Journal of Innovations
in Business and Industry

Vol. 01, No. 03 (2023) 155-160, doi: 10.61552/JIBI.2023.03.006 - http://jibi.aspur.rs

METHODOLOGICAL ASPECTS OF SIMULATION MODELING OF EMERGENCY INTERACTION OF LIFE SUPPORT FACLITIES

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Received 29.04.2023.
Revised 12.07.2023.
Accepted 21.08.2023.

Keywords:

Life support system, accidents, intersystem interaction, negative consequences, general algorithm.

Original research

A B S T R A C T

An important component of the sustainable functioning of urbanized territories are life support systems that provide the main indicators of the quality of life of the population both in normal conditions and in emergency situations of man-made and natural character. Such systems primarily include power supply systems, gas supply, heat supply, water supply, transport, etc. Accidents in life support systems lead to large-scale and long-term negative social, material, financial and environmental consequences. Especially severe consequences are associated with intersystem accidents, when the termination or restriction in functioning affects two or more life support systems. The report discusses methodological issues of simulation of emergency interaction of life support systems, an algorithm and a general scheme for resilient assessing are proposed.

1. INTRODUCTION

An important component of the stable functioning of urbanized territories are life support facilities, which provide the main indicators of the quality of life of the population both in normal conditions and in emergency situations of man-made and natural character (Yoo et al., 2003; Badina et al., 2022). Such facilities include, first of all, power, gas, heat, water, transport and other facilities (Jacobson & Delucchi, 2011). Accidents in life support facilities lead to large-scale and long-term negative social, material, financial and ecological consequences (Sovacool, 2008). Particularly severe consequences are associated with intersystem accidents (ISA), when the termination or limitation of functioning affects two or more life support facilities (LSF).

The study of intersystem accidents within the framework of risk theory and the concept of adaptive resilience considers the development of such methods and models that allow to assess not only the risks of intersystem accidents, but also to assess the duration and costs of restoration of life support facilities and territory (Jiang et al., 2020; Taarup-Esbensen, 2020). The development of mathematical models of emergency interaction of life support facilities is an urgent research area for a number of years (Jia et al., 2007, Lee et al., 2009; Habibet et al., 2016). Taking into consideration the difficulties of formal description of the interaction of heterogeneous life support facilities, the focus has been on modeling the emergency behavior of electric power facilities (Parker et al., 2003; Dobson et al., 2005), modeling the interaction of two facilities, for example, electric power and gas supply facilities (Lesnykh et al., 2016), electric power and water supply (Yu & Baroud, 2019). There is a number of problems that make it difficult to model the emergency interaction of two or

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more life support facilities (Su & Shih, 2003). First of all, it is different dynamics of emergency disturbance propagation in the facilities: in the electric power facilities the propagation is almost instantaneous, in the gas supply facilities it can reach several hours, and in the heat supply facilities - several days. Another difficulty is related to the formalization of the disturbance transfer function between the facilities (Oró et al., 2015). If for the energy facilities the energy equivalent (Lesnykh et al., 2016) can be used, for other facilities the description of such a function requires additional research.

2. MODELING THE EMERGENCY INTERACTION OF LIFE SUPPORT FACILITIES

The main purpose of modeling the emergency interaction of life support facilities is to assess the level of adaptive resilience of LSF to intersystem accidents. The total negative consequences (direct and indirect social, material, financial and environmental damage), the duration and costs of the restoration of LSF to the normal level of functioning can act as criteria of adaptive resilience (Liu et al., 2022).

ISA modeling is conducted for the selected territory, to which the structure and categories of consumers, the specified composition and structure of life support facilities correspond. Life support facilities are attached to the main groups of consumers (public utilities, industry, services, etc.) (Culhane et al., 2022).

The most effective method that allows to realize a model of such processes, taking into account the influence of a large number of random factors is simulation modeling (Bauer et al. 2006). Let us consider sequentially all the main elements of the ISA simulation modeling algorithm. The proposed algorithm is a development of the conceptual model of interaction of life support facilities during intersystem accidents (Liu et al., 2019; Lesnykh & Timofeeva, 2021).

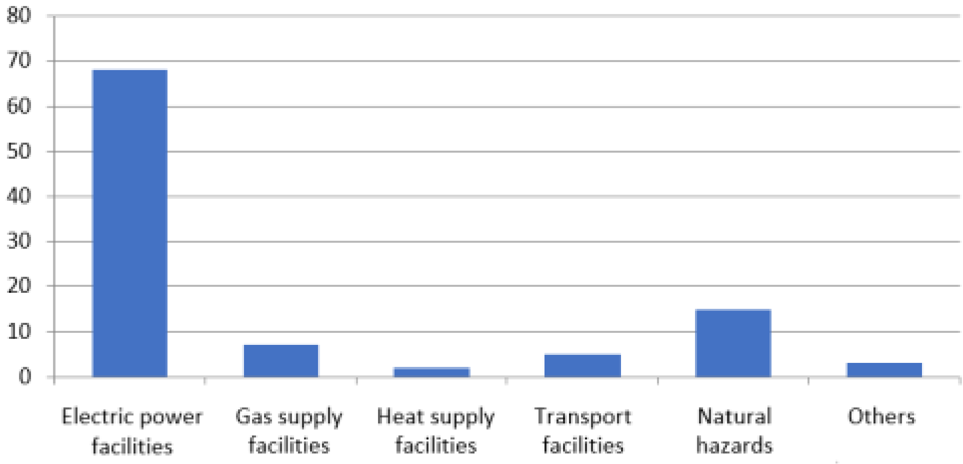

Figure 1. Histogram of ISA distribution by triggering event location

Step 1. For the given initial data, the modeling of emergency processes begins with the selection of the initiating life support facility. Analysis of statistical data also showed that the most frequent initiating event of intersystem accidents are accidents in electric power facilities, the histogram of the frequency distribution of ISA initiating of life support facilities is shown in Figure 1. This diagram is converted into a distribution histogram and can be used in the first step of ISA modeling to generate the type of initiating accident facility.

To select the initiating system of intersystem accidents, you can use statistical data for a particular territory and a particular composition of life support facilities. Analysis of the operation of life support facilities revealed the following main causes of accidents (Yunus & Abdulkarim, 2022):

• Dilapidation, poor preparation of engineering infrastructure for the heating season (36%);

• failure to comply with the rules of technical operation of equipment, unskilled actions of maintenance personnel (32%);

• natural factors and natural disasters (21%);

• unauthorized power cuts, gas explosions, fires, etc. (11%)

Statistics on 80,000 accidents and incidents during the year show that 47% occur in water supply facilities and 16% - in heat supply facilities. According to the data collected, repairs last on average 8.5 hours .

Step 2. After determining the initiating ISA facility it is necessary to determine the cause of the accident and identify the emergency element of the life support facility (for example, LSF-1). Determination of the emergency element of the LSF-1 facility is carried out for a given configuration of the facility (composition and number of main elements, types of relationship between the elements) is carried out with Monte Carlo method based on statistical data on the causes and frequency of accidents at LSF-1 objects.

Step 3. The next stage of ISA modeling is the selection of the accident development scenario in LSF-1. Complexities of formation of emergency scenarios, especially for a large-scale space distributed life support facility with a large number of equipment elements, lead to the need to form a typical set of scenarios based on a preliminary analysis of statistical data.

Step 4. For the chosen scenario of the emergency situation a number of indicators are assessed: the number of elements of LSF-1 involved, material, social, financial and environmental consequences of the scenario, the duration of elimination of consequences and restoration of normal functioning of LSF-1. The assessment of consequences and duration of restoration is performed both on the basis of data obtained from regulatory documents, and on the basis of probability distributions or expert assessment to generate values of random parameters of the model.

The assessment of damage to consumers and the life support facility should be carried out with the possibility of redundancy, such as the use of a second source of electricity or reserve water supplies, which can reduce the amount of possible damage to consumers.

To assess total damage, direct and indirect damage must be determined on the basis of regulatory documents or using statistical data, including the distribution of damage as a random value.

The value of indirect losses in relation to direct losses is not constant, but varies depending on the type of production facility, type of products, scale of production, etc. According to the data (Arkhipets, 2005), this ratio for the main industrial sectors for industrial safety events (accidents, incidents) can vary from 30 to 300%. In this work, based on the analysis of a number of studies, it was found that between the damage from the failure of industrial equipment and the total losses of the enterprise associated with the restoration of production, downtime and other economic losses, there may be a larger scale ratio of 1:14 to 1:23. That is, indirect damage can exceed direct damage by an order of magnitude or more.

The assessment ratio between direct and indirect damage for labor safety events (fatalities, severe and minor injuries) is also a problem in its own right. This value varies within a fairly wide range. A ratio of 1:6 can be used for preliminary assessments (Timofeev, 2009).

Step 5. This element of the algorithm is key in the ISA modeling, because it is associated with the identification of elements of LSF-1, which may lead to the transfer of emergency perturbations to the interconnected life support facilities.

A formal representation of the interrelations between systems when an ISA occurs is a multidimensional matrix of interactions. This matrix should contain the following information: type of initiating system, number of the considered node; type of "receiving" system, number of the considered node; probability of influence; duration of expected outage; scale of expected consequences. The basic form of the interaction matrix must contain the values of conditional probabilities of transfer of emergency perturbation from the element of one facility to the element(s) of the other facility(ies).

Table 1 shows an example of an interaction matrix of two life support facilities. Each element of the P_{ij} matrix represents the conditional probability that an accident that occurred in the *i*-th element of the first facility will lead to an accident in the *j*-th element of the second facility. The values of the matrix elements are obtained as a result of the analysis of statistical data, or on the basis of expert assessment.

Table 1. Example of an interaction matrix between two life support facilities

Objects of Facility	1	2	3	…	*i*	…	*N*
1	$\boldsymbol{P_{11}}$	$\boldsymbol{P_{12}}$	$\boldsymbol{P_{13}}$	**…**	$\boldsymbol{P_{1i}}$	**…**	$\boldsymbol{P_{1N}}$
2	$\boldsymbol{P_{21}}$	$\boldsymbol{P_{22}}$	$\boldsymbol{P_{23}}$	**…**	$\boldsymbol{P_{2i}}$	**…**	$\boldsymbol{P_{2N}}$
3	P_{31}	P_{32}	P_{33}	…	P_{3i}	…	P_{3N}
…	…	…	…	…		…	…
j	P_{j1}	P_{j2}	P_{j3}	…	P_{ji}	…	P_{jN}
…	…	…	…	….		…	
M	P_{M1}	P_{M2}	P_{M3}	..	P_{Mi}	…	P_{MN}

Simulation of occurrence of emergency processes in the interconnected facility takes place in accordance with the values of conditional probability in the interaction matrix. If the modeling shows the possibility of perturbation transfer from LSF-1, for example, to LSF-2, then the type of perturbation function, type and characteristic of interrupted communication (energy or material equivalent), the duration of interruption and other characteristics are determined.

Random processes and quantities which values are random and for the calculation of which Monte Carlo-based statistical testing procedures are used include the following:

- The cause of the accident;
- Emergency element;
- Scenario of the development of the emergency process;
- The duration of the elimination of the accident;
- The value of direct and indirect damage;

- The possibility of transferring perturbation to interconnected facilities, etc.

The general scheme of the simulation ISA modeling algorithm is shown in Figure 2.

The implementation of the above simulation scheme will make it possible to assess the level of adaptive resilience of life support facilities, as well as to identify elements of these facilities that can initiate the intersystem development of emergency situations ("bottlenecks").

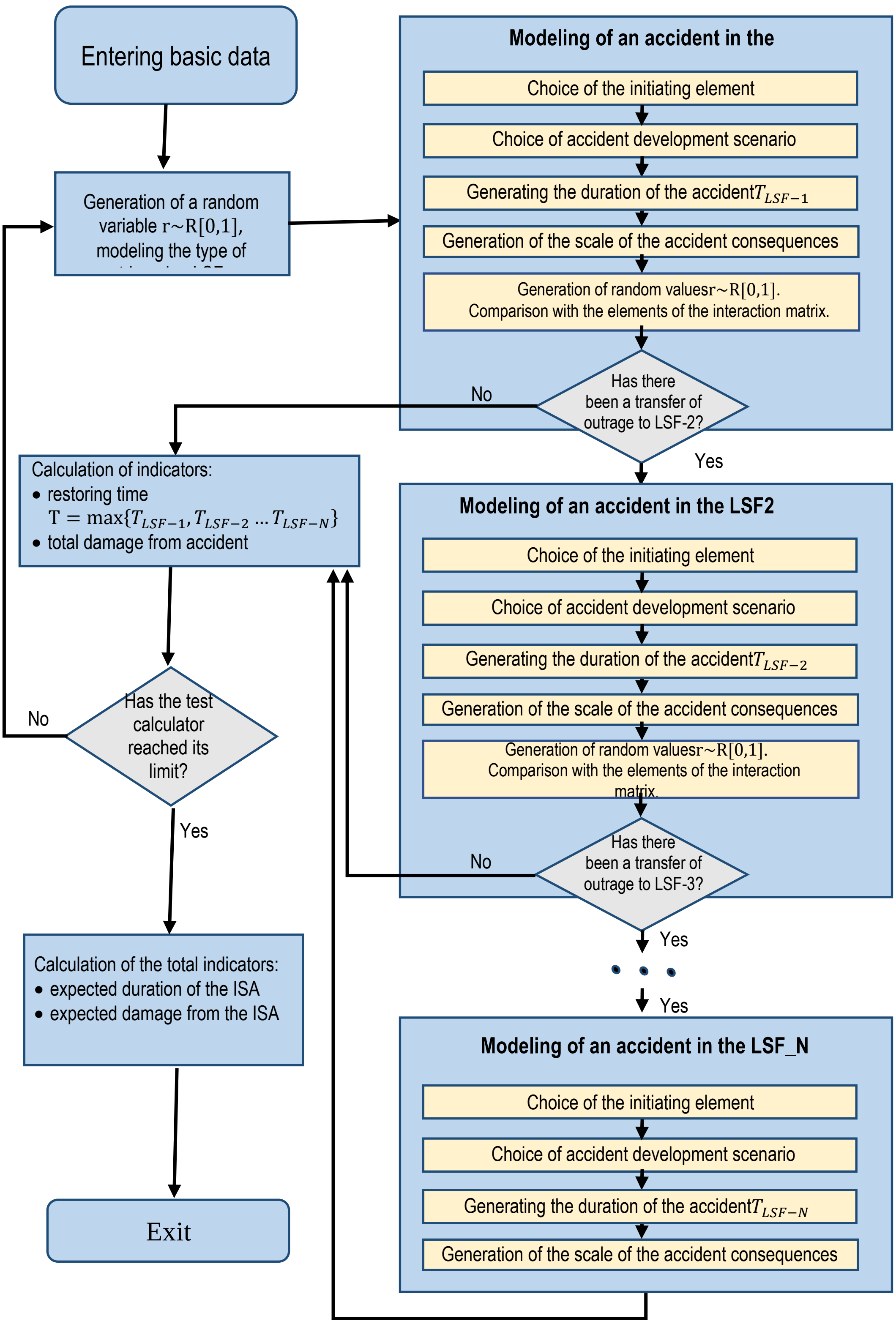

Figure 2. General scheme of the simulation ISA modeling algorithm

3. CONCLUSION

The work defines a methodical approach to the modeling of emergency interaction of life support facilities, develops the basic provisions and an algorithm for the simulation model describing this process. The ways for further research are outlined.

The most time-consuming task of future research is to develop and implement a system of ISA simulation models. It is advisable to begin this task with small cities or isolated territories, that will allow us to consider interconnected life support facilities in the limited area, as well as a limited number of possible ISA scenarios. In the future, this experience can be transferred to larger-scale infrastructure-complicated territories.

The main task of future research will focus on finding "bottlenecks" in the interconnected life support facilities that can initiate the intersystem development of emergency situations. Solving this problem with the help of simulation models will make it possible to assess the current level of adaptive resilience of life support facilities and, if necessary, justify the appropriate measures to reduce the risk of ISA.

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