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Original article

Simulation Modeling of the Process of Accident Risk Realization during Stripping Operations at an Open-Pit Coal Mine

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Abstract
Introduction. The need to increase the level of comprehensive safety, reduce accident and injury rates, minimize the risk of failures, accidents and catastrophes determines the relevance of research on the relationship of elements of the "human–machine–environment" (H–M–E) system during open-pit mining. One of the most effective mechanisms for studying the functional characteristics of the H–M–E system of a coal mine is to conduct simulation modeling in order to identify problematic situations that trigger accidents with catastrophic consequences and injury to personnel. Simulation modeling of a technological process involves constructing a model of a real system and setting up computational experiments to describe the behavior of the system and evaluate various strategies that ensure its functioning. The aim of the research was to adapt simulation modeling technologies to solve the problem of complex safety during open-pit mining. Within the framework of the study, the task was to determine the elements that made the greatest contribution to the implementation of risks in the H–M–E system during stripping operations at a coal mine. The simulated subsystems were "human", "machine", "environment", and "weather conditions".
Materials and Methods. Stripping process was considered in the ARIS eEPC (extended Event Driven Process Chain) methodology as a business process linking a set of subprocesses and/or business operations. To build a simulation model in the AnyLogic software environment, the business process of stripping works in ARIS eEPC notation was described by a graph representing a structure consisting of objects and connections between them. This approach allowed us to structure the sequence of events and operations and determine alternative outcomes that arose during stripping operations.
Results. As part of the research, a method was developed for translating the formal model of the stripping business process in ARIS eEPC notation into a combined simulation model of AnyLogic. Based on the developed method, a series of machine experiments was carried out. The elements influencing the realization of the risk of accidents in the H–M–E system of a coal mine were determined.
Discussion and Conclusion. For the first time in the domestic practice of research of the H–M–E system, simulation modeling technologies have received an application for the analysis of complex safety indicators during open-pit mining. According to the simulation experiment results, it was found that the main influence on the decrease in the reliability of the "machine" subsystem was exerted by the human factor, which, together with the psychophysiological properties of a person, enhanced the development of the domino effect when implementing various types of risks. The presented results and experimental approbation of simulation modeling technology can have advanced use in the analysis of complex technical systems safety, taking into account the influence of human and man-made factors.

Keywords: simulation modeling, “human-machine-environment” system, analysis of risk at an open-pit coal mine, agent-based modeling of overburden face, AnyLogic, eEPC, ARIS

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Научная статья

Имитационное моделирование процесса реализации риска аварии при проведении вскрышных работ на угольном разрезе

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Аннотация

Введение. Необходимость повышения уровня комплексной безопасности, снижения показателей аварийности и травматизма, минимизации риска отказов, аварий и катастроф предопределяет актуальность исследований взаимосвязи элементов системы «человек – машина – среда» («Ч–М–С») при проведении открытых горных работ. Одним из наиболее эффективных механизмов исследования функциональных характеристик системы «Ч–М–С» угольного разреза является проведение имитационного моделирования с целью выявления проблемных ситуаций, являющихся триггерами аварий с катастрофическими последствиями и травмированием персонала. Имитационное моделирование технологического процесса предполагает конструирование модели реальной системы и постановку вычислительных экспериментов для описания поведения системы и оценки различных стратегий, обеспечивающих её функционирование. Целью данного исследования является адаптация технологий имитационного моделирования для решения проблемы комплексной безопасности при проведении открытых горных работ. В рамках исследования поставлена задача определения элементов, вносящих наибольший вклад в реализацию рисков в системе «Ч–М–С» при проведении вскрышных работ на угольном разрезе. В качестве моделируемых подсистем выступают «человек», «машина», «среда», «погодные условия».

Материалы и методы. Процесс вскрышных работ рассмотрен в методологии ARIS eEPC (extended Event Driven Process Chain) как бизнес-процесс, связывающий совокупность подпроцессов и/или бизнес-операций. Для построения имитационной модели в программной среде AnyLogic бизнес-процесс вскрышных работ в нотации ARIS eEPC описан графом, представляющим структуру, состоящую из объектов и связей между ними. Данный подход позволяет структурировать последовательность событий и операций и определить альтернативные исходы, возникающие в процессе выполнения вскрышных работ.

Результаты исследования. В рамках исследования разработан метод трансляции формальной модели бизнес-процесса вскрышных работ в нотации ARIS eEPC в комбинированную имитационную модель AnyLogic. На основе разработанного метода проведена серия машинных экспериментов, определены элементы, оказывающие влияние на реализацию риска аварий в системе «Ч–М–С» угольного разреза.

Обсуждение и заключение. Технологии имитационного моделирования впервые в отечественной практике исследований системы «Ч–М–С» получили приложение для анализа показателей комплексной безопасности при проведении открытых горных работ. По результатам имитационного эксперимента установлено, что основное влияние на снижение надежности подсистемы «машина» оказывает человеческий фактор, который в совокупности с психофизиологическими свойствами человека усиливает развитие эффекта домино при реализации рисков различных типов. Представленные результаты и опытная апробация технологии имитационного моделирования могут иметь расширенное использование при анализе безопасности сложных технических систем с учетом влияния человеческого и техногенного факторов.

Ключевые слова: имитационное моделирование, система «человек – машина – среда», событийный анализ риска на угольном разрезе, агентное моделирование вскрышного забоя, AnyLogic, eEPC, ARIS

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Introduction. During stripping operations at coal mines, the issues of improving safety, reducing accidents, and eliminating cases of injury have always been and still are in the focus of special attention. It is they that give relevance to all research in this field. A modern view on the problem of formation of prerequisites for accidents at a coal mine suggests considering them in the format of the H–M–E system developed in [1, 2]. The system includes an operator-driver of an excavator, a bulldozer, a drilling rig, a dump truck driver (man), a mine excavator, a bulldozer, a drilling rig, a dump truck (machine), a stripping face, a coal face, a drilling unit (working environment). These subsystems interact with each other according to a given technology and the established organization of work within the technological process. In addition to the main components of the system, its model includes connections between them and the surrounding environment, which includes weather conditions, mining and geological factors (rock strength, groundwater level, stability of the side of the section).

Functioning of the H–M–E system is accompanied by the implementation of various types and risk groups that need to be identified in a timely manner and take the necessary measures to protect the system and mitigate the consequences in case of danger. An effective mechanism for investigating functional characteristics of the simulated H–M–E system of a coal mine and identifying problematic situations that trigger accidents with catastrophic consequences and injury to personnel is simulation modeling.

Simulation modeling of a technological process involves constructing a model of the system under study and setting up computational experiments in order to describe its behavior and evaluate (within the limits imposed by some criterion or their combination) various strategies that ensure functioning of this system [3]. Simulation modeling is a key tool for studying the behavior of real systems, though it does not solve optimization problems. It rather represents a technology for evaluating the values of functional characteristics of the simulated system, allowing us to identify its problem areas [4]. Simulation models are widely used in the prediction of logistics systems behavior, design and location of enterprises, optimization of the existing processes, training of personnel, etc.

Currently, there are three main directions in the field of simulation modeling: system dynamics, discrete-event and agent-based modeling. These directions differ in the level of abstraction of the models modeled in their environment. Three levels of simulation modeling abstraction are noted: strategic (high-level strategies that model the behavior of people, organizations), tactical (building models of queuing systems and business process models), operational (building models of mechatronic systems, street and pedestrian traffic, etc.) [5, 6].

The process of stripping operations at a coal mine can be considered in the ARIS eEPC methodology (extended Event Driven Process Chain — extended notation of the description of the process chain) as a description of the flow of sequentially performed works, arranged in the order of their execution [7]. This situation is presented as a business process linking a set of sub-processes, and/or business operations, and/or business functions, during which certain resources are consumed and a product is created (a tangible or intangible result of human labor: an object, a service, a scientific discovery, an idea) that is of value to the consumer [8].

Simulation modeling is carried out in the AnyLogic software environment, which is a flexible multi-agent modeling platform that is used to create a variety of simulation models in the field of business, engineering, logistics and other fields. Various means of specification and analysis of results available in AnyLogic allow us to build models (dynamic, discrete-event, agent-based) that simulate almost any real process, perform computer analysis of models without conducting real experiments and complex computational procedures [9].

Based on the objectives of the study and taking into account the experience of using simulation modeling technology, the following tasks were formulated that should be solved in this work:

1. Describe the process of stripping in eEPC notation.
2. Translate the stripping face model from the eEPC notation into a combined model of AnyLogic software environment; conduct a series of simulation experiments.
3. Compare the results of simulation experiments modeling of the process of risk occurrence and its development into a cause-and-effect sequence of a catastrophic accident and injury to personnel during stripping operations in the H–M-E system of a coal mine.

Materials and Methods. Business process of stripping operations at a coal mine in the eEPC notation [10, 11] can be described by a graph as $G = \{X, V\}$, where X and V are the main components of the model (Fig. 1)

In Figure 1, G (graph) is a structure consisting of objects and links between them. In this context, the graph describes the stripping process and its logical structure. It helps to visualize the sequence of events and operations, as well as to determine what alternative outcomes may arise in the course of work. Figure 2 shows the main types of graph objects used in the construction of the simulation model.

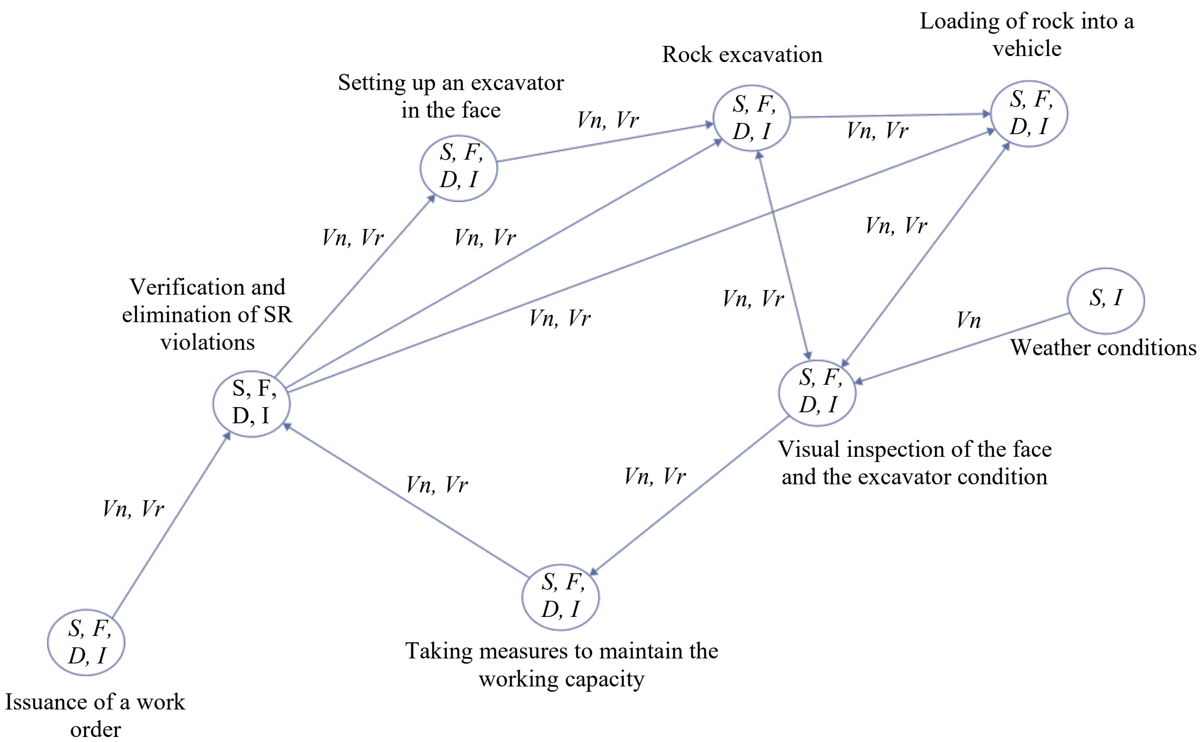

Fig. 1. Graph of the stripping process

1. X — set of model objects (graph vertices), where X = {S, F, D, I} and consists of four types of objects:

• S (events): these objects represent various events or stages that occur during stripping operations, for example, "Setting the excavator in the face", "Rock excavation", "Loading of rock into a vehicle". An example of the implementation of this object in a simulation model is presented by the service block "Beginning of the mining cycle" in Figure 2 *a*.

• F (function): functional objects that can be used during technological operations. These are operations necessary for the successful completion of the process, for example, visual monitoring of the current state of the excavator or the face, monitoring the position of the dump truck and other technological equipment or people in the face. An example of the implementation of this object in a simulation model is presented by the service unit "Visual inspection of the face" in Figure 2 *b*.

• D (operation): operations required to perform stripping operations, for example, technical inspection or repair of an excavator, elimination of violations of safety rules, and so on. An example of the implementation of this object in a simulation model is presented by the service unit "Excavator failure detection" in Figure 2 *c*.

• I (XOR/OR rule): these objects define the logic of branching and merging in the process. The OR rule indicates that after executing several alternative events, the process can continue if at least one of them is completed. For example, a machinist checks the working condition of an excavator at the beginning of a shift. This event can have two outcomes: "technical condition is correct"; "malfunctions have been detected". Both outcomes lead to the realization of different branches of the model development events. The XOR operator means that only one of several alternative ways of developing the model is selected. For example, when an excavator equipment failure is detected by a machinist, the XOR operator sets the probabilities of alternative outcomes: "the working condition of the excavator has been restored", "malfunctions have been identified that do not affect the operation of the excavator", and "operation of the excavator is unsafe". An example of the implementation of this object in the simulation model is presented by the SelectOutput block "Excavator failure type, XOR rule" in Figure 2 *d*.

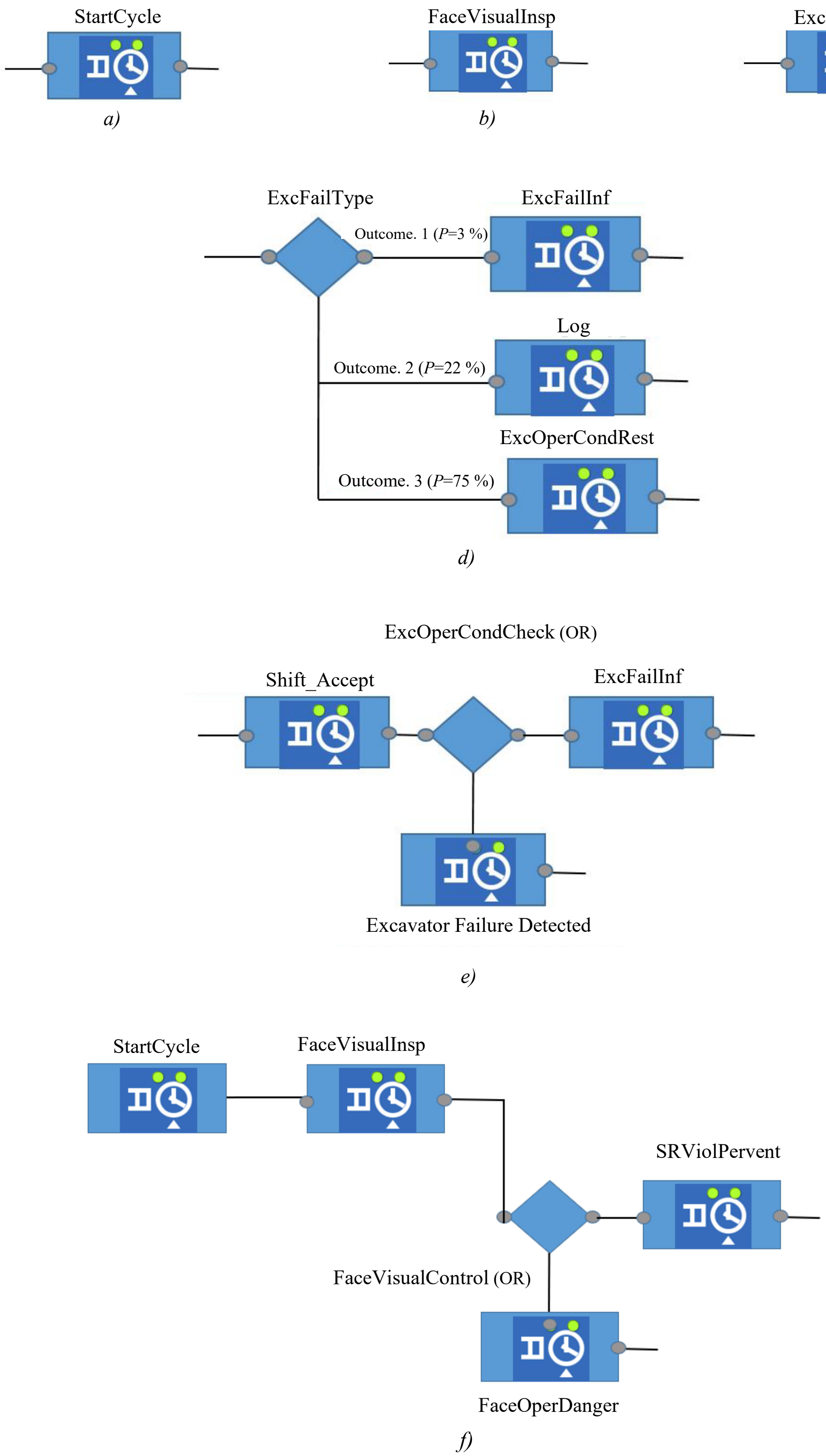

Fig. 2. Diagram of graph objects implementation in the simulation model:
a — "event" (the beginning of the mining and excavation cycle); *b* — "function" (visual inspection of the face); *c* — "operation" (detection of excavator failures); *d* — "XOR rule" (implementation of the type of excavator failure); *e* — "arc" (transition from shift acceptance to checking the working condition of the excavator); *f* — "edge" (alternative ways of branching the further process with visual control of the state of the face)

2. V — the set of arcs and edges that connect objects from the set, that is, the vertices of the graph. V is divided into two subsets:

- Vn (arcs): these relationships between objects indicate a sequence of events or operations. For example, "Shift acceptance" is associated with "Checking the working condition of the excavator", as this is the next step in the process. An example of the implementation of the "arc" in the simulation model is shown in Figure 2 *e*.
- Vr (edges): edges connect vertices with XOR/OR rules, which determine which alternative branching paths may occur in the process. For example, after the start of "Rock excavation" there may be an edge that connects to the OR operator. This means that after the extraction of the rock from the pillar, several different events may occur ("safety violation has been committed", "there is no safety violation"), and the process will continue if at least one of them is completed. An example of the implementation of an edge in a simulation model is shown in Figure 2 *f*.

Agent component of the model in AnyLogic is implemented using the base object — an active object. The active object has parameters, variables that can be considered agent memory, statecharts express behavior: object states and state changes under the influence of events and conditions. The agent in the simulation model of the stripping process is the "Environment" block. The logic of the model provides that the "Environment" influences the magnitude of the driver's error when processing incoming information. In the model, the influence of the "Environment" on the perception of information by the driver is realized by modeling the state of weather conditions. Heavy rain leads to deterioration in visibility from the driver's cab, which may be the reason for incorrect perception of information about the state of the face or the current state of the excavator components. A strong wind raises a cloud of coal dust, which also disrupts visual contact between the driver and the face. Therefore, when the "Environment" does not generate a signal about changes in weather conditions, the probability of a driver's error in 1 hour of work is 94%, when a signal from the "Environment" enters, the probability of an error increases to 96% per hour of work. The generation of changes in weather conditions is carried out randomly.

The Discrete Event Model in AnyLogic is implemented using probability distribution functions and can be described as $\mathrm{ALM} = \{\mathrm{Oper}, \mathrm{Var}\}$. Such a model is used when events occur at discrete points in time and can affect the course of the process, and allows you to model and analyze the stripping process taking into account random factors and variability.

1. Oper — a set of event transition objects between operations performed, includes the following elements:

- Source: a place where events begin or are created, for example, the beginning of the production of works by the excavator operator after receiving the work order;
- SelectOutput: a mechanism that determines where an event will be directed after it has occurred. For example, after the driver has completed visual inspection of the condition of the face, SelectOutput will help determine which action will be the following one: continue work or proceed to the elimination of industrial safety violations in the face.

2. Var — a set of variables that are used in the model to store data or process state. For example, these are variables that track the execution time of each operation or event.

The interaction of the elements of the proposed model in the process of occurrence and realization of risk is discussed below on the example of performing a technological operation for excavating rock from an overburden by a driver of a hydraulic quarry excavator. The aim of conducting an experiment on simulation modeling of the process of stripping operations at a coal mine in the ARIS eEPC notation was to determine which of the subsystems ("human", "machine", "environment") makes the most significant contribution to the causal chain of prerequisites for the implementation of risk in the H–M–E system

Results. The simulation modeling method is applicable for a priori assessment of the possibility of risk realization and its development into technogenic accidents. At the same time, the requirement for the mass and stochasticity of the process under study is observed, which allows the use of simulation modeling to predict the implementation of risk and accident and injury parameters.

At the first stage of the modeling process, the stripping face model from the eEPC notation is translated into a combined model of the AnyLogic software environment, which allows you to determine the probabilities of events in the XOR and OR branching rules. Based on the proposed method, a model is built in AnyLogic. After obtaining the structure of the combined simulation model, the numerical characteristics of the model objects necessary for simulation modeling are determined: indicators for eEPC functions (work completion time), the number of performers (organizational units), probabilities of events in the branching rules, probabilities for XOR and OR. A description of the correspondence of objects of eEPC notation model and elements of the combined simulation model in the AnyLogic language is given in Table 1.

Table 1

Description of the correspondence of objects of eEPC notation model and elements of combined simulation model in the AnyLogic language

Object of the eEPC model	Graphic designation	Corresponding AnyLogic element	Description of the AnyLogic element
Function $F \in X \in G$	Function	State $S_t \in S_{ch} \in A \in ABM$ state	Simple state of the statechart (state diagrams)
Initial Event $S_s \in S \in X \in G$	Event	Transition $T_{rn} \in S_{ch} \in A \in ABM$	Transition from the hyperstate of the statechart to a simple state. It can also be determined by the timer set by the analyst
Event S_m, $Sf \in S \in X \in G$			
Material resources			
Operation (Product/ Service) $P \in X \in G$	Operation/Service	Variable $Var \in E \in ABM$ variable	Variables are used to model changing characteristics to store simulation results. The change in quantitative resources occurs in the state of the statechart, it is programmed in the Java language
Branching rules			
OR rule $R_{or} \in R \in X \in G$	OR	Transition $T_{rn} \in S_{ch} \in A \in ABM$	When switching from a simple state of the statechart to a hyperstate, the Action transition method in Java programs the logic of the agent's decision-making
XOR rule $R_{xor} \in R \in X \in G$	XOR		

As a prototype of agents, combinations of eEPC operations are used, which are performed in each of the subsystems "human", "machine", "environment". The behavior of agents is realized by the modules "operation", "function", and "event". The transition between operations is carried out with a time delay, which is determined stochastically, that is, each simple operation is given a time delay for transmitting a signal to the next operation. This delay is described by the probability distribution function corresponding to this operation. The probabilistic logic of XOR and OR branching rules is implemented during the transition between operations and is programmed in the corresponding stochastic nodes of the model.

For technological operations of the stripping process, the probability distribution function of its execution time is determined based on the following indicators:

– statistical data obtained from the results of time study observations;

– calculated parameters (calculation of time intervals of operations based on statistical data);

– expert judgments. In the absence of statistical data, the expert value of the time distribution function of operations or the probability of an event for a stochastic node was assumed. An example of choosing a probability distribution function for a simulation model is given in Table 2.

Table 2

Example of choosing a probability distribution function

Event	Probability distribution function	Logic of choosing a distribution function
Discrete transitions from shift acceptance to the start of the mining and excavation cycle. Transition intervals between operations are expressed in time units, min., hour		
Checking the technical readiness of the excavator, min.	Unform (3, 7)	Time interval is chosen based on timing
Perception and processing of information by the machinist during the cycle of excavation and loading operations. The intervals of transitions between operations are expressed in time units, s.		
Visual control of the state of the face, min.	Unform (1, 3)	Time interval is chosen based on timing
Realization of risk when performing stripping operations. Transition intervals between operations are expressed in time units, sec., min.		
Actuation of the excavator protection for the ball valve, s.	Exponential (166.67, 0.005)	Expert assessment Opening time of the safety valve is considered as a random event. The opening time of the safety valve is a random variable with an average value (mathematical expectation) μ, the probability density function of the exponential distribution has the form f(x) = λ * exp(-λx), where x — opening time of the valves, λ = 1/μ — intensity parameter. The opening time of the safety valve (x) is from 5 to 15 ms. at the speed of movement of the locking piece from 10 to 30 cm/s. The ball and conical valves have the highest speed, which are triggered in 6 and 8 ms., respectively. For the safety valve, the limitation of the response time within 0.9 seconds is taken into account to avoid failure of the actuating element. The value of λ (intensity) calculated as the inverse of the opening time: for a ball valve: λ = 166.67 ms., for a conical valve: λ = 125 ms.
Probabilities of occurrence of events in the branching rule XOR and OR		
Accuracy of the reaction of the driver	Output true: Gamma (1, 1.42857142857, 0.7)	Expert assessment For modeling, we use the gamma distribution, since it allows us to determine the probabilities of the duration of time before a certain event, i.e. the reaction of the driver to deviations in extreme conditions. X = 0.7 — hidden reaction time + processing of a unit of information = 42 s. or 0.7 min. Since there are no statistical data or expert estimates, the assumed values for the parameters are accepted α = 1 and β = 1/x=1/0.7=1.42857142857 (the inverse value of the minimum reaction time)

The "Environment" agent behavior is set by a state diagram (Java code that randomly generates weather changes: rain or wind). The simple conditions of the state diagram correspond to the eEPC functions. The agent state diagram consists of several simple states that the agent enters after each function is performed. The probabilistic logic of the XOR and OR branching rules is implemented in the Java Action transition method when changing states.

Figure 3 provides the page for launching the simulation model in AnyLogic. When initiating a simple experiment in the AnyLogic environment, the model starts with the specified parameter values, supports time mode, animation and debugging of the model. Before starting the launch, you need to select the start date of the experiment, time and number of drivers in the shift. The number of drivers in a shift by default is equal to the number of faces and the number of excavators in a shift.

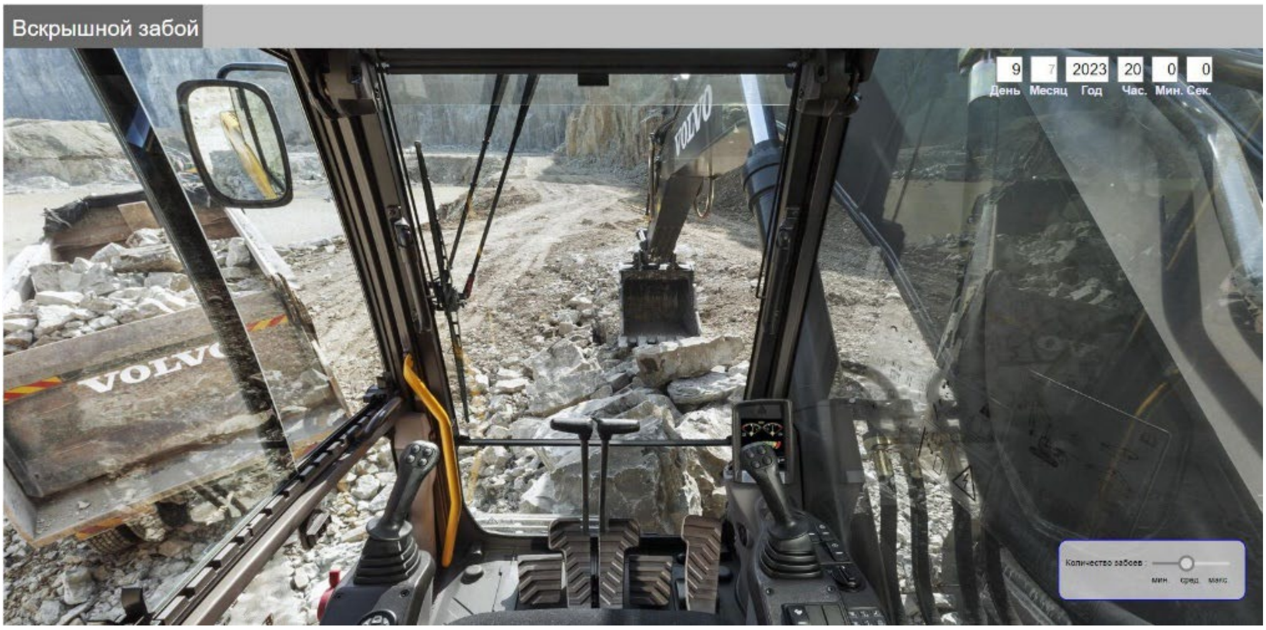

Fig. 3. Launch page for the simulation of the combined simulation model of the stripping face

Figure 4 provides a fragment of the model (shift acceptance) based on the eEPC model, its active objects and environment. Active objects are entities that can perform actions, change their state and interact with each other inside the model. They are elements that have their own behavior and can affect other objects and elements of the model. An environment is an area in which active objects perform their actions, move and interact with each other (for example, a physical space — a stripping face, an excavator cabin). In a discrete-event environment, active objects process events, change their state, and interact through event queues.

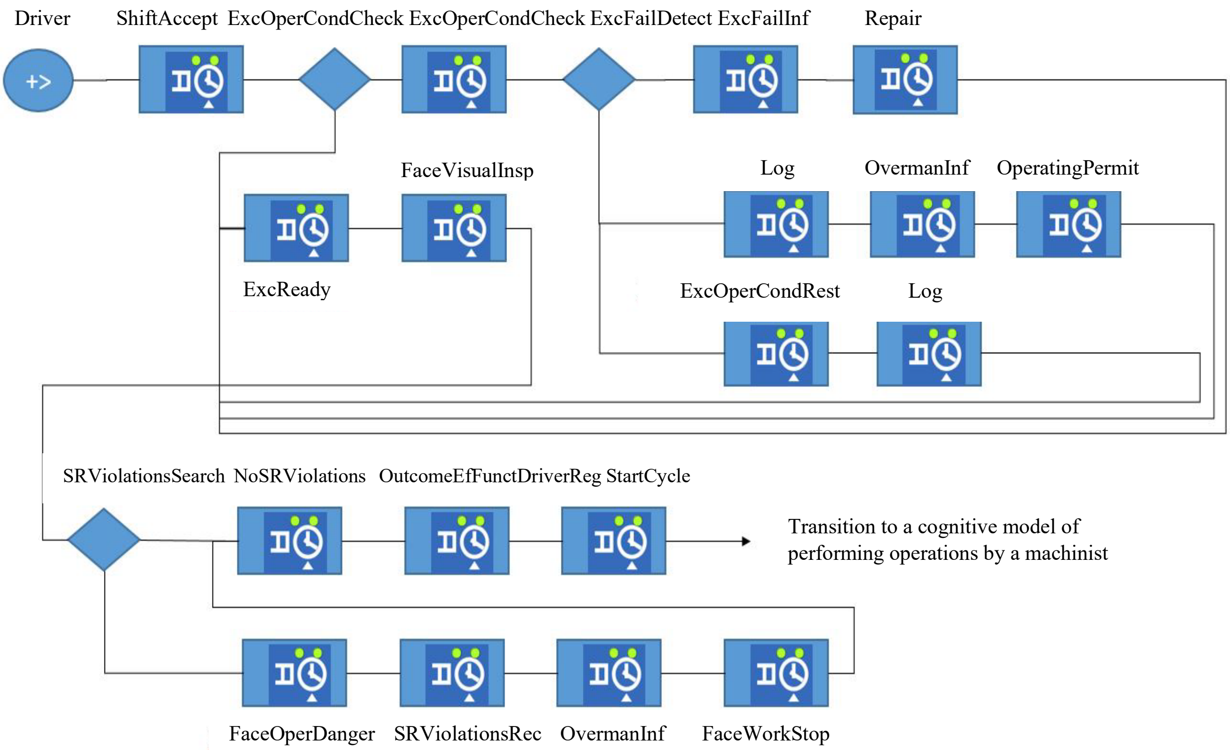

Fig. 4. Active objects and their environment in the AnyLogic combined simulation model

Tables 3–9 present the comparison results of the data of modeling the process of risk occurrence and its development into a cause-and-effect sequence of a catastrophic accident and injury to personnel in the H–M–E system of the coal mine. Simulation studies in the AnyLogic system were carried out for the same model period of time (11 model hours — shift duration) and with the same input data (with 10 experimental identical runs of the model). In each of the experiments, the number of machinists, excavators and faces was five per shift.

Table 3

Statistics of reliability indicators of the "machine" and "environment" subsystem in the H–M–E system of the coal mine during shift acceptance, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
"Environment" subsystem											
Operation of the face is unsafe	11	5	10	6	15	13	13	16	13	24	13
Operation of the face is safe	89	95	90	92	85	87	87	84	88	76	87
"Machine" subsystem											
Emergency failure	–	–	–	–	–	–	–	–	–	–	–
Complex malfunctions	–	–	–	–	–	–	–	–	–	–	–
Troubleshooting issues	–	100	–	–	100	–	–	–	100	–	100
Operation time	100	100	100	100	100	100	100	100	100	100	100
Repair time	–	–		–	–	–		–	–	–	–

At the acceptance of the shift by the drivers, the malfunctions that could be eliminated were detected, which did not affect the unplanned downtime of the excavators, as a result of which the excavators were in operation all the time.

In 87% of cases, when accepting a shift, the drivers did not detect violations of the requirements of the rules of industrial safety in the face. In 13% of cases, violations were detected, which led to the downtime of the stripping face "until the violations were eliminated".

Table 4

Statistics of the reasons for reliability decrease of the subsystems "machine", "environment" when performing a cycle of excavation and loading operations, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
"Environment" subsystem											
Violations on the human factor	46	61	52	67	53	60	64	65	56	48	57
Violations due to the unsatisfactory state of the external environment	54	39	48	33	47	40	36	35	44	52	43
"Machine" subsystem											
Failures during operation	21	9	25	31	18	24	16	17	25	20	21
Failures due to poor organization of work	79	91	75	69	82	76	84	83	75	80	79

During the cycle of excavation and loading operations, at visual inspection by the machinists, deviations in the operation of the excavator were detected and local violations of industrial safety requirements in the overburden were allowed. About 57% of the violations in the face were due to the human factor, which was due to the insufficiently efficient organization of the operating personnel work (lack of proper control by the line engineers and technicians, suspension of work due to violations). Similarly, the insufficiently effective organization of work affected the failures of the excavator during the execution of work (failure to carry out scheduled repairs, run-to-failure).

Table 5

Statistics of the driver's reaction to the loss of the dynamic equilibrium of the H–M–E system, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
Complete elimination of the deviation	44	46	42	55	56	56	55	63	46	49	51
Partial elimination of the deviation	24	26	32	22	25	27	18	20	22	30	25
The deviation cannot be eliminated	32	28	26	22	19	17	27	17	32	21	24

During the realization of emergencies, in 51% of cases, the drivers completely eliminated deviations from the normal operating mode of the excavator and the face. At the same time, the proportion of partially eliminated violations and violations that could not be eliminated was approximately the same.

In the rows of Table 6, statistics on the actions of the driver in case of violation of the dynamic equilibrium of the system are presented in fractions according to the following scenarios: 1 — "partial elimination of the deviations occurred", 2 — "deviations cannot be eliminated".

Table 6

Statistics of the driver's actions to the loss of the dynamic equilibrium of the H–M–E system, %

Experiment no./ operation	1	2	3	4	5	6	7	8	9	10	Average
Precise action	–/–	7/10	10/–	–/1	–/–	9/14	8/–	7/–	7/5	–/–	8/7
Erroneous action	100/100	93/90	90/100	17/16	96/100	91/86	92/100	93/100	93/91	100/100	86/88
Inaction	–/–	–/–	–/–	–/–	6/–	–/–	–/–	–/–	–/5	–/–	6/5

With partial elimination of the deviation in 86% of cases, the attempts of the drivers to stabilize the operation of the H–M–E system were erroneous and only 8% were successful. As a result, erroneous actions led to an increase in the proportion of deviations that could not be eliminated.

Table 7

Statistics of alternative outcomes of the model, %

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Average
Adverse environmental effects	24	22	23	16	24	24	20	19	26	30	23
Excavator failure	12	4	14	16	8	11	7	9	10	7	10
Inefficient organization of work	43	41	38	32	40	38	42	41	28	35	38
Operating personnel	22	33	25	36	28	27	31	31	36	28	30

Most often, the combined model realized alternative outcomes associated with inefficient organization of work and operating personnel. Thus, the human factor was the main reason for the loss of dynamic equilibrium by the H–M–E system during the stripping face simulation.

Table 8

Statistics on the risk type realization in the H–M–E system of the open-pit coal mine, %

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Average
Dangerous mistake	53	55	33	61	55	61	55	48	46	68	53
Dangerous failure	45	40	61	36	39	39	42	48	49	32	43
Operating personnel	3	5	6	3	6	0	3	4	6	–	4

According to statistics, the risk associated with the assumption of a dangerous mistake by machinists during stripping operations was most often realized; its share was 53%. The share of dangerous excavator failure accounted for 43% of cases, operating personnel — 4%. Thus, the trigger for the development of risk was the human factor due to the insufficiently effective organization of work. The effect of the human factor was amplified by the error of the driver in the process of work, which could lead to a domino effect when risks were realized.

In the rows of Table 9, the results of modeling the three outcomes of the experiment in the realization of risk are presented through a fraction: 1 — "dangerous error", 2 — "dangerous failure", 3 — "uncalculated external influence".

Table 9

Statistics of experiment outcomes in the realization of risk in three scenarios, number of cases

Experiment no./ type of outcome	1	2	3	4	5	6	7	8	9	10	Total
Dangerous situations have occurred	20/ 17/ 1	29/ 21/ 3	12/ 22/ 2	20/ 12/ 1	17/ 12/ 2	20/ 13/ –	17/ 13/ 1	12/ 12/ 1	16/ 17/ 2	15/ 7/ –	178/ 146/ 13
Dangerous situations have been eliminated	19/ 17/ 1	26/ 18/ 3	12/ 21/ 1	17/ 12/ 1	16/ 10/ 1	20/ 13/ –	16/ 12/ 1	9/ 10/ 1	16/ 16/ 2	14/ 6/ –	165/ 135/ 11
"Human" subsystem failure	–/ –/ –	1/ 1/ –	–/ 1/ –	3/ –/ –	–/ –/ 1	–/ –/ –	–/ 1/ –	1/ –/ –	–/ –/ –	–/ –/ –	5/ 3/ 1
Catastrophe	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
Incident, accident, failure	–/ –/ –	1/ 1/ –	–/ 1/ –	3/ –/ –	–/ –/ 1	–/ –/ –	–/ 1/ –	1/ –/ –	–/ –/ –	–/ –/ –	5/ 3/ 1
Injury to personnel	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
"Machine" subsystem failure	1/ –/ –	2/ 2/ –	–/ –/ 1	–/ –/ –	1/ 2/ –	–/ –/ –	1/ –/ –	2/ 2/ –	–/ 1/ –	1/ 1/ –	8/ 8/ 1
Catastrophe	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –
Incident, accident, failure	1/ –/ –	2/ 2/ –	–/ –/ 1	–/ –/ –	1/ 2/ –	–/ –/ –	1/ –/ –	2/ 2/ –	–/ 1/ –	1/ 1/ –	8/ 8/ 1
Injury to personnel	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –	–/ –/ –

Analyzing the results of modeling the outcome of "Dangerous error" risk, we can conclude that in 93% of cases the system was able to bring to dynamic equilibrium due to the activation of the excavator protection and the precise reaction of the driver. Nevertheless, the protection of the excavator failed more often, as a result of which the "machine" subsystem had a greater impact on the implementation of this risk. In turn, the failure of the excavator protection may occur due to untimely scheduled repairs or failure to carry out scheduled inspections of the operation of regular protections and locks of the excavator, which was a consequence of the human factor.

When implementing the outcome of the risk of "Dangerous Failure", it was possible to bring the system into dynamic equilibrium in 92% of cases. At the same time, failures of the "machine" subsystem also constituted the main cause of the occurrence of a risky event "Incident/accident/refusal".

When implementing the outcome of the risk of "Uncalculated external influence", it was possible to bring the system into dynamic equilibrium in 85% of cases. At the same time, one failure was registered for the "man" subsystem and the "machine" subsystem.

Discussion and Conclusion. Based on the results of simulation experiments on modeling the process of risk occurrence and its development into a causal chain of a catastrophic accident and injury to personnel in the H–M–E system of the coal mine, it was concluded that the most significant contribution to the prerequisites for the realization of risk in the H–M–E system was made by the "man" subsystem. Despite the fact that when implementing the outcomes of "Dangerous failure" and "Dangerous error", the risks of "Incident/accident/failure" occurred due to a decrease in the reliability of the "machine" subsystem, they were caused by the actions or inaction of personnel, that is, the human factor.

The decrease in the reliability of the "environment" subsystem, according to the results of the simulation experiment, was 57% due to the human factor (intentional deviations from the work project, the admission of violations in the race for volumes). And only 43% was due to the consequences of the unsatisfactory state of the face. In turn, the unsatisfactory condition of the face was a consequence of low performance discipline of the machinist in combination with insufficiently effective production control by line engineers and technicians.

The decrease in the reliability of the "machine" subsystem was also a consequence of the influence of the human factor, since failures of mining equipment in 79% of cases occurred due to insufficiently efficient organization of work, which led to an increase in unplanned downtime of the main technological equipment.

It should also be noted that during the simulation experiments, there were no realizations of the risk of accidents with catastrophic consequences and injury to personnel during stripping operations. The following conclusions can be drawn from this fact:

1. Safety and control measures applied during stripping operations are effective and prevent the occurrence of serious accidents or injuries successfully.
2. A safety model or methodology of work was used, which demonstrated high efficiency in preventing potentially dangerous situations.
3. The results of the experiments indicated competent training of personnel in the rules of safe performance of stripping operations and strict compliance with the established procedures.
4. The absence of cases of injury to personnel indicated that all systems and equipment were functioning at a level that kept the risk of injury at the maximum permissible values.

At the same time, it should be emphasized that the absolute absence of accidents and injuries to personnel during the run of the simulation model does not guarantee complete safety of future operations. In order to confirm the results of simulation experiments and further ensure safety, it is recommended to conduct a systematic risk assessment, analyze previous incidents and constantly improve mechanisms and procedures aimed at maintaining/improving the level of safety at the coal mine.

Simulation modeling technologies for the first time in the domestic practice of research of the H–M–E system have received an application for the analysis of complex safety indicators during open-pit mining. The presented results and testing of simulation technology can be widely used in the analysis of safety of complex technical systems, taking into account the influence of human and technogenic factors.

References

1. Barishpolets VA, Makhutov NA, Bekker AD, Bobrov YuV, Vlasov YuV, Gadenin MM, et al. *Bezopasnost' Rossii. Pravovye, sotsial'no-ekonomicheskie i nauchno-tekhnicheskie aspekty. Bezopasnost' slozhnykh cheloveko-mashinnykh sistem.* Barishpolets V.A. (red.). Monograph. Moscow: IHPF Znanie; 2021. 432 p. (In Russ.).

2. Makhutov NA. *Security of Russia. The human factor in security problems.* Moscow: IHPF Znanie; 2008. 688 p. (In Russ.).

3. Shchiryi AO. Sovmeshchenie sobytiinoi i poshagovoi skhem diskretnogo imitatsionnogo modelirovaniya. *News of the Tula state university. Technical sciences.* 2022;(12):338–342. https://doi.org/10.24412/2071-6168-2022-12-338-343 (In Russ.).

4. Khemdi A Takha. *Vvedenie v issledovanie operatsii.* Moscow: Williams Publishing house; 2005. 912 p. (In Russ.).

5. Zyryanov AA, Dorrer MG. Otsenka pokazatelei biznes-protsessov na osnove GERT-setei. *Conifers of the boreal area.* 2012;30(5–6):57–63. URL: https://cyberleninka.ru/article/n/otsenka-pokazateley-biznes-protsessov-na-osnove-gert-setey/viewer (accessed: 12.09.2023). (In Russ.).

6. Zyryanov AA, Dorrer MG. Translyatsiya modeli biznes-protsessov v notatsii ARIS eEPC v GERT-set'. In: *Proceedings of XI international conference on financial and actuarial mathematics and eventology of safety.* Krasnoyarsk; 2012. P. 187–197. URL: http://fam.conf.sfu-kras.ru/adds/XI-fames-2012-05-16-e-version.pdf (accessed: 09.09.2023). (In Russ.).

7. Sheer AV. *ARIS-modelirovanie biznes-protsessov.* 3-d ed. Moscow: Williams Publishing house; 2009. 223 p. (In Russ.).

8. Glukhova KI, Bekmansurova AR, Kuchina TN. Poryadok deistvii pri avtomatizatsii biznes-protsessov. *Chronos: estestvennye i tekhnicheskie nauki.* 2020;5(33):9–10. https://doi.org/10.24412/2712-9691-2020-533-9-10 (In Russ.).

9. Shtykova AS. Obzor nekotorykh vozmozhnostei sredy Anylogic. *Forum molodykh uchenykh.* 2017;2(6):301–306.

10. Dorrer MG, Lantsev EA, Shargaeva AI. Sobytiinyi analiz biznes-protsessov v notatsii eEPC. In: *Trudy XV Mezhdunarodnoi konferentsii po eventologicheskoi matematike i smezhnym voprosam.* Krasnoyarsk; 2011. P. 89–96. URL: https://sciup.org/140277916 (accessed: 09.10.2023). (In Russ.).

11. Lantsev EA, Dorrer MG. Creating agent-based model from the business process discrete-event model. *Computing, Telecommunication, and Control.* 2013;3(174):44–52. URL: https://infocom.spbstu.ru/userfiles/files/articles/2013/3/05_lantsev.pdf (accessed: 09.10.2023). (In Russ.).

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