of its principles of unity, hierarchy, and modularity.

Comparative positions of a model and a prototype

In case the control over the ongoing model changes is missing, an event world might be formed over time, which is less and less similar to the reality prototype. After some time, the simulated (imitating real) and modelled (being the prototype of the model) processes will differ by certain observable and recorded features. For example, modelling the operation of disassembling trains at a marshalling yard can lead to appearance of specific visual effects due to inaccurate or incorrect interpretations of the features of the technology for disassembling trains (a constantly high speed of pushing trains to the hump will cause a gradual increase in speed of movement of uncoupled wagons (blocks of them) along the incline of the hump, that will in turn make newly uncoupled wagons catch up with previously uncoupled ones, and will result in impossibility of setting switches to guide groups of wagons to different tracks of the marshalling yard; humping of uncoupled blocks of wagons that need further pushing for compression might cause collision of tanks with explosive cargo, leading to difficult-to-simulate emergency conditions; frequent release of uncoupled blocks of wagons of disassembled train from the hump to the marshalling yard tracks with overrated wagon speeds might lead to damage to cargoes and wagons with difficult-to-reconstruct model states).

Therefore, it is important to highlight the positions for comparison regarding techno logical operations in which certain objects are involved, which will make it possible to compare the simulated process and the process being modelled (Pic. 1).

The comparison is supposed to be carried out based on a standard (reference benchmark) which is a certain stipulated technological process of processing wagon flows at a real railway station, with which similar model operations will be compared. The states of the model objects participating in such a technological process can be monitored by the moments of completion of individual operations (arrival of a train at the station, securing the train on the receiving tracks of the marshalling yard, wagon unloading).



Pic. 1. Positions for comparing model processes with real processes (compiled by the author).

The model state is always fixed as a static frame of some executed operation. This frame is stably kept unchanged for a certain time, dictated by the technological process of processing wagon flows. Such a time delay is observed in real processes and is associated with waiting for the next operation to be performed (for example, for a train on the departure tracks park it is waiting for assigned time within departure schedule to go to the main railway track, for an unloaded wagon it is waiting for a shunting locomotive that will remove the wagon from the track intended for unloading). In this case, there comes a certain break in the change in the states of objects, which during the previous phases have moved to other spatial positions associated with movement of rolling stock along the tracks, deformation of the track superstructure under the influence of weight of the wagon or stresses in the rails due to the shock effect at the joints.

When matching processes, it is important to ensure that the condition of bijectivity (unambiguity) of initial comparative positions for real and model objects is met. In this case, certain difficulties may arise due to the incomparability of the achieved states. For example, operation of disassembling trains at a marshalling yard starts with pushing of a train over the hump after a shunting locomotive has been coupled. But the coordinate positions of the coupling points of locomotives on the receiving tracks do not coincide for real and model situations due to previous inaccuracies in consideration of various factors that

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influenced the assessment of the speed of model objects. However, if the magnitude of the difference in positions of points of the locomotive of the simulated image and of the prototype does not exceed the limits of the scatter of these values for different trains with the same number of wagons received at the station and for receiving and departure tracks with a commensurate length, then we can assume that the initial positions are identical. In this case, the coordinate positions of the model locomotive with such a difference constitute a control point for further referencing of the simulation results.

The values of such important considered characteristics as speed of movement of uncoupled blocks of wagons when rolling down a hump, loading time for wagons at the cargo terminal, duration of movement of locomotives supplied to the train along the route to the train, etc., may be different for compared positions for the model and the standard. In this case, it is also necessary to evaluate the model deviations and decide on acceptable fluctuations in the results of replication of technological processes within the variability zone.

The coincidence of the sequence of element operations for the simulated process and the process being modelled also constitutes an important point of comparison. For example, a weighing operation is required after loading a grain-hopper wagon, which, depending on design of the wagon scale, is performed in various ways: by pushing the wagon onto the scales with or without uncoupling, with a stop on the scales or in motion. In the model representation, the weighing of the wagon can be determined by a single generalized scheme of moving the rolling stock through the scales, the total time is equal to the technological time for the full cycle of this operation. When simulating such and similar operations, the question arises about the degree of specification of the corresponding process, reflecting significant links with prototype technology. Therefore, the model allows the convolution of insignificant operations, which ultimately leads to an increase in duration of some integrating circuit, which includes micro-operations hidden from visualization without loss of design quality and any impact on the modelling goals.

If a model technological operation is performed with violations of the physics of processes or requirements of the technology, then a destructive event[1] may occur. When simulating the operation of a railway station, states should be considered destructive if they lead to:

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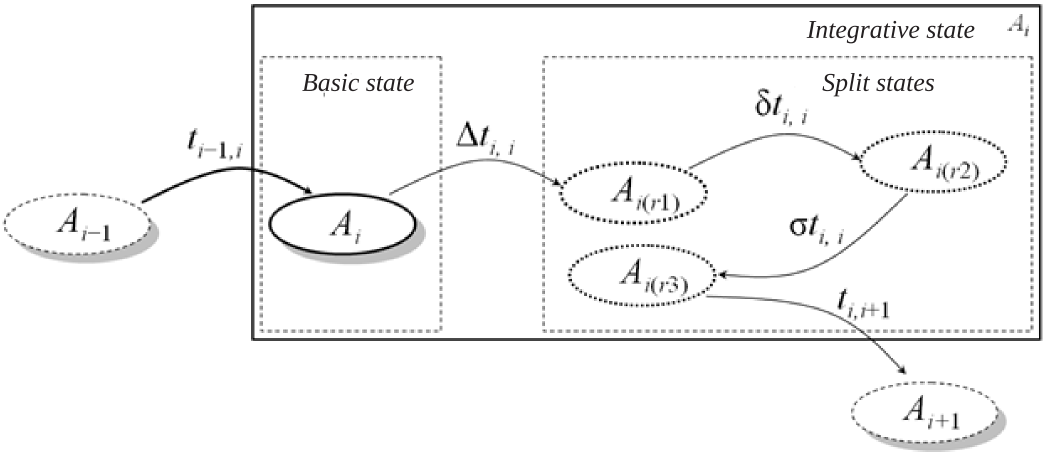
[1] The author in the original Russian text introduces a new, not previously used, term that can be literally translated as a noun «destruct». That is not equal to term «destructor», but makes allusion to antonym to the term «construct» used in programming. – *Ed. note.*



Pic. 2. The relationship between the basic and split states (compiled by the author).

– emergence of paraphysical structures that are not observed in the real environment (for example, a long separation of wheels of a rolling stock from the movement supporting plane; loading of bulk cargo into a wagon under a slope angle sharply different from the natural one);

– performance of operations with characteristics prohibited by technological requirements (speed of movement of uncoupled block of wagons at the hump decline exceeds 30 km/h; time for unloading oil products from the tank is 10 hours; height of the rolled metal stack in the warehouse is 5 m);

– violation of traffic safety standards (excessive gap between the point and the frame rail of the turnout switch; false information on the free track; collapse of cargo on open rolling stock);

– negative consequences of violation of safety standards (derailment or collision of rolling stock).

It should be noted that modelling of technological operations with hazardous conditions has a wide capacity of incorrect development and completion of simulated processes. However, these opportunities are specific and associated with development of special catastrophe (accident) modelling in which such states are allowed [4].

Thus, comparison of the model process and the process being modelled according to the corresponding positions of comparison (see Pic. 1) will allow controlling development of the model within a certain range of allowable deviations from a typical technological process.

Such a model approach is borrowed from real technical systems, where further development of a process is predetermined by specific goals of achieving the required state. If, at the moment of completion of a certain operation, a significant deviation of the control parameter is diagnosed, then the appropriate system resources will be provided to implement measures leading to the normalised value of the control parameter at time of completion of the next operation. For example, if normal time spent by a local wagon at a railway station is significantly exceeded, measures will be taken to accelerate supply of rolling stock to loading and unloading points.

Such an impact on the dynamics of development of processes also makes it possible to modify the trend lines of model events with an incorrect description of processes towards their compliance with the observed consequences of the action of the laws of physics and the technological requirements.

Modelling the state of station objects considering waiting time and downtime

Let O_i be an elementary operation performed at the station (for example, securing the train on the receiving track); $t_{i-1,i}$ – time of transition to this state; O_{i+1} – next elementary operation, which occurs after a certain time interval $t_{i,i+1}$ (for the given example, this is time of the train dissembling). In addition to duration of the main transition time to a new state, the model introduces possible additional waiting time $\Delta t_{i,i}$, associated with other operations preceding O_{i+1} (for example, movement of a shunting loco-

Table 1

Relationships of operations, attributes, and states of station objects

Types of operations	Nature of changes	
	attributes	state
A	all of them change	changes
B	some of them change	does not change
C	time of stay in the current state increases	does not change

Compiled by the author.

motive to the train, the release of the exit route from the reception tracks to the hump). In addition, beginning of the execution of O_{i+1} can be delayed by time $\delta t_{i,\,i}$, providing a certain systemic effect (for example, waiting for a shunting locomotive to be delivered on the receiving tracks due to the need for this locomotive's operation in the marshalling yard to assemble a train), but also considering uproductive downtime $\sigma t_{i,\,i}$, which for real railway stations is, as a rule, a consequence of the human factor impact. Thus, duration of the transition to a new state of the railway station facility is determined by the required technological time and possible additional waiting time:

$t_{\text{trans}(i+1)} = t_{i,\,i+1}\ (+\ \Delta t_{i,\,i})\ (+\ \delta t_{i,\,i})\ (+\ \sigma t_{i,\,i})$.

As a rule, normal development of the process requires new transitions without any time delays ($t_{\text{trans}(i+1)} = t_{i,\,i+1}$).

Any state of an object is characterized by a certain set of attributes. The transition of an object to a new state is accompanied by a change in these features. Time spent in this state is the main attribute of the object. In certain cases, an object, being in this state, can undergo attributive changes. For example, a rolling stock stationed on the receiving tracks undergoes technical and commercial operations, while remaining in the same spatial position.

The transition to a new state is considered as the execution of the next operation within the technological cycle and arises as a result of some external influence on the object, leading to a change in its position. In the absence of such an impact, the object is waiting for the next operation. In this state, this object changes some of its properties (in particular, total duration of stay in the achieved state). Therefore, waiting is considered as a conditional transition to a quasi-state close to the current state, but insignificantly changed. In this case, a kind of *splitting* of the achieved state A_i into the series $A_{i(rj)}$ occurs (Pic. 2).

For the example shown in Pic. 2 when the train is on the receiving tracks (basic state), a transition to several split states, which do not lead to a change in spatial position, is possible under the following influences:

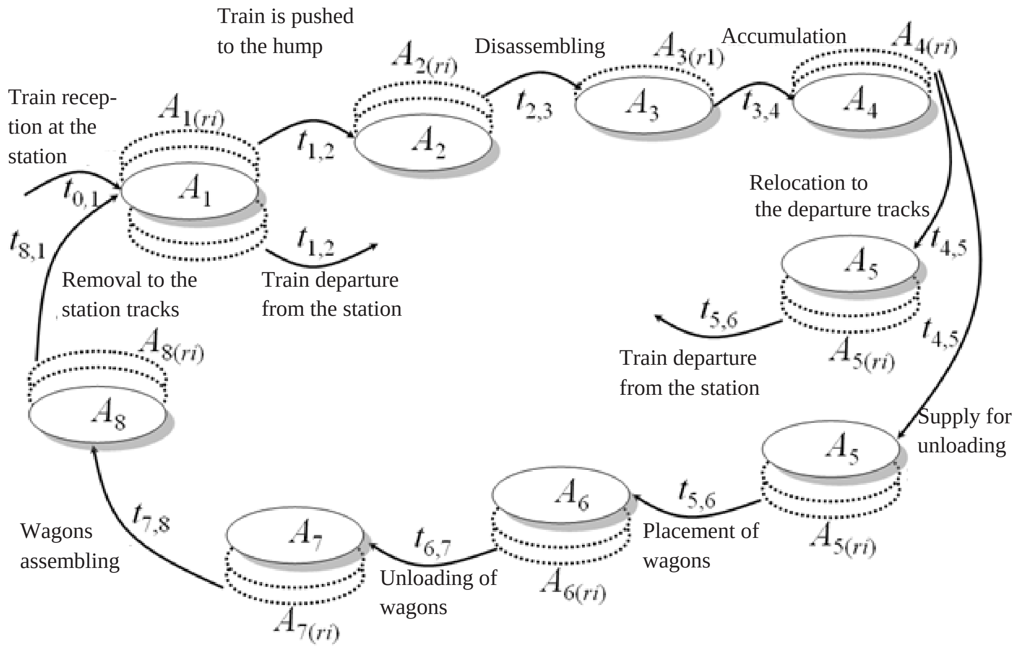
– $\Delta t_{i,\,i}$ – performance of the operation of technical inspection of wagons while the train is on the receiving tracks in a position secured by brake shoes. As a result, a transition to some split state $A_{i(r1)}$ occurs;

– $\delta t_{i,\,i}$ – supply of the shunting locomotive after pushing wagons for compression in the marshalling yard, which makes waiting for the train on the receiving tracks with the transition to another split state $A_{i(r2)}$ associated with the basic one;

– $\sigma t_{i,\,i}$ – unproductive time losses associated with other causes (for example, failure of the modelling system due to a dangerous failure) that arose after completion of the technical inspection operation and contributed to the transition from $A_{i(r2)}$ to another split state $A_{i(r3)}$.

Such split states $A_{i(rj)}$ are forms of existence of the integrative basic A_i and, in fact, represent positions that do not qualitatively differ from the basic state that has given rise to them and are in the region of its gravitation, since they are characterized by a slightly changed set of attributive parameters. Therefore, all quasi-states $A_{i(rj)}$ of a single A_i are considered as functionally related to it, forming a group of energy harmonics, which become starting ones during the transition to a new state A_{i+1} (for example, in Pic. 2 it is the dissemblance through the operation $t_{i,\,i+1}$ of pushing the train to hump).

Thus, waiting periods and downtime are also operations, since they lead to changes in the properties of an object, increasing the time it spends in a given state. All types of operations are due to the technological process and contribute to achievement of the main targets set for functioning of the technical system (safety of the transportation process, safety and security of goods and rolling stock, high-quality



Pic. 3. The structure of model operations of a simulated section station (compiled by the author).

satisfaction of requests from consumers of transport services, etc.). In this regard, waiting and downtime perform an important systemic function of the expedient interaction of the technological community of objects, levelling speed of individual operations regarding interrelated results, which are reduced to the single time of their achievement. The system strives to achieve the goal in the most efficient way with the minimum expenditure of resources. Therefore, waiting is a systematic measure of the economical use of all station resources, which allows getting a result with a minimum total cost.

Waiting time differs from downtime by the linkage to technological expedience. In case of waiting, the transition to the next operation is delayed due to the overall cost savings for the entire chain of operations of the corresponding process. Downtime occurs in operation of a real system and is associated, as a rule, with the mistakes of decision-makers. In the station model, downtime can be considered as a software ability to stop the timer to solve problems that go beyond simulation goals (for example, analysis of the achieved state of the model to assess effectiveness of the algorithm of its operation or stopping the functioning of the model due to a software failure).

Of all the possible transitions (operations), three types can be distinguished:

– operations unconditionally transferring the object to another spatial state (removal of wagons from the access track after unloading) (type *A*);

– operations fixing this spatial state for carrying out other routine operations (commercial and technical inspection of the train after securing it on the reception tracks; uncoupling of wagons with pushing them to the hump) (type *B*);

– operations holding the achieved state (waiting time and downtime of rolling stock) (type *C*).

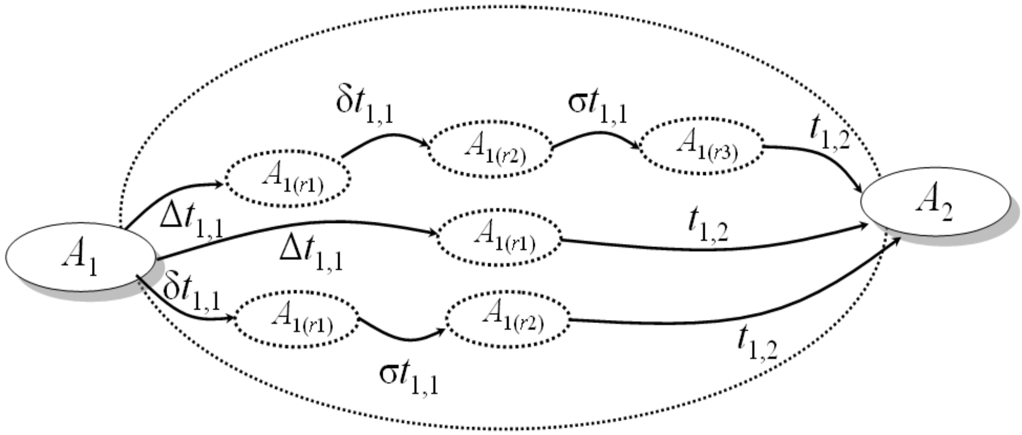
The characteristics of these operations are shown in Table 1.

Model reconstruction of technological processes at the station

Let us identify technological operations performed at the railway station and subject to model reconstruction. The consolidated generalized list of these operations includes those that lead to a change in the spatial position of rolling stock units:

– reception (departure) of the train (delivery) to the station;

– uncoupling (coupling) of wagons from the train (delivery, supply);



Pic. 4. Relationships of states A_1 and A_2 through $A_{1(rj)}$ (compiled by the author).

– disassembling the train (delivery, supply);

– accumulation of the blocks of wagons of a train (delivery, supply) on the sorting (sorting-departure) tracks;

– supply (removal, rearrangement) of the train (delivery of a group of wagons, of a wagon);

– loading (unloading, reloading) of a delivered wagon;

– arrangement (assembling) of a delivered (transferred) train.

Using this listing, it is possible to compile a necessary list of the technological construct of the objects of the model environment. Let the graph of states and transitions shown in Pic. 3 be implemented for the model of a local station.

The given graph of states of rolling stock objects allows us to simulate the technological processes of processing various categories of wagon flows: transit without processing ($t_{0,1} \rightarrow A_1 \rightarrow t_{1,2}$), transit with processing ($t_{0,1} \rightarrow A_1 ... A_5 \rightarrow t_{5,6}$), and local wagon flow ($t_{0,1} \rightarrow A_1 ... A_8 \rightarrow t_{8,1}$). Any basic state A_i goes over to A_{i+1} through a whole series of split states $A_{i(rj)}$ due to different waiting situations. The number of split states differs for different A_i basic positions. For example, when a train is disassembled on a hump, there may be a stop of dissembling (a split state $A_{3(r1)}$), which leads to waiting and a corresponding increase in time spent in this state. In other cases, waiting arises due to the influence of a number of causes of different nature, and this determines formation of a spectrum of split states inheriting each other (Pic. 4).

Pic. 4 shows three possible variants of intermediate split quasi-states of the transition from A_1 to A_2.

Process modelling quality assessment

Before performing the subsequent operation O_{i+1}, the compliance of the achieved state of the objects that will participate in this operation with the requirements of the technological process is checked. The development of the model reconstruction correlates with the current operational state (loading of the elements of station subsystems, the schedule for arrival and departure of trains, planning of local operations). If, at the moment of model time t_k, transition to new states is expected for several technological operations involving different station facilities, then the value of the corresponding estimated function of losses from waiting is calculated for all variants of distribution of available resources between the declared operations. The list of distributed resources includes shunting locomotives, wagons, yard tracks, station routes of movement, loading and unloading points, train departure schedule from the station. As a result of comparing various options for transition to a new state A_{i+1}, the most cost effective one is determined with formation of a corresponding set of quasi states $A_{i(rj)}$, containing waiting time from the set $\{\Delta t_{i,i}, \delta t_{i,i}, \sigma t_{i,i}\}$. A similar calculation is performed for all objects of the station transforming into new states at the time of deployment of the model situation t_k.

The reliability of prototyping is assessed by the calculated value of the index using a scale of signs indicating the probability that simulated processes will go beyond the border of allowed requirements. When the values of that probability are exceeded, a system of stimulating influences is developed, correcting the consequences of the influence of factors that are capable to incorrectly determine the subsequent model states.

The scale of signs responsible for development of the process of a given operation, being also potential sources of erroneous model interpretation, is formed for all events that occur with objects during the specified operation. Thus, the next operation is carried out within the model after assessing the compliance of the achieved states of objects with the requirements stated in the features of the corresponding scale.

It should be noted that not all station operations are considered potentially simulated. The list of simulated technological operations of a 3D station (see Pic. 3) does not include *parastructural* ones, which are difficult to be modelled, and their exclusion from a simulation does not lead to a loss of quality of naturalization of technological processes. Parastructural operations include the previously classified type *B* of fixing operations and some others (weighing wagons, wording and transferring documents between station departments, rolling stock maintenance and repairing). Visualization of these operations within the model is associated with the recreation of avatar images of technical employees involved in station processes. These algorithmically time-consuming computer procedures define the general realistic background of the dynamic 3D station model. Detailing the model towards visual reconstruction of processes based on parastructural operations develops a prototyping environment with deep cause-and-effect relationships of objects. In the author's opinion, this is the level of structural stratification of model constructs with formation of supra-technological process compositions that go beyond redistribution of factor variations (for example, determining the level of professional qualification of a userpic analogue of a particular employee of the technical department). Thus, it seems possible to create *paratechnological* models with goal-oriented stimuli of object systems that have motivational and behavioural properties inherent in socio-oriented information systems.

Conclusions.

Thus, it is possible to develop an information environment for modelling station technological operations with visualization through a three-dimensional representation of all spatial changes associated with movement of rolling stock along the tracks of the station. The execution of each subsequent technological operation is preceded by an analysis of the achieved state and construction of a plan for further work by finding a rational option for the use of available resources distributed between the planned operations. Such a computer dispatcher compares the rate of operations performed with achievement of the maximum result, expressed by a certain loss function, leading to additional waiting time when performing technological operations.

Beyond technological waiting time, an unproductive downtime $\sigma t_{i,i}$ is introduced into the station model, which in real operating conditions is interpreted as the result of unproductive work of the management employees who have insufficient qualifications or is associated with other features. In the digital analogue of the prototyped station, this component is not yet tied to a specific model situation, but in the future it may be used to develop a more efficient and, at the same time, more realistic dynamic model of a railway station.

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