Hardware-Software Complex for Predicting the Development of an Ecologically Hazardous Emergency Situation on the Railway

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Abstract—A hardware-software system has been implemented to monitor the environmental state (EnvState) at the site of railway (RY) accidents and disasters. The proposed hardware-software system consists of several main components. The first software component, based on the queueing theory (QT), simulates the workload of emergency response units at the RY accident site. It also interacts with a central data processing server and information collection devices. A transmitter for these devices was built on the ATmega328 microcontroller. The hardware part of the environmental monitoring system at the RY accident site is also based on the ATmega328 microcontroller. In the hardware-software system for monitoring the EnvState at the RY accident site, the data processing server receives information via the MQTT protocol from all devices about the state of each sensor and the device's location at the RY accident or disaster site, accompanied by EnvState contamination. All data is periodically recorded in a database on the server in the appropriate format with timestamps. The obtained information can then be used by specialists from the emergency response headquarters.

Keywords—ecological safety; hardware-software complex; monitoring; environment; emergency situation; railway transport

I. INTRODUCTION

RAILWAY transport (hereinafter referred to as RT) is a significant polluter of the atmosphere, adjacent water bodies, and soil due to emissions and discharges from the operation of traction rolling stock (hereinafter referred to as RS).

Note that railways in the EU, the USA, and Asia also transport a large number of various cargoes with various fire and explosive properties, which, in case of accidents with their participation, adversely affect the environment (hereinafter referred to as Env) [1]. Therefore, it is clear that at all levels of the organization of transportation of dangerous goods (hereinafter referred to as HAZMAT) due attention should be paid to the implementation of measures to protect the environment, the rational use of natural resources, and ensuring the environmental safety of people's livelihoods. The implementation of appropriate measures should ensure the balance, constancy and flexibility of natural systems. Accordingly, the violation of such natural systems can lead to

severe negative consequences and environmental disasters. All of the above and determines the relevance of developing measures to reduce the negative factors affecting the consequences of emergency situations (ES) and disasters involving railway rolling stock during the transportation of dangerous goods.

The liquidation (elimination) of the consequences of railway emergencies (hereinafter referred to as the railway accidents) with environmentally hazardous goods is a chain of interrelated processes. Moreover, these processes require a number of activities. These measures are aimed at preventing various threats to people, protecting the environment, preserving cargo, rolling stock, railway transport facilities, infrastructure, etc. in the shortest possible time. At the same time, the rational use of various resources (financial, material, human, computing, etc.) that are necessary to carry out these activities is also important. Thus, the balanced terms for the recovery of the transport system and the resources necessary for this are the criteria for the effectiveness of the system for eliminating the consequences of railway emergencies during the transportation of dangerous goods. Note that the scientific literature does not fully disclose many problematic issues related to computer decision support for assessing the situation, including those related to assessing and predicting the development of the environmental situation at the site of accidents in railway emergencies, as well as the development of control actions for the elimination consequences of a railroad accident. This determined the relevance of our study.

II. LITERATURE REVIEW

As shown in [2], [3], [4], the problem of studying the causes of railway emergencies and disasters, their impact on people, rolling stock, and railway transport infrastructure prompted scientists to study the processes of eliminating railway accidents. In turn, the experience of liquidation of transport accidents and disasters shows that those that are accompanied by fires of these dangerous goods pose the greatest threat [5].

From the analysis of the development of accidents with such dangerous goods, presented in [6], [7], it can be concluded that the environment has some inertia in response to the external action of dangerous accident factors. As shown in [7], the

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environment counteracts the dangerous factors of accidents, including railway transport, that is, it has the properties of self-maintenance and self-regulation. Accordingly, under certain conditions, this can lead to the inhibition of catastrophic processes, up to their termination.

In order to predict the state of the environment, a large number of mathematical and simulation models are now used [8], [9], [10], [11]. To build such models, differential equations are often used that describe various physical and chemical processes of the propagation of pollution in the atmosphere, soil, rivers, and reservoirs under various boundary conditions. These conditions take into account, in particular, the spread of such pollution, under given meteorological conditions, the power of pollution sources, etc.

The methods of linear regression analysis, pattern recognition, sequential graphical regression, and others are also widely used [12, 13].

The works [13], [14] show that the use of intelligent decision support systems (hereinafter DSS) will allow the head of the operational headquarters to carry out information, technological, analytical and organizational support for the iterative process of analyzing the situation that has developed at the site of a RY ES or a disaster. The DSS makes it possible to prepare and evaluate solutions, as well as to select the final decision on the localization of the RY ES and the elimination of its consequences. Solving such a problem without the appropriate models, hardware and software is extremely difficult.

In study [14], it's demonstrated that for analyzing the situation that has arisen as a result of an accident or disaster during the transportation of dangerous goods (HAZMAT), there's a need for automated means of assessing environmental safety.

Authors in [15], [16] emphasize that for effective emergency response operations, it is essential to have mechanisms for predicting the development of the accident and reliable communication between all participants involved in the emergency response process.

In [17], the authors discussed the challenges of protecting the environment (Env) during the containment, neutralization, and blocking of pollutants during oil spills, which are, in particular, transported by railway transport (RT).

In [18], [19], methods for assessing the environmental risks of emergencies on RT are presented. The authors consider the main aspects of forming environmental risks in the context of making transport processes more environmentally friendly. In [19], they also propose methods for assessing the probability and some principles for managing environmental risks on RT.

In the analyzed studies, however, the aspect of combined use of intelligent systems and automated tools for changing the state of the Env to forecast the situation's development at the site of a railway emergency or disaster is scarcely addressed. Therefore, the pressing issue is the selection of a model for predicting the development of hazardous factors of an accident with HAZMAT on RT and the development of a hardware-software complex for predicting the development of an environmentally dangerous accident for RT.

III. The purpose and objectives of the study.

is the development of a hardware-software complex for forecasting the development of environmentally hazardous accident situations for railway transport. To achieve the set research goal, it is necessary to address the following tasks:

1) *Implement a cybernetic model to determine the probabilities of the railway transport system (RTS) being in a safe operating condition when transporting hazardous materials, depending on various technological and organizational measures.*

2) *Develop and test a hardware-software complex for forecasting the development of environmentally hazardous accident situations for railway transport.*

IV. Methods and models

Research methods - the study used a comprehensive systems approach, which includes an analysis and summarization of global experience, as well as the authors' own investigations on issues related to the development of scientific environmental safety management methods during the mitigation of accident consequences on railway transport. Methods of the theory of queuing systems (QST) are applied for a formal description of the functioning of the system "environment - accident object - emergency response units." Methods of object-oriented programming were also employed during software implementation and formal description of the actions of emergency units as functioning processes of QST without time constraints on the ADO.net technology platform.

Let's represent the functioning of an emergency situation (AS) on railway transport (RTS) in the form of a state graph (Fig. 1). Let's consider the state graph of RTS during the transportation of hazardous materials (HAZMAT), as presented in Fig. 1, as a Markov stochastic process scheme with discrete states and continuous time [11, 12, 20, 21].
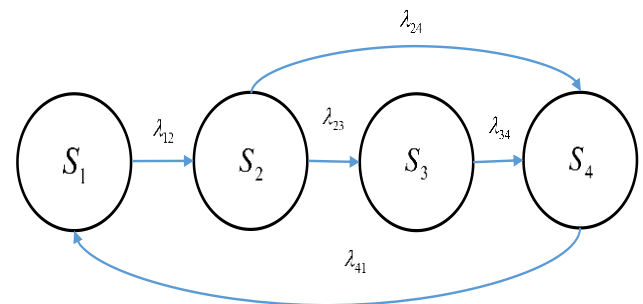

Fig. 1. State graph of railway transport (RTS) during the transportation of hazardous materials (HAZMAT)

Let's define the states of the transport system during the transportation of hazardous materials (HAZMAT) as follows:

S_1 – state of safe operation of the system before the onset of an emergency situation (AC).

S_2 – state of the impact of hazardous factors of an emergency on railway transport (RTS). This state ends when the "source" of the flow of hazardous factors disappears (for example, when all the hazardous materials (HAZMAT) burn out during a fire even before the emergency response teams arrive, i.e., the time for these teams to arrive is longer than the "critical time" for this emergency).

S_3 – state of emergency localization on the railway transport (RTS). The duration of this state depends on the volume of work that needs to be done first to stop the loss of cargo, and then to save the remaining cargo if it was partially lost.

S_4 – state of emergency consequence elimination. Its duration depends on the volume of work that needs to be done for this purpose.

Then, the Kolmogorov system of equations for such a graph will look as follows [20], [21]:

$$\begin{cases} \dfrac{dP_1}{dt} = -\lambda_{12} \cdot P_1 + \lambda_{41} \cdot P_4, \\[2mm] \dfrac{dP_2}{dt} = -(\lambda_{23} + \lambda_{24}) \cdot P_2 + \lambda_{12} \cdot P_1, \\[2mm] \dfrac{dP_3}{dt} = -\lambda_{34} \cdot P_3 + \lambda_{23} \cdot P_2, \\[2mm] \dfrac{dP_4}{dt} = -\lambda_{41} \cdot P_4 + \lambda_{34} \cdot P_3, \end{cases} \quad (1)$$

where λ_{ij} – the intensities correspond to certain events during the emergency elimination on railway transport (RTS);

P_i – the probability of the system transitioning to the i – th state.

Initial conditions: $t = 0$, $P_1 = 1$, $P_2 = P_3 = P_4 = 0$.

For the steady-state regime, the system of final probability equations will be following:

$$\begin{cases} \lambda_{12} \cdot p_1 = \lambda_{41} \cdot p_4, \\[1mm] (\lambda_{23} + \lambda_{24}) \cdot p_2 = \lambda_{12} \cdot p_1, \\[1mm] \lambda_{34} \cdot p_3 = \lambda_{23} \cdot p_2, \\[1mm] \lambda_{41} \cdot p_4 = \lambda_{34} \cdot p_3, \end{cases} \quad (2)$$

To calculate the system's dwell time within the aforementioned boundaries, the emergency response units on site during a railway accident (AC на RTS) will need an automatic environmental status monitoring system (EnvState). Such a system can provide a plethora of specific data required during the modeling of the probability parameters of emergency response. The hardware implementation of such a system is discussed later in the work.

The software implementation of model (1) – (2) is based on the use of ADO.net technology within the Visual Studio programming environment, see Fig. 2. In Figure 2, as an example, a situation is shown where five types of requests are analyzed. These requests come in with the intensity corresponding to the λ_{ij} event flow rates. Requests, respectively, describe the work on localizing the emergency situation and mitigating its consequences, as a queueing system without time restrictions on servicing "demands" (dangerous factors that need a response) and staying in the service queue. With such a theoretical approach, one can use both classical and adapted for specific tasks mathematical methods of the queuing theory.

One of the requests must always have the highest priority (be serviced out of turn). The probability of a request type change during the emergency response work at the accident site should be considered. It is also important to consider the probability of a request leaving the queue. This situation can occur if a request has been in the queue for too long and no channel can process it at the current moment. The time for request formation and its processing during the testing of the software part of the system can, for instance, be generated as random numbers within a specified range using a random number generator. The queuing system should provide modeling objects with tools for assigning unique identifiers and for generating random values.

Adjustment of all modeling parameters is performed in a separate window immediately before starting the modeling of the emergency response work and, specifically, for mitigating environmental consequences (EnvState).

During the emergency response work at the railway accident (RAC) site, the corresponding units typically deal with different types of service requests. These requests are executed with varying intensity (productivity). Emergency response units and resources can be used simultaneously to perform various types of tasks. Depending on the nature of the accident and the plan to mitigate its consequences, these tasks can end at different times. The data for modeling the duration of the emergency response work will also be determined by the results obtained from the mobile environmental status monitoring system (EnvState), see Figs. 3, 4.
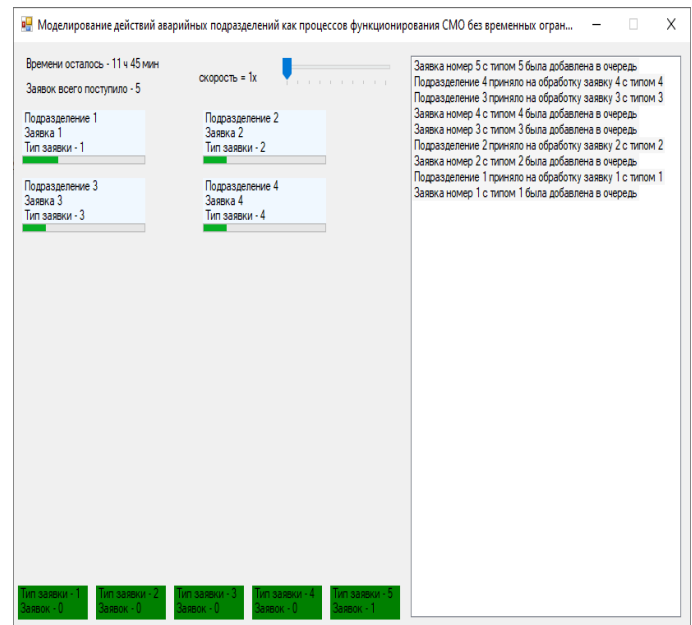
1 - Number of requests from emergency response units;
2 - Unit number;
3 - Modeling results.

Fig. 2. General view of the software part of the system modeling the workload of emergency response units at the site of a railway emergency

This module of the mobile environmental monitoring system (Fig. 3) can be used as a high-precision detector for hazardous air and soil conditions at the site of a railway emergency.

Fig. 3. General view of the software part of the system modeling the workload of emergency response units at the site of a railway emergency

Fig. 4. Assembled mobile environmental monitoring system (with some sensors)

The air sensor module contains a combination of CCS811, Si7021, and BME280 sensors. These sensors can measure most air and soil parameters, for example, at an accident site on the

railway. The display of the necessary information in the mobile environmental monitoring system is executed in the form of a web interface, see Fig. 5. This interface also serves as a system for administering the operation of devices with sensors.

On the web interface page, see Fig. 5, data from the sensors of the mobile environmental monitoring system are displayed for the following parameters: ionizing radiation; data from the dust sensor; ambient temperature; air humidity; concentration of eCO2 and other substances; levels of carbon monoxide and other gases, etc.

Fig. 5. Page displaying additional information with charts about the air condition at the railway accident site

The web interface of the mobile monitoring system for the environmental conditions (EnvState) is written in the following programming languages: PHP, HTML, CSS, JS, Python, SQL. The hardware part of the mobile system is tested based on Atmega328 and ESP8266 microcontrollers. The modularity of the mobile system provides various variations of sensor

connections to microcontrollers. The system is designed to connect up to 100 devices with five sensors on each.

Assessment of the situation using the mobile monitoring system, modeling the workload of the emergency response units with the developed software product, diverse planning of activities needed to respond to the emergency, communicating the adopted decisions to the performers, monitoring the processes of executing such decisions, and developing corrective measures are carried out by managers of all emergency response management levels, see Fig. 6. Typically, all these measures are implemented under time constraints. This usually happens under uncertain information about the circumstances of the emergency or disaster. At the same time, there are threats to people, objects, passenger and freight trains, and the decision-maker may be under stress. Moreover, the decision's execution is hindered by factors characteristic of the railway transport system.
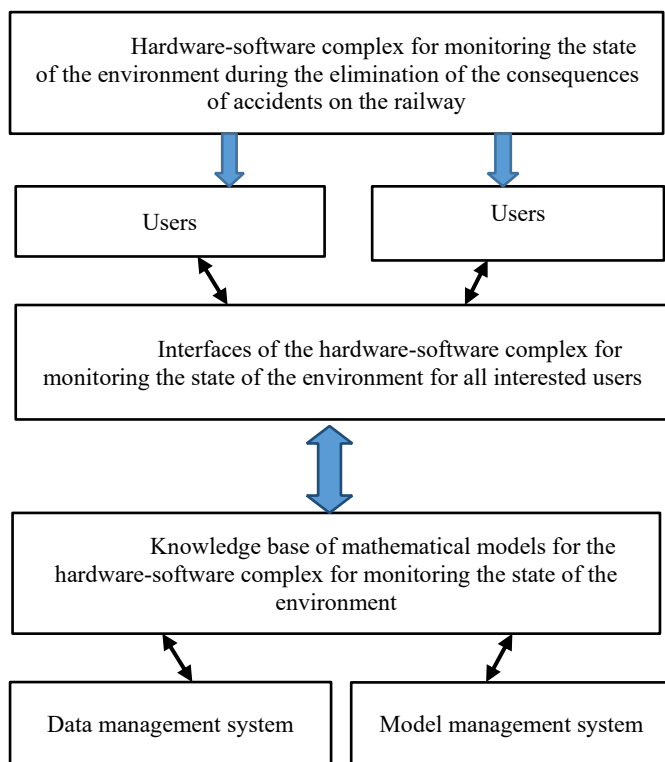

Fig. 6. Basic architecture of the hardware-software complex for monitoring environmental conditions (EnvState) with modules for automated ecological safety assessment during the elimination of the consequences of emergencies on the railway transport system (RTS).

Therefore, the composition of the situation centers of management points should include sufficiently powerful complexes of information analysis automation tools. The purpose of these tools is to quickly and objectively assess the situation, form decisions for information and computational tasks related to predicting the development of ecologically dangerous emergencies or catastrophes. Such complexes contribute to the development of action plans for specialized units to eliminate emergencies and take measures to comprehensively support the actions of liquidators.

Using data obtained from instrumental pollution measurement tools of the environmental conditions (EnvState), see Fig. 3,4, directly at the emergency site (data on the state of the air, soil,

water sources, etc.), the hardware-software complex for monitoring the state of EnvState can not only model different scenarios for the development of the situation at the emergency site but also obtain preliminary risk and consequences assessments of the emergency. The output of the hardware-software complex monitoring the state of EnvState will provide information containing an assessment of the state of EnvState for the studied area at the site of the railway transport system emergency or disaster. The obtained information can be used by various management structures. For example, such information will be useful in the process of developing measures to eliminate the consequences of an emergency.

V. DISCUSSION OF THE RESULTS OF THE COMPUTATIONAL EXPERIMENT

During the computational experiments, quantitative relationships were established between the intensity of exposure to hazardous factors of railway emergencies, the time of arrival, deployment, and effectiveness of actions by emergency response units, and the efficiency of performing emergency work related to minimizing environmental damage from hazardous goods transported by rail transport systems. The results of computer modeling using the developed application demonstrate that significant reduction in the negative impact of railway emergency consequences on the environment is possible with a shortened duration of emergency work. The outcome is also influenced by reducing the time to assemble units and apply forces and means of necessary efficiency. An increase in assembly time requires a multiple-fold increase in the efficiency of such forces and means. During simulation computational experiments on the hardware-software complex monitoring the environmental state at the site of a railway emergency, it was found that if the means of addressing the consequences of a railway emergency do not match its nature and/or are extremely inefficient, then even with their timely assembly at the site of liquidation, they will not be effective. Or, if the emergency response measures are efficient enough, but their concentration at the site of the incident was delayed, they will also be ineffective. The results of the study can be used in the implementation of similar systems in other areas, for example, in automotive transport, "Smart City" systems, and others.

CONCLUSION

Based on the conducted research, the following results were obtained:

A model has been proposed based on service theory methods, which, unlike existing ones, allow for justifying various schemes for organizing emergency and recovery works by structural units of the railway transport functional subsystem.

A hardware-software complex for monitoring the environmental state at the site of a railway emergency has been designed and implemented. The complex consists of the following main parts: a software part of the system that simulates the workload of emergency response units at the site of a railway emergency; a unified data processing server and information collection devices. For these devices, the transmitter is built on the ATmega328 microcontroller basis. For component devices of the complex monitoring the environmental state at the site of a railway emergency, a

transmitter based on the ESP8266 microcontroller was used, ensuring stable communication according to the 802.11n standard. In the implemented hardware-software complex, the data processing server receives information via the MQTT protocol from all devices about the state of each sensor and the location of the device at the railway accident site associated with environmental pollution. All data are periodically recorded in a database on the server in the appropriate format with timestamps. WEB-interface is used to access the stored data. This allows managing the hardware-software complex for monitoring the environmental state at the site of a railway emergency on any devices that have a web browser. The hardware-software complex for monitoring the environmental state at the site of a railway emergency was successfully tested on the railways of Ukraine and Kazakhstan for stability and speed of operation.

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