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ORIGINAL PAPER
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CONTROL OF TECHNOLOGICAL PROCESSES USING A FUZZY CONTROLLER OF THE SYSTEM FOR MANAGEMENT OF CARGO DELIVERY BY RAILWAY

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ABSTRACT

Motives: One of the final indicators of service reliability of the transport system is the cargo delivery time, compliance of which is not yet controlled due to the lack of appropriate methods and tools of operational management. The concept of quality of assessment of cargo delivery, namely the reliability of compliance with the time obligations by transportation participants, is associated with the process modeling and the accuracy of determination of the estimated time of completion of each stage of the technological process of cargo delivery.
Aim: The purpose of the study is to present the model of a fuzzy controller as a principle of forming of a railway process management system, which is based on the possibility to operate with linguistic representations of elements.
Results: A new solution to an important problem is obtained – the formation of managerial influence using a fuzzy controller for management of technological processes of cargo delivery by rail at the current level of requirements for the efficiency of transportation organization. The usage of the offered method provides a solution to the problems of operational control practice in the formation of tools for operational control of technological processes for the railway dispatcher unit.

Keywords: transport system, delivery time, cargo, client-oriented approach, management of technological processes, fuzzy controller.

INTRODUCTION

One of the solutions to the problem of management of technological processes on the railway is to determine possible deviations from the standard time of the state and operations with objects managed by dispatcher units in order to take timely measures to reduce possible losses. The dispatcher unit is often forced to make decisions in unexpected situations and in conditions of uncertainty. On the other hand,

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compliance with cargo delivery time is one of the most important requirements to the operation of the transport system. In paper [Gruntov, 1986] it is noted that one of the final indicators of service reliability of the transport system is the cargo delivery time, compliance of which is not yet controlled due to the lack of appropriate methods and tools of operational control. The author of the paper states that the available technologies do not allow to ensure the accuracy of cargo transportation [Prokhorchenko, 2016].

It should be noted that real operational situations differ significantly from those taken into account when drawing up the long-term regulatory and technological documents [Levin, 2018]. The operational management unit analyzes events that have already occurred and makes decisions using experience and intuition.

At the same time, a significant number of transportation participants, which we have now, and an increase in their number in the future, make it necessary to accurately comply with the standards of technological processes. In order to implement technology management and to make a decision, the dispatcher unit needs a forecast, because the events that have occurred can be only analyzed [Petrashevsky, 2006, pp. 53–58, Kozachenko et al., 2016, pp. 39–47]. Brandimarte and Zotteri in their paper [Brandimarte & Zotteri, 2007, pp. 342–343] indicate the need for accurate forecasting of time points; they are interpreted as "transit points" (LTg), which is necessary especially in complex material management models in multi-echelon delivery chains. The researchers present a classification of prediction methods by classical statistical methods for modeling freight delivery processes. The decision-making process of the dispatcher, in turn, requires information support for obtaining managerial influence on the implementation of operations and stages of the technological process. At the same time, deciding on the most efficient operation of the transport system, the choice of optimal delivery technology from a variety of alternatives should be carried out using optimization models noted in [Hammadi & Ksouri, 2013]. Multifactor models which take into account the characteristics of the transport process and the availability of constraints allow for operational control in real-time and coordination of the delivery process participants in the innovative transport system [Bobrovskii et al., 2014].

The modern market principle of client-oriented approach also provides for the delivery of cargo on time. In a number of special issue papers [Karimi et al., 2015], the authors cite the view that, complex logistics processes and supply chains are among the most important activities in the modern society economy in recent years. They are affected by rapid changes in consumer demand, changes in orders, transport and communication stoppages, and the like. The supply chains are considered [Zhixiang & Svenja, 2014], taking into account social and environmental components.

The authors of the book [Teodorovic & Janic, 2016] define the central problem of transportation network development as a lack of integration between transportation modes and methodological approaches, and, in their work, do not draw any dividing lines between modes of transportation, the authors use essential common topics such as "traffic flow", "capacity and level of service", traffic control, transportation planning, and environmental impacts. In this aspect of the problem under consideration, it is especially important to predict the time of the transfer of goods from one mode of transport to another and compliance with time requirements. The concept of quality of assessment of cargo delivery, namely the reliability of compliance with the time obligations by transportation participants, is associated with modeling of the process and the accuracy of determination of the estimated time of completion of each stage of the technological process (TP) of cargo delivery. Obviously, the control of transportation time is the main factor in the management of technological processes, including the cases, when several subsystems interact, the way this happens at ports, on the borders of countries, or when railways and powerful industrial enterprises cooperate [Levin, 2020, Gapanovich & Shabelnikov, 2010, pp. 23–25].

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LITERATURE REVIEW

The papers [Strelko et al., 2019b, Butko et al., 2019, Strelko et al., 2019a, Babyak et al., 2020, Strelko et al., 2020] study the indicator of the assessment of operational deviation by stages of transportation and that allows us to numerically estimate the degree of implementation of technological processes occurring in cargo transportation, and the quality of management of cargo transportation by rail. TP performance assessments are provided to dispatcher's unit in real time using linguistic definitions of transportation conditions to make managerial influence and monitor the implementation of rolling stock performance indicators. Authors of the papers [Strelko et al., 2019b, Butko et al., 2019, Strelko et al., 2019a] offer to accumulate data on the transportation process, including data on deviations from the estimation in the existing information base to control the adequacy and evolution of the model. German scientists [Haehn et al., 2020, pp. 1611–1614] use probabilistic methods to minimize spreading of initial delays that occur at the train departure. Secondary delays occur due to conflicts with the schedules of other trains. The method offered in this paper increases the stability of the train schedule, but does not solve the problem of management of the technological processes of current operational work.

MATERIALS AND METHODS

Thus, the compliance with TP standards may not be a priority task of the dispatching management system due to the lack of methods and tools for processes execution control. This creates the need to develop new methods and algorithms for obtainment of a management decision for the implementation of operations and stages of the technological process and to develop a tool for solving the problem of transportation technology management. At the same time, it should be taken into account that transportation processes are characterized by such properties as uncertainty, randomicity and irregularity. The traditional mathematical language based on theory of sets and two-valued logic is not sufficiently adapted to describe such uncertainties [Sergin, 2004]. Therefore, we will consider the possibilities of solving TP management problems by means of mathematical modeling of processes with uncertainty using the concept of fuzzy sets [Grigorak & Savchenko, 2015, Danko et al., 2008].

Purpose of the study is to present the model of a fuzzy controller as a principle of forming of a railway technical process management system, which is based on the possibility to operate with linguistic representations of elements.

RESULTS

In order to form a management system for technological processes at the railway, the following actions were carried out:

1. The structure of the fuzzy controller was developed.
2. The methodology for management of the technological process was developed.
3. The methods for construction of all elements of a fuzzy controller are described.
4. The simulation of TP with (and without) fuzzy control was performed.
5. It was shown that setting the fuzzy controller allows to bring the objective function closer to the optimal value and to improve the TP, including within the frame of management of the delivery time.

Further the structure of the fuzzy controller was studied as part of circuit of the transportation process management within the consideration of the indicator "Cargo Delivery Time" (Fig. 1).

To manage the process, it is necessary to synthesize a fuzzy controller based on data on the actual cargo delivery process. The information system shall contain the following data for the previous period, as shown in Chart 1.

Statistical parameters:

– Minimal delivery time: 25.00 hours;
– Maximal delivery time: 63.50 hours;
– Average delivery time: 34.98 hours;
– First, second (median) and third quartiles: 32.66, 34.36 and 36.34 hours accordingly.

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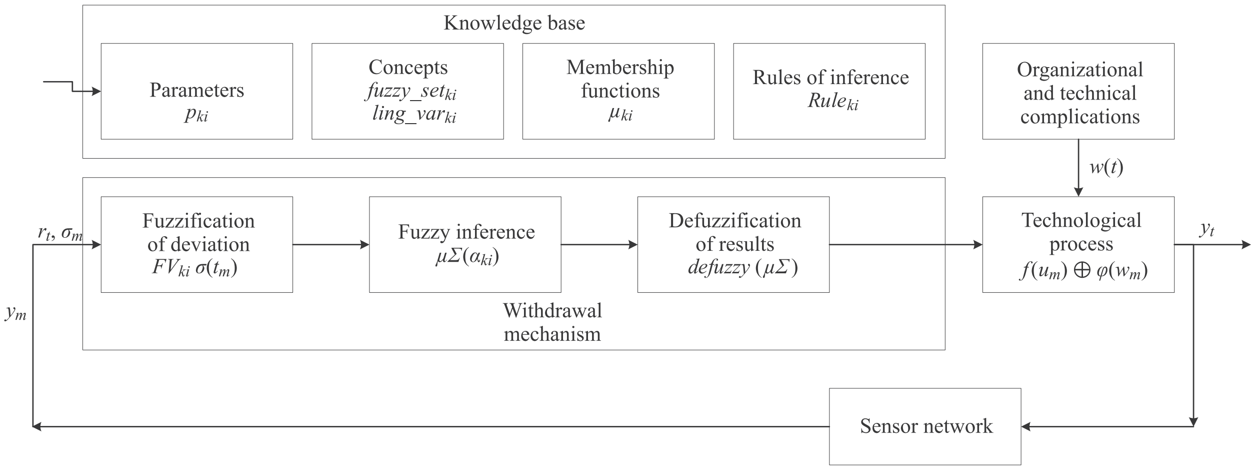

Fig. 1. Circuit of the fuzzy transportation process management
Source: own elaboration.

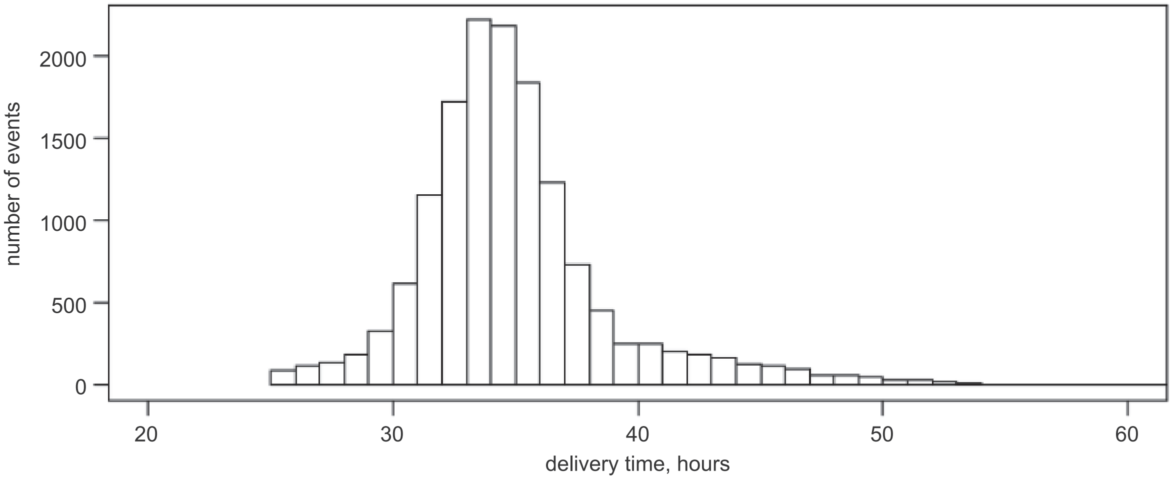

Chart 1. Data on cargo delivery time
Source: own elaboration.

The same data in the form of deviation from the schedule is shown in Chart 2.

Statistical deviation parameters:

– Minimal deviation of delivery time: -9.98 hours;
– Maximal deviation of delivery time: 28.53 hours;
– Average deviation of delivery time: 00.00 hours;
– First, second (median), and third quartiles: -2.32, -0.62, and 1.36 hours accordingly.

Let us accept the universe – the range of deviation values that can occur in the operation of the system: for example, U = [-15 hours; 30 hours].

We introduce concepts for estimations of the current state and fuzzy values that correspond to them:

1. Approximately on time, let's mark it as SV;
2. Delay approximately:
   a. for 1 hour – Z1;
   b. for 2 hours – Z2;
   c. for n hours – Zn;
3. Arrival ahead of schedule approximately:
   a. 1 hour ahead – V1;
   b. 2 hours ahead – V2;
   c. n hours ahead –Vn;

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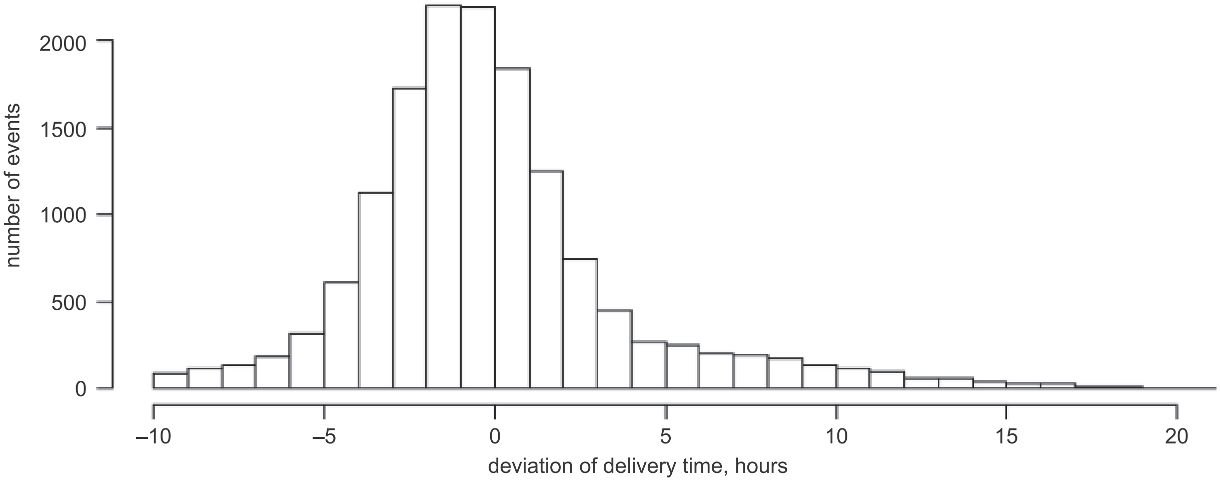

Chart 2. Deviation in cargo delivery time
Source: own elaboration.

We introduce concepts for estimations of the target state and fuzzy values that correspond to them:

1. Approximately on time delivery, we will mark it as G0;
2. Delivery behind the schedule, approximate delay on:
   a. for 1 hour – GZ1;
   b. for 2 hours – GZ2;
   c. for n hours – GZn;
3. Delivery ahead of schedule, approximate early arrival:
   a. 1 hour ahead – GV1;
   b. 2 hours ahead – GV2;
   c. n hours ahead – GVn.

We introduce, for example, triangular membership functions for fuzzy input and output functions.

Chart 3 shows examples of membership functions for input variables SV, Z1, Z3, and V4.

The membership functions of the input and output variables are constructed in the same way for the entire universe U = [-15; 30] (Chart 4). In this case, they are a topping of triangular functions with a base length of 2 hours, constructed for all possible (according to our assumption) deviations in the delivery time.

Inference rules can be formed in the form of productions:

IF the deviation is State THEN the goal is Goal

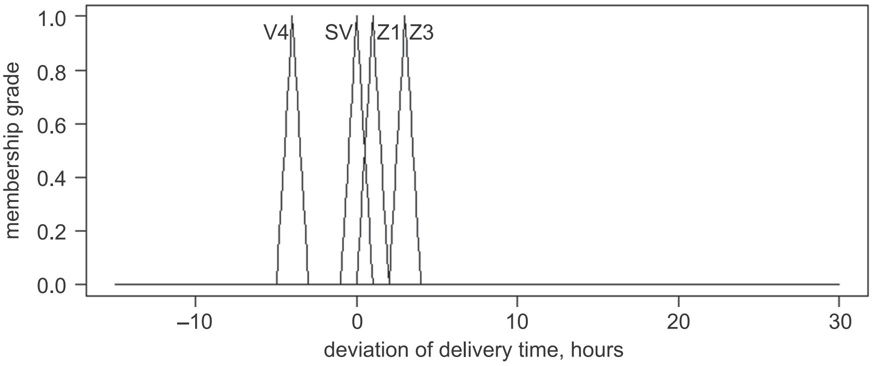

Chart 3. Graphic representation of four membership functions
Source: own elaboration.

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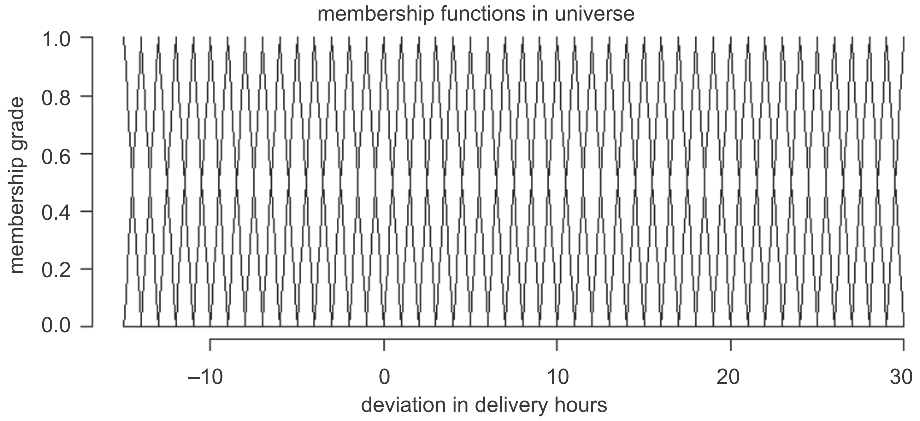

Chart 4. Membership functions over universe U = [-15; 30]
Source: own elaboration.

For example:

1. IF the deviation is SV, THEN the goal is G0;
2. IF the deviation is Z1, THEN the target is G0;
3. IF the deviation is Z2, THEN the target is GZ1;
4. IF the deviation is Z3, THEN the target is GZ2;
5. IF the deviation is V1, THEN the goal is G0;
6. IF the deviation is V2, THEN the target is GV1;

Rule 1 prescribes not to change deviations, that is, to perform work at a planned pace.

Rules 2–4 provide for reduction of delay by about one hour, that is, they require completing tasks at an accelerated pace.

Rules 5–6 provides for reduction of the arrival ahead of schedule by about one hour, that is, they require completing tasks in a slower pace.

The same rules can be presented in the form of a table 1.

Table 1. The inference rules

Input value	*V2*	*V1*	*SV*	*Z1*	*Z2*	*Z3*
Target value	*GV1*	*G0*	*G0*	*G0*	*GZV1*	*GZV2*

Source: own elaboration.

The considered components "Knowledge Base" make up the content of the blocks "Parameters", "Concepts", "Membership functions" and "Inference rules", respectively, and can vary or be supplemented depending on the specific aspects of the control task.

The mechanism of inference of fuzzy rules on sets in production form implements Mamdani Fuzzy Inference (algorithm of Mamdani Fuzzy Inference) with implementation options determined by the applied t-norms, t-conorms, defuzzification methods, and so on.

The problem of process identification is solved at the stage preceding the estimation of the values of simple statistics (such as the average value, median, standard deviation, percentiles, etc.) since it involves identification of the actual adequate statistical scheme or process model.

Chart 5 shows data on deviations from the standard values during performance of certain technological operations in the form of a histogram. The data indicate a certain asymmetry of deviations, but the statistical significance of the observed asymmetry is not obvious. Based on such data, in addition to calculation of statistical moments and ordinal statistics, it is possible, if necessary, to construct a fuzzy set "deviation from the standard" with the membership function, which is defined as the normalized function of distribution density shown in Chart 5 as a detailed approximation. However, such detailed approximation may be excessive and instead of detailed, it is possible to construct a simple approximation, such as a triangular membership function.

The bimodal nature of statistics often indicates an existing combination of two processes, and a simple

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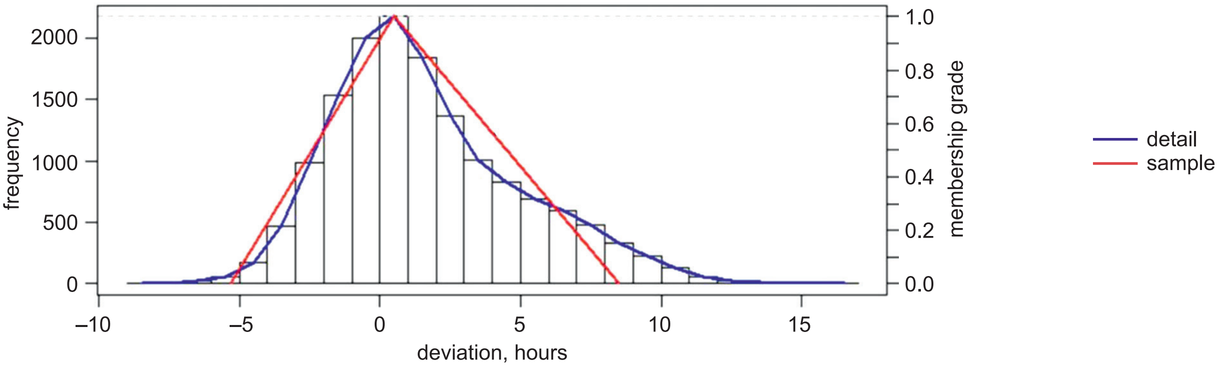

Chart 5. Membership function according to survey data
Source: own elaboration.

approximation looks excessively rough, as can be seen from Chart 6.

This situation requires additional analysis of the process, possibly restructuring of the component model, highlighting other or additional factors, etc.

To build a simulation model of technological process management, we assume the following assumptions.

The standard cargo delivery time is considered known and corresponds to the technical and organizational capacity of the operational mechanism.

In this case we can limit ourselves to considering only the deviation δ of processing time from the standard value.

We consider the entire processing time to be divided by *N*. At each i-th section, nv events occur that increase or decrease the deviation δ by a random variable w.

The numbers nv have a Poisson distribution with an average value of *v*. The distribution of w values is selected according to the simulated situation.

The total increase or decrease in deviation at the i-th section is calculated as the sum of

$$\delta_i = \sum_{j=1}^{n_v} \Delta w_j .$$

If the deviation of cargo processing time is normalized by the maximum value, we calculate the significance of the i-th section bi as the ratio of the standard processing time on the section to the standard time on the entire route. In the case of a uniform division into N sections, *b=1/N.*

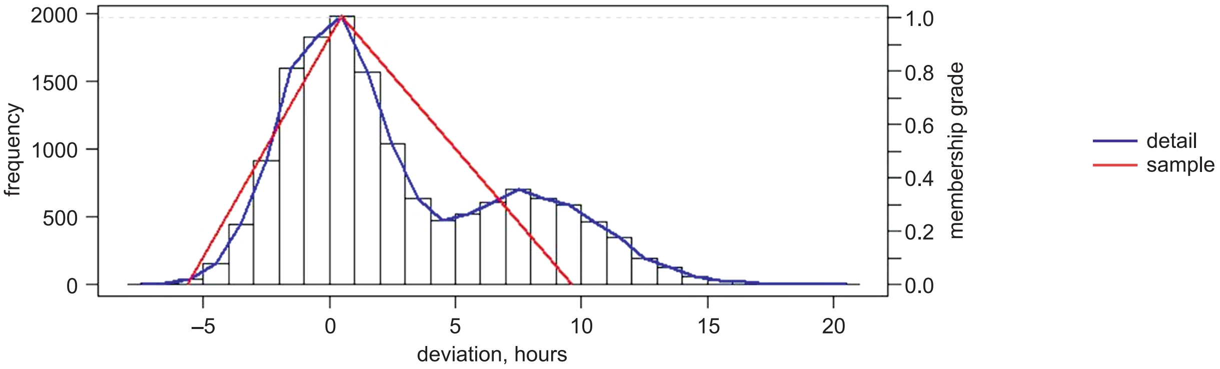

Chart 6. Data with suspicion of combination of processes
Source: own elaboration.

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The total accumulated deviation δ_k^Q on the *k-th* section of the route is determined in the following way:

if a fuzzy controller is not used: $\delta_k^Q = \sum_{i=1}^{k} \Delta b_i \delta_i$,

in particular, on the entire route $\delta = \sum_{i=1}^{N} \Delta b_i \delta_i$.

if a fuzzy controller is used: $\delta_k^Q = \psi(\delta_{k-1}^Q) + b_i \delta_i$,

in particular, on the entire route $\delta = \psi(\delta_{N-1}^Q) + b_i \delta_i$,

where $\psi(\delta_{k-1}^Q) = u(t_{k-1})$ is the management solution of the inference mechanism of the fuzzy controller on the k – th section of the route.

Target value of deviation δ_{target}=0.

The values of w_i, δ_i, δ_k^Q and are conveniently measured in fractions of one:

w_i = -0,03 means that a random event occurred that resulted in a decrease of the deviation by 3%

δ_i = 0,03 means that the deviation at the *i*-th section is 3%

δ = 0,11 means that the total deviation on the route is 11%

δ_k^Q = 0,08 means that the total deviation at the *k*-th section of the route is 8%.

Significance of the section $b_i = 1/N$

Average number of precedents at the section $\nu = 3$

Maximal expected deviation value at the section δ_{max} = 0.15

The fuzzy variables *State* and *Goal* are shown in Chart 7.

The inference rules provide for acceleration in the case of arrival behind the schedule and deceleration in the case of arrival ahead schedule. Such management is fully justified in case of availability of a schedule that fully corresponds to the capabilities and goals of operational mechanisms.

Table 2. The inference rules

State	*E6*	*E5*	*E4*	*E3*	*E2*	*E1*	*InT*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*
Goal	*P5*	*P4*	*P3*	*P2*	*P1*	*M*	*M*	*M*	*L1*	*L2*	*L3*	*L4*	*L5*

Source: own elaboration.

Let us assume that the processing time disturbance *w* are evenly distributed in the interval [[-δ_{max}; δ_{max}], i.e. the arrival behind and ahead of schedule are considered equally probable. The result of simulation of the processing time for the assumptions made and the centroid defuzzification method is shown in Chart 8. When a fuzzy controller is used, the deviations are reduced, on average, by 2.2 times.

If the delays are more likely, i.e. w are evenly distributed over the interval [-⟦0,8δ⟧_max; 1,2δ_max], the behavior of the system changes significantly: there is a system delay drift from the schedule, as the mathematical expectation of w values is now positive, however, the regulator is able to correct and minimize deviations in time using the accepted parameters and rules of the model with the "meanmax" defuzzification method, as can be seen in Chart 9.

The case, when the standard cargo delivery time is considered unknown or unrealistic for execution

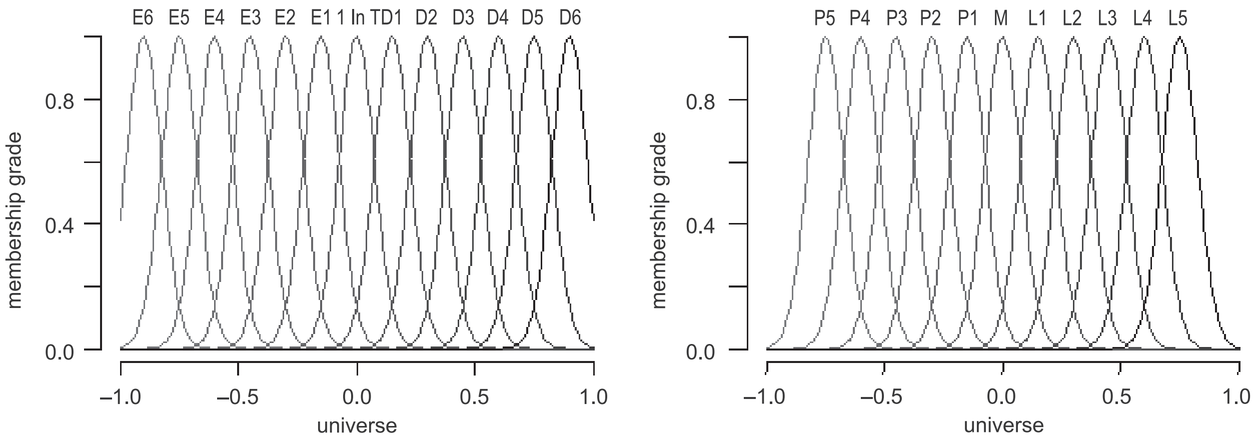

Chart 7. Membership function of values of fuzzy variables
Source: own elaboration.

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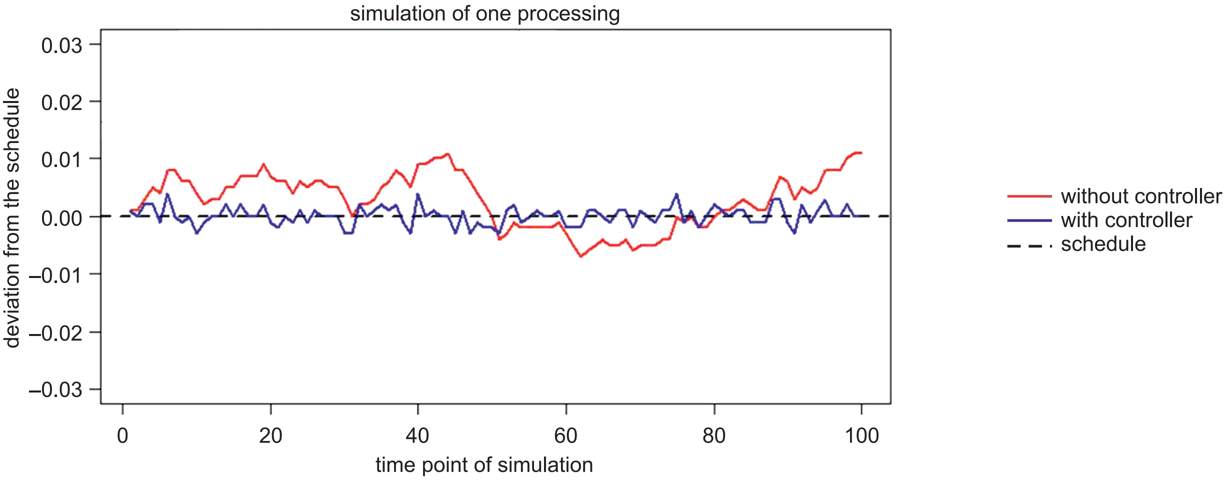

Chart 8. Processing time taking into account equally probable deviations
Source: own elaboration.

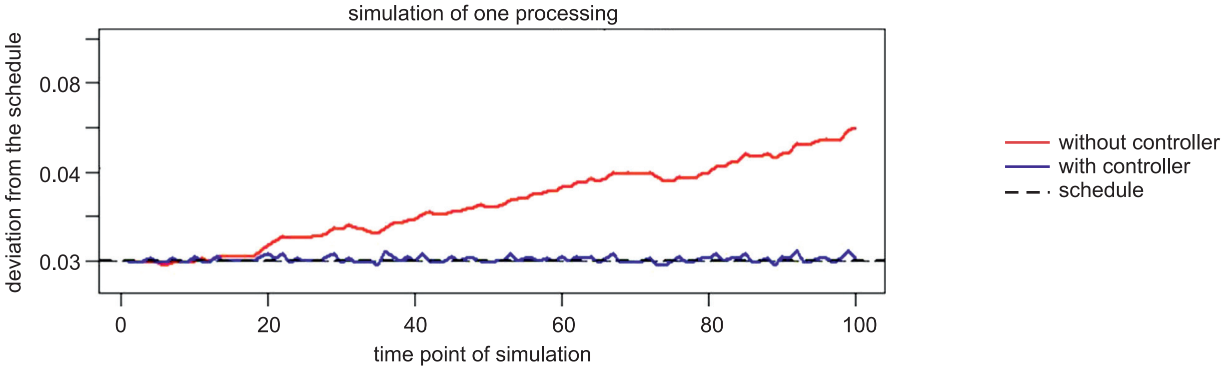

Chart 9. Processing time taking into added positive mathematical expectation of time disturbance of processing time *w*
Source: own elaboration.

(which is the same thing), requires separate consideration.

The results obtained are the principles of automated management of technological processes for railway transport, which are based on:

Justification of data: Data on the execution of all TP steps is saved automatically with a sufficient level of detail in IC.

Adequacy of representations: Statistical models of operational mechanisms (TP steps) are regularly updated based on the data of the last period.

Consistency of goals: management goals and objectives of operational mechanisms (TP steps) are linked through economic performance results.

Safety of standardization: standard indicators are based on current stable statistical criteria and evolve towards improvement of the economic efficiency of TP.

The use of the offered principles provides a solution to the problems of operational practice in the formation of tools for operational management of technological processes for the railway dispatcher units.

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CONCLUSIONS

1. The scheme and means of simulation modeling of technological processes of cargo delivery with and without the use of fuzzy control have been developed. The structure of a fuzzy controller and methods for constructing all its elements are developed.

2. The simulation modeling of technological processes with and without the use of a fuzzy controller is performed. Setting up a fuzzy controller allows to reduce the deviation of indicators of technological process performance from standard values and to improve the technological processes of cargo delivery management.

Author contributions: authors have given approval to the final version of the article. Authors contributed to this work as follows: Hanna Kyrychenko developed the concept and designed the study, Oleh Strelko collected the data, Yurii Statyvka analysed and interpreted the data, Yuliia Berdnychenko prepared draft of article, Yuliia Berdnychenko revised the article critically for important intellectual content.

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