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Article

Assessment of the protection level of continuous production based on the Markov life cycle model

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Abstract. The article discusses the current level of development of automation technologies for continuous production, taking into account the compliance with the requirements of the fourth industrial revolution Industry 4.0. A new classification of the levels of industrial safety of production processes is proposed, taking into account the stages of the plan for the localization and elimination of emergency situations. The states of the life cycle of continuous production are determined, taking into account the proposed classification. A mathematical model of the states of the life cycle of continuous production has been developed and their interrelations have been determined. Based on the analysis of the statistical data on the states of the life cycle of flat glass production, the probabilities of transitions between the states of the production life cycle are determined. As a result of the statistical analysis of the probabilities of state transitions for the production of sheet glass, it became possible to use the apparatus of Markov processes. The use of the apparatus of Markov processes made it possible to assess the probabilities of finding continuous production in each state of the life cycle. The MathCAD software package computed the probabilities for each state of the life cycle of sheet glass production. To determine the probabilities of life cycle states in the MathCAD software package, simulation modeling has been performed. The comparison of the results of calculating the probabilities of the states of the life cycle of production, obtained by the method of simulation and analytical calculation, has been carried out. The values of the calculated probabilities of the state of the life cycle of continuous production make it possible to use the “Arbiter"software package for the analysis of durability, survivability, safety, technical risk, expected damage and production efficiency.

Keywords: protection level, continuous production, Markov model, life cycle, simulation

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Оценка уровня защиты непрерывного производства на основе модели жизненного цикла Маркова

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Аннотация. В статье рассматривается современный уровень развития технологий автоматизации непрерывного производства с учетом соответствия требованиям четвертой промышленной революции Индустрии 4.0. Предложена новая классификация уровней промышленной безопасности производственных процессов с учетом этапов плана локализации и ликвидации чрезвычайных ситуаций. Состояния жизненного цикла непрерывного производства определяются с учетом предложенной классификации. Разработана математическая модель состояний жизненного цикла непрерывного производства и определены их взаимосвязи. На основе анализа статистических данных о состояниях жизненного цикла производства листового стекла определяются вероятности переходов между состояниями жизненного цикла производства. В результате статистического анализа вероятностей переходов состояний для производства листового стекла стало возможным использовать аппарат марковских процессов, что позволило оценить вероятности нахождения непрерывного производства в каждом состоянии жизненного цикла. Программный пакет MathCAD рассчитал вероятности для каждого состояния жизненного цикла производства листового стекла. Для определения вероятностей состояний жизненного цикла в программном пакете MathCAD было выполнено имитационное моделирование. Проведено сравнение результатов расчета вероятностей состояний жизненного цикла продукции, полученных методом имитационного и аналитического расчета. Значения рассчитанных вероятностей состояния жизненного цикла непрерывного производства позволяют использовать программный комплекс «Арбитр» для анализа долговечности, живучести, безопасности, технического риска, ожидаемого ущерба и эффективности производства.

Ключевые слова: уровень защиты, непрерывное производство, модель Маркова, жизненный цикл, моделирование

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Introduction

The current level of development of automation technologies allows the creation of production facilities that, under constant control of operators, can produce one type of product in an automatic mode. Modern automotive, glass, chemical and metallurgical enterprises mainly meet the requirements to automatic production. In order to meet the requirements of the fourth industrial revolution Industry 4.0, such industries must implement technologies of intelligent monitoring and autonomous decision-making to ensure real-time optimization of the activities of enterprises [1]. Many modern production facilities can be classified as hazardous facilities where physicochemical reactions take place at high pressure and with the release of heat, poisonous substances are used and wastes of I and II hazard classes are formed, etc. All this negatively affects the personnel of the enterprises and the environmental situation in the areas adjacent to the enterprises. Assessment of the level of industrial safety at different stages of the life cycle of continuous production is necessary to support decision-making to reduce possible environmental damage and improve the safety of production in general. Assessments of the level of industrial safety are the initial data for the Arbiter software package, which allows you to analyze the stability, survivability, safety, technical risk, expected damage and efficiency of production.

1. Classification of industrial safety levels

In the typical classification of industrial safety levels of production processes [2], the following levels are defined:

1) the design process;
2) the automatic control process;
3) the operator control process;
4) the action of the emergency protection system;
5) the action of active protection;
6) the action of passive protection;
7) impact on objects surrounding the enterprise.

This classification does not take into account the requirements of the methodological instructions RD 09-536-03 “On the procedure for developing a plan for the localization and elimination of emergency situations (PLEES) at chemical-technological facilities” for hazardous production facilities of I, II and III hazard classes[1]. In the operational part of the PLEES, three levels of emergency situations are defined: “A” describes a situation within one block of the object (workshop, installation, production site), which is a structural subdivision of the organization, “B” is characterized by the transition outside one block of the object (workshop, installation, production site) and its development within the organization, and “C” is a situation defined as development and going outside the territory of the organization, with the possibility of the impact of damaging factors on the population of nearby settlements and other organizations (objects), as well as

[1]RD 09-536-03: Methodical Instructions on the Order of Development of the Emergency Situations Localization and Liquidation Plan (ESLLP) at Chemical-Engineering Facilities. Available at: https://www.russiangost.com/p-19757-rd-09-536-03.aspx, https://standartgost.ru/g/pkey-14294816816/\T2A\CYRR\T2A\CYRD_09-536-03 (accessed 22 January 2021).

the environment. In the current decree of the Government of the Russian Federation of 15.09.2020 No. 1437 "On approval of the Regulation on the development of action plans for the containment and elimination of the consequences of accidents at hazardous production facilities", the PLAS levels "A" and "C" are used. Level "B" is reflected in the design documentation for facilities of I, II and III hazard classes. A new classification of industrial safety levels of production processes is proposed, taking into account the stages of the plan for the localization and elimination of emergency situations (Fig. 1).

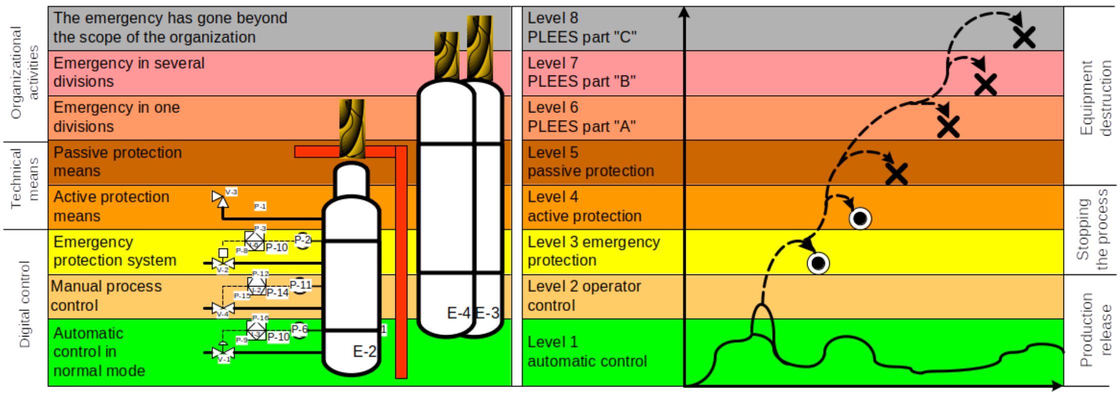

Fig. 1. Levels of industrial safety (collor online)

Level 1 shows the functioning of the technological process (TP) in the design mode. When external influences appear, the automatic control system provides process control. If the automatic control range is exceeded, alarms should be displayed for the operator at level 2, and the operator can manually control the process and bring it to a normal state at level 1. The operator can set new modes of operation of the TP. These two levels ensure the production of quality products.

If the critical parameters of the technological process are exceeded, despite the operator's actions, the industrial safety system is automatically activated (level 3). The industrial safety system ensures a safe shutdown of the process. Levels 1–3 are implemented by automated systems based on hardware and software complexes.

Process protection levels 1 to 7 are implemented within the enterprise. Level 8 is the responsibility of the administration of the region where the hazardous facility is located. It includes a system of measures to prepare for the protection and to protect the population and material assets from the dangers of man-made emergencies.

Level 4 provides active protection based on a system of safety valves, rupture discs, etc. At levels 3–4, product discontinuities occur. The equipment can be brought back into service after maintenance.

Level 5 is implemented by passive protection based on dams of oil parks and other protective systems. Level 6 characterizes an emergency situation within one block of an object (workshop, installation, production site). Level 7 includes a system of measures of the enterprise to prepare for the protection and to protect personnel and material assets from the dangers of man-made emergencies. Equipment destruction occurs at levels 5–8.

To increase the level of industrial safety, it is necessary to analyze the states of the life cycle of continuous production. The proposed classification of industrial safety levels is interconnected with various stages of the life cycle of continuous production. To analyze the level of industrial safety, it is necessary to determine the state of the life cycle of continuous production. Analysis of the reliability, durability, survivability, safety, technical risk, expected damage and efficiency of the production life cycle can be performed using the ARBITER software package [3]. However, to use it, it is necessary to determine the probabilities of finding continuous production in different states of the life cycle.

2. Formalization of life cycle states of continuous production

The process of managing the life cycle of production includes the stages from its design to complete dismantling [4]. Analysis of GOST R 56135-2014 "Life Cycle Management of Military Products. General provisions" and GOST R 57318-2016 "Industrial automation systems and integration. Application and management of systems engineering processes" shows that the following stages of the production life cycle can be determined: 1) production design for the release of a new product range, 2) production commissioning, 3) regular operation, 4) production maintenance, 5) modernization, 6) decommissioning of production.

Taking into account the levels of industrial safety for continuous production, it is proposed to distinguish the states: S_{01} — installation of tasks and structures for TP, S_{02} — installation of TP equipment, S_{03} — installation of a TP control system, S_{04} — bringing TP to normal mode, S_{05} — TP functioning in a regular automatic mode, S_{06} — TP functioning in normal manual control mode, S_{07} — TP functioning in emergency protection mode, S_{08} — TP functioning in active protection mode, S_{09} — TP functioning in passive protection mode, S_{10} — TP functioning in emergency mode of level "A", S_{11} — TP functioning in emergency mode of level "B", S_{12} — functioning of the TP in the emergency mode of level "C", S_{13} — stopping the normal mode of the TP and the release of high-quality products, S_{14} — maintenance, repair or dismantling of the TP control system, S_{15} — maintenance, repair or dismantling of TP equipment, S_{16} — maintenance, repair or dismantling of tasks and TP structures.

The relationship between the states of the production life cycle is shown in Fig. 2 in the form of a graph. States 1–3 refer to the creation of production and its modernization, 4 and 13 states correspond to the commissioning of production, 5 and 6 — the state of normal operation of production, from 7 to 12 — the state of accidents at production, from 14 on 17 — the state of utilization of production.

3. Simulation of life cycle states of production

A Markovian random process corresponds to the functioning of systems, which are characterized by a certain finite set of discrete states $S_1, S_2, \ldots, S_n$, the change of which occurs instantly at strictly defined predetermined known times 1, 2,. . . , k,. . . , K. When studying such systems, it is assumed that the probabilities of the transition P_{ij} of the system S in one step from the state S_i to the state S_j are known, which do not change from step to step (since the chain is homogeneous) [5]. Table 1 shows the probabilities P_{ij} of transitions between the states of the production life cycle, which are obtained on the basis of the analysis of statistical data on the states of the life cycle of flat glass production for the period 1997–2021.

In [5], an analysis of the analytical and simulation discrete Markov chain was carried out using the MathCAD software package for calculating the parameters. Let us simulate the life cycle of the production of flat glass based on the use of the apparatus of the

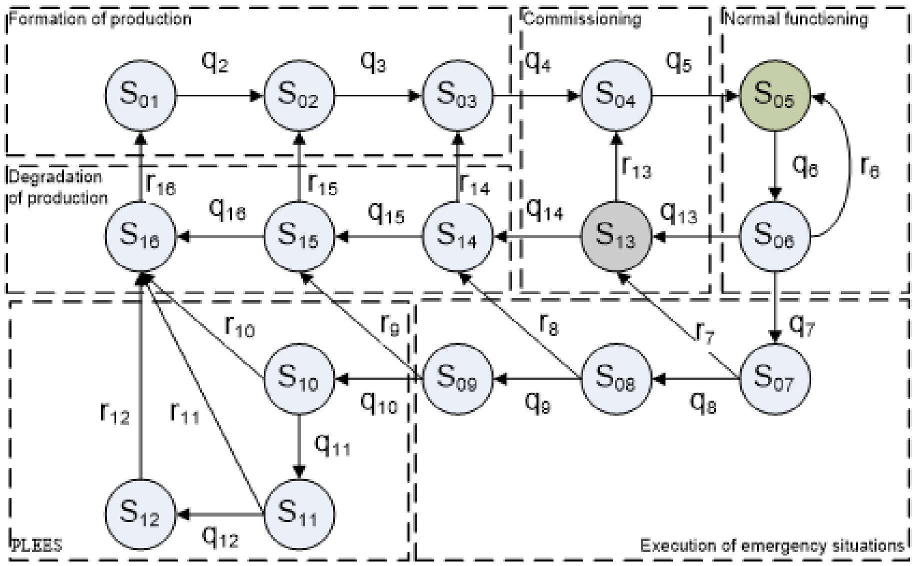

Fig. 2. The relationship between the states of the life cycle of production

Table 1

Probabilities P_{ij} of transitions between states of the life cycle of production

P_{ij}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.3	0.7														
2		0.2	0.8													
3			0.1	0.9												
4				0.1	0.9											
5					0.8	0.2										
6					0.75	0.1	0.05						0.1			
7							0.2	0.05					0.75			
8								0.1	0.05					0.85		
9									0.1	0.05					0.85	
10										0.1	0.05					0.85
11											0.1	0.05				0.85
12												0.1				0.9
13				0.8									0.1	0.1		
14			0.7											0.1	0.2	
15		0.7													0.1	0.2
16	0.8															0.2

Markov chain. On the basis of the matrix of transition probabilities (Table 1), a system of linear equations M is constructed.

Such a system of equations with zero free terms has an infinite set of solutions [5]. To obtain a unique solution, replace the last equation M with the relation $P_{ni} = 1$, where $i = 1..n$. To solve systems of linear algebraic equations of the form $MP = B$, where B is a vector of free terms, Mathcad uses the standard function lsolve (M, B), which returns a vector of unknown probabilities P. The results of analytical modeling are shown in Table 2. To determine the probabilities of the states of the life cycle of production in the MathCAD software package, the Si states are simulated by sequentially implementing the procedure for determining the outcome of tests by lot in accordance with the specified values of the transition probabilities (Table 1). The simulation results are shown in Table 2.

The values of the probabilities of the states of the life cycle, obtained as a result of

Table 2

Probabilities P_{ij} of transitions between states of the life cycle of production

No.	Lifecycle state name	Analytical modeling probability	Simulation probability	Difference
1	S_{01} — installation of tasks and structures for TP	$2.391e-4$	$2.314e-4$	$-7.667e-6$
2	S_{02} — installation of TP equipment	$9.342e-4$	$9.509e-4$	$1.665e-5$
3	S_{03} — installation of a TP control system	$3.624e-3$	$3.626e-3$	$2.452e-6$
4	S_{04} — bringing TP to normal mode	0.03	0.03	$5.738e-5$
5	S_{05} — TP functioning in a regular automatic mode	0.755	0.755	$-2.651e-4$
6	S_{06} — TP functioning in normal manual control mode	0.168	0.168	$1.648e-4$
7	S_{07} — TP functioning in emergency protection mode	0.01	0.01	$1.171e-5$
8	S_{08} — TP functioning in active protection mode,	$5.824e-4$	$5.879e-4$	$5.512e-6$
9	S_{09} — TP functioning in passive protection mode	$3.235e-5$	$3.08e-5$	$-1.555e-6$
10	S_{10} — TP functioning in emergency mode of level “A”	$1.797e-6$	$2.1e-6$	$3.025e-7$
11	S_{11} — TP functioning in emergency mode of level “B”	$9.986e-8$	$3.00e-7$	$2.001e-7$
12	S_{12} — functioning of the TP in the emergency mode of level “C”	$5.548e-9$	0	$-5.548e-9$
13	S_{13} — stopping the normal mode of the TP and the release of high-quality products	0.027	0.027	$2.573e-7$
14	S_{14} — maintenance, repair or dismantling of the TP control system	$3.591e-3$	$3.601e-3$	$9.706e-6$
15	S_{15} — maintenance, repair or dismantling of TP equipment	$8.286e-4$	$8.437e-4$	$1.506e-5$
16	S_{16} — maintenance, repair or dismantling of tasks and TP structures.	$2.092e-4$	$1.995e-4$	$-9.683e-6$

simulation modeling and by the method of analytical calculation, do not differ with an accuracy of the fourth decimal place.

Conclusion

On the basis of the proposed new classification of the industrial safety levels of production processes, taking into account the stages of the plan for the localization and elimination of emergency situations, the states of the life cycle of continuous production are determined. A mathematical model of the states of the life cycle of continuous production has been developed and their interrelations have been determined. Based on the analysis of statistical data on the states of the life cycle of sheet glass production, the probabilities of transitions between the states of the production life cycle are determined. In the MathCAD software package, the probabilities for each state of the life cycle of sheet glass production were calculated using the analytical method and the method of simulation. Obtaining the calculated probabilities allows further use of the Arbiter software package [3] for the analysis of the durability, survivability, safety, technical risk, expected damage and efficiency of the production life cycle.

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