

БЕЗОПАСНОСТЬ В ЧРЕЗВЫЧАЙНЫХ СИТУАЦИЯХ

SAFETY IN EMERGENCY SITUATIONS

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AN OVERVIEW OF THE REGIONAL SECURITY THEORY AND METHODOLOGICAL FOUNDATIONS

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Abstract. *Background.* The study is aimed at the development of theoretical and technical-organizational foundations for managing the safety and resilience of regional critical infrastructures. At the initial stage of our research, the analysis and positioning of the state-of-the-art theory of regional security among the existing fundamentals in the field of managing the development and functioning of complex dynamic systems are carried out. This is necessary for the subsequent enhancement of the formal apparatus used in modeling and automating the processes of ensuring the security of regional socio-economic systems and critical infrastructures of the region. *Materials and methods.* From the standpoints of a systems approach and the general principles of network-centric control, the methodological foundations of the theory of regional security as an independent and advanced field of knowledge are considered. The methodology of the regional security theory is built on the basis of well-known research areas: the stability theory, the reliability theory, risk management, the sensibility theory, the viability theory, the resilience theory and other scientific concepts that are ideologically complementary to the science of the security of socio-economic systems and develop it in goal-setting, missions, used methods and means. *Results and conclusions.* The range of regional security theory problems and its place among other scientific disciplines subject to the class of the object under study (regional socio-economic system), control modes and the impact nature of the external and internal factors are determined. At a qualitative level, ways are proposed to extend and adapt the developed theory of regional security to the problems of managing the resilience of regional critical infrastructures. The application substantiation of the considered regional security methodology for fully solving these problems is given.

Keywords: systems analysis, regional security theory, control, methodological foundations, stability, reliability, resilience, risk management

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ТЕОРЕТИЧЕСКИЕ ОСНОВЫ УПРАВЛЕНИЯ РЕГИОНАЛЬНОЙ БЕЗОПАСНОСТЬЮ

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Аннотация. *Актуальность и цели.* Работа направлена на разработку теоретических и организационно-технических основ управления безопасностью и жизнеспособностью региональных критических инфраструктур. На первом этапе исследований проводится анализ и позиционирование теории региональной безопасно-

сти среди существующих теоретических разработок в области управления развитием и функционированием сложных динамических систем. Это необходимо для последующего совершенствования формального аппарата, используемого при моделировании и автоматизации процессов обеспечения безопасности региональных социально-экономических систем и критических инфраструктур региона. *Материалы и методы.* С позиций системного подхода и общих принципов сетцентрического управления рассмотрены методологические основы теории региональной безопасности как самостоятельной и перспективной области знаний. Методология теории региональной безопасности построена на базе известных научных направлений: теории устойчивости, теории надежности, риск менеджмента, теории чувствительности, теории живучести, теории жизнеспособности и других концепций, идеологически комплементарных науке о безопасности социально-экономических систем и развивающих ее в целом. Задачами, используемых методах и средствах. *Результаты и выводы.* Определен круг проблем теории региональной безопасности и ее место среди других научных дисциплин с учетом класса исследуемого объекта (региональной социально-экономической системы), способов управления и характера воздействия внешних и внутренних факторов. На качественном уровне предложены пути расширения разрабатываемой теории региональной безопасности на задачи управления жизнеспособностью региональных критических инфраструктур. Дано обоснование применения методологии региональной безопасности к комплексному решению этих задач.

Ключевые слова: системный анализ, теория региональной безопасности, управление, методологические основы, устойчивость, надежность, жизнеспособность, риск-менеджмент

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Introduction

Regional security is a relatively young and promising research streamline in the security sciences making a significant contribution to the development of the state-of-the-art security theory of complex systems. However, the basic theoretical statements and approaches of this dynamically developing branch of knowledge still require in-depth study and analysis. The entire world research community, including the leading scientists of our country, is actively involved in problem-solving related to the development of the theory and methods of regional security management. Meanwhile, it should be mentioned that in practice many of these problems still remain not fully resolved. At the present stage of the country's development characterized by escalation, pressure, tension and uncertainty of the geopolitical situation in the world, ensuring regional security and resilience of the regional critical infrastructures is one of the foreground strategic tasks of the state, along with the organization of complex interdisciplinary research in this problem domain. Regional security is an important component in the country's national security system. The need to develop an integrated knowledge system in the field of regional security is stipulated by the emergence of new challenges under global threats growth: crisis phenomena in the world economy, international conflicts, global climate change, energy shortages, natural disasters, pandemics, etc. As a result, all that requires the development of theoretical and technical-organizational foundations for regional security ensuring and support, scientifically grounded methods and tools for management problem-solving of risk and security of the regional critical infrastructures, as well as new technologies built on their basis and applicable in practice to maintain the resilience of various categories critical facilities of the region under the impact of internal and external threats of various nature and scale.

It must be admitted that there is still no unified theory of regional security generalized for various fields of economic activity and branches of knowledge (humanitarian, natural and technical sciences). The scientific and technical literature is mainly dominated by verbal representations on the regional security as a field of research, along with strict formalized definitions, which are practically missed. It is well known from practice that the security problem agenda of the regional system functioning is directly related to the parameters variation of system state as a result of the impact of negative internal or external factors on the system elements. That leads to the initiation of crisis phenomena and emergence situations. Thus, regional security ensuring is not possible without the stability and controllability analysis of critical facilities and infrastructures of the region. At the same time, the violation of regional security is in theoretical terms determined by the state transition dynamics of the socio-economic system or its individual critical elements from a state of stability to an unstable state.

Sustainable development and regional security are interconnected to each other: the lower the tension is in the social sphere, the higher the environmental sustainability and efficiency of the economy are, than the higher the life quality of the region population and the level of its security are, and the more perfect the system of regional security ensuring is, than the more stable the all critical facilities, processes and infra-

structures operates. Then the principle and formula of "regional security ensuring via sustainable development" can be reasonable used as a basis for developing and implementing the security management methodology of the regional socio-economic systems.

The concept of "regional security" is quite clearly defined and formalized in [1]. In general, regional security is understood as such a protectability state of the regional socio-economic system when the impact of external and internal factors does not lead to deterioration or impossibility of system functioning and development. This definition is considered well acceptable, but needs some minor clarification. Since the given definition of regional security interprets it through the system (region) state, which is specified by a set of parameter values of the system elements fixed at some instant, in the most general form the regional security ensuring expects the arrangement of favorable conditions when the impact of external and internal factors does not lead to the state parameters deterioration of the critical elements of regional system or to the impossibility of their functioning and development.

The objective of this study is analysis and positioning the theory of regional security among the existing theoretical evidence in the field of development and functioning management of the complex dynamic systems. This is necessary both to identify the specific features of the theory of regional security and determine the classes of problems solved by methods characteristic to this theory, and to improve the mathematical apparatus used in modeling and automating the processes of security ensuring of regional socio-economic systems and critical infrastructures of the region.

The work has a traditional structure and consists of two main. In the first section, from the standpoint of a systems approach, the methodological foundations of the theory of regional security and its place among the related research concepts: stability theory, reliability theory, control theory, risk management, sensitivity theory, survivability theory, resilience theory that are ideologically complementary to the security science of the socio-economic systems and developing it in goal-setting, scope, agenda, methods and tools used, are considered. The second section is debatable and touches upon general issues of extending the methodology of regional security to the management problems of the regional critical infrastructure resilience, as well as the basic principles of the system engineering theory and practice for regional security ensuring under the impact of external and internal disturbances on the controlled object (infrastructure).

Background

Historically, the need to ensure the protectability of socio-economic systems from various types of threats and the prospect of the science of regional security have always existed throughout the entire period of research on the security problems and issues of society and the state. However, regional security as an independent research guideline was arisen and come out in progress relatively not long ago. At present, the theory of regional security is an interdisciplinary knowledge system on methods and approaches to protection and resilience support of the regional socio-economic systems. Despite the seemingly applied orientation of this doctrine *prima facie*, regional security, as a scientific discipline, has a high predictive value and usefulness for solving new, sometimes unexpected and non-standard problems that origin within the management process of the risk-sustainable development of regional socio-economic systems. This discipline is supported by well-known theoretical laws and systematized empirical facts on the nature of threats and dangers, operates with its own categories and abstractions, contains axioms and theorems, has a logically built methodology for analysis and counteraction the negative trends. According to the National Security Strategy of the Russian Federation [2], the public policy in the field of regional security ensuring is carried out in three main areas:

- 1) problem monitoring and threat prevention of emergency and crisis situations initiation in the regions, the implementation of anti-crisis measures appropriate to the situation;
- 2) scenario analysis, forecasting and mitigation of the security violation risks of regional critical infrastructures;
- 3) system development and enhancement of the distributed situational centers at the regional level for a comprehensive problem-solving of security ensuring and evaluating of critical facilities of the region, as well as efficiency enhancement of public administration in this area.

These problem-solving in practice is impossible without a deep insight of the theoretical foundations, principles and approaches on which the modern theory of regional security is based. Thus, the essential impact on fundamental development of the theory of regional security in the formation and key ideas generation phase was made by such universally recognized and established scientific conceptions as the general system theory and system analysis, control theory, decision theory, risk theory, catastrophe theory, stability theory, reliability theory, survivability theory, probability theory, operations research, sensitivity theory and many other disciplines that are in some way related and similar to security in terms of goal setting and missions. The most common problems that unite these theories cover the following: modeling and analysis of

the behavior of complex dynamic systems (socio-economic, natural-industrial, technical, cyber-physical, etc.) under uncertainty on mathematical models; studying the characteristics dynamics of the complex objects that are under the influence of internal and external factors (disturbances) and determine the structural integrity, functionality and resilience of these systems; development of mechanisms for stabilizing dynamic systems and the processes running in it under conditions of critical situations emergence and loss of stability; synthesis of regulators – systems for stability and protectability control of complex objects in the process of influencing their functioning by multiple threats under various development scenarios of the adverse events, object behavior and modes of operation of these objects.

The problems-solving stated above is based on the application of a systems approach, which also underlies all the listed above research concepts, ideologically adjacent to the security theory. The systems approach allows visually representing and modeling the structure of critical facilities, critical infrastructures and security support systems, conducting system functional decomposition, defining behavior mechanisms and patterns of system elements and specificities of their interaction, describing input and output influences and the nature of the external environment, identifying the trends in system operation, as well as assessing both the relevance of goals and action chains to achieve them and the adequacy analysis of chosen system control algorithms subject to hypotheses suggested and modeling objectives assigned. Using the methods of system analysis, it is possible to establish, how the system components behavior differs from the system as a whole (e.g. when the system elements function stably, but at the same time the system itself is unstable, or otherwise). Another situation is typical for the class of macrosystems [3] such as regional socio-economic systems, when an object (system) has a deterministic type of behavior, and its subsystems operate in some non-deterministic way. These features emphasize the applied value of the systems approach using for the management problem-solving of the macrosystem security and in the theory of regional security. Examples of studying various aspects of regional security based on the methods of system analysis, cybernetics and operations research are given in [4-9].

Then, let us consider the methodological basis of the theory of regional security and its relationship with congenial research concepts, on the major ideas and statements of which it is built. Thereto, let us analyze and examine the conceptual model of the regional socio-economic system, presented in the form of a black box and including critical infrastructures and critical facilities (Fig. 1), which are significant in respect to ensuring the security and resilience of this macrosystem.

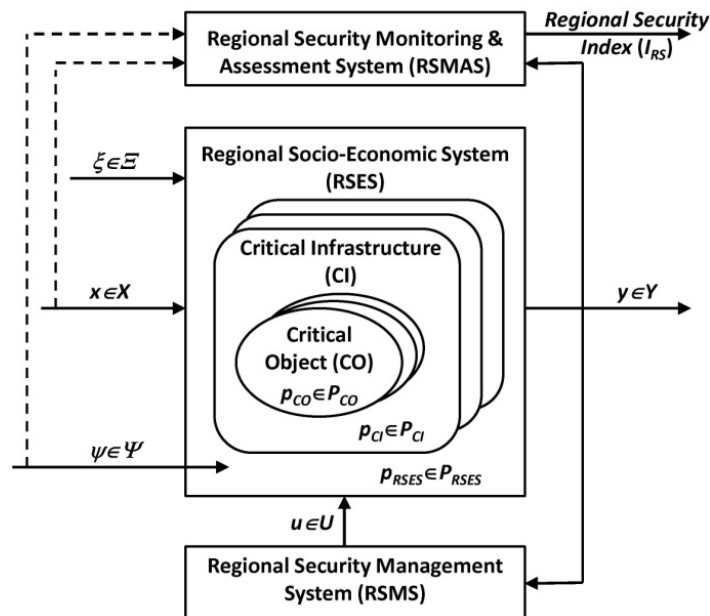


Fig. 1. Conceptual model of the regional socio-economic system (macrosystem) with a view to managing and ensuring regional security

According to the study [10], such a model in operator form can be formally defined as follows:

$$CM_{RSES} : X \times \Xi \times U \times P \times \Psi \times [0, T] \rightarrow Y, \quad (1)$$

where $x \in X$ is a set of identifiable input actions (impacts of the external environment on the system); $\xi \in \Xi$ is a set of the environment parametric disturbances, i.e. the external random influences such as

threats and dangers; $u \in U$ is a set of control actions (crisis-proof or protective measures) generated by the security management system (regulator) and aimed at the regional system stabilization under parametric disturbances via implementing an appropriate control algorithm (program); $p \in P$ is a set of structural parameters of the system (critical facilities and regional critical infrastructures); $\psi \in \Psi$ is a set of internal threats and dangers; $[0, T]$ is a action period of the system; $y \in Y$ is a set of state variables of the regional system that determine the trajectory of dynamic system in the security domain at the development cycle $[0, T]$; « \times » is a sign of the Cartesian product.

Internal and external actions (threats) are implementing through certain known functions $p = p(\psi)$, $x = x(\xi)$ and impact on the system behavior by destabilizing actuation and changing the system parameters $p \in P$ and input variables $x \in X$, respectively. Then, using differential form of model specification, if acceptably, the system model (1) can be presented of the form:

$$\dot{y} = f(x(\xi), u, p(\psi), y, t), \quad (2)$$

where f is a known vector-function; $x(\xi), u, p(\psi), y$ are vectors of the sets X, U, P, Y , respectively, with entry conditions $y(t_0) = y_0$.

The mathematical apparatus of sensitivity theory [11] can be in attempt effectively used to formalize the concepts of threat and danger. Following [12], external and internal impacts on the dynamic system's behavior are formalized in an analytical form as follows. Let a critical object of the region or a regional critical infrastructure be formally defined in the following differential form:

$$\dot{y} = f(y, p(t), t), y(t_0) = y_0,$$

where $\bar{y} \in Y$ is a n -dimensional state vector of system parameters; $p(t)$ is a m -dimensional vector of system parameters with rating value $p = p_0$; f is a vector-function; t is operating time.

System parameters $\bar{p} \in P$ depend on time. Therefore, the identified input actions are considered as the known functions and refer to among these parameters also.

If the function f assumes Taylor expansion in the neighborhood of point $p = p_0$:

$$y(t, p) = y(t, p_0) + \frac{\delta y(t, p)}{\delta p} \Big|_{p=p_0} (p - p_0) + \dots,$$

then the form $\frac{\delta y(t, p)}{\delta p} \Big|_{p=p_0}$ is a sensitivity vector of the n -component state vector $\bar{y} \in Y$ with respect to $\bar{p} \in P$.

When considering external $\bar{\xi} \in \Xi$ and internal $\bar{\psi} \in \Psi$ impacts as the parameters $\bar{p} \in P$ that exert influence on the sensitivity of state variables $\bar{y} \in Y$ of the regional socio-economic system, its critical infrastructures or individual objects, then these impacts (threats) are potentially dangerous, and the concepts of external and internal threats can be formalized in the following form:

$$\exists \xi_i \in \Xi : \left| \frac{\delta y(t, \xi_i)}{\delta \xi_i} \right|_{\xi_i = \xi_{i,0}} > 0, \quad i = \overline{1, K}, \quad \exists \psi_j \in \Psi : \left| \frac{\delta y(t, \psi_j)}{\delta \psi_j} \right|_{\psi_j = \psi_{j,0}} > 0, \quad j = \overline{1, L}.$$

The study [12] proves that the form $s(t) = \frac{\delta y(t, p)}{\delta p} \Big|_{p=p_0}$ satisfies a vector differential equation:

$$\dot{s} = \left[\frac{\delta f(y, p_0, t)}{\delta y} \right] s \Big|_{y=\bar{y}} + \frac{\delta f(\bar{y}, p, t)}{\delta p} \Big|_{p=p_0}, \quad (3)$$

where $\bar{y} = y(t, p_0)$ and $s(0) = \frac{\delta y_0}{\delta p} \Big|_{p=p_0}$.

The solution of equation (3) allows to analysis the sensitivity indices dynamics of the system and estimate the feasibility of potential threat implementation, i.e. the hazard occurrence.

The problem of identifying a set of adverse combinations $\Pi \subset \Xi \times \Psi$ of the internal $\psi_j \in \Psi$ and external $\xi_i \in \Xi$ impacts, initiating critical situations in the system, has the most concrete practical interest for the researchers and security system developers. As a rule, the given critical combinations of the $\psi_j \in \Psi$ and $\xi_i \in \Xi$ impact chains are assigned and identified under simulation experiments on system model or composite models of independent system components.

The completeness of the conceptual model (1)-(2) is limited only by information on the system and the processes occurring in it, available to the security control actors at the time of decision-making, and is adequate within the framework of the assumptions made on the behavior manner of the security objects, their attributes and parameters. Model (1)-(2) can be used to estimate the causes of unstable behavior and the stability limits of the system and its elements, in particular, at the initial phases of the development life-cycle of regional crisis situations (namely the emergence and activation of threats and dangers) [13]. However, this model does not deal with all other phases of the life-cycle (development, penetration, impact, regeneration) and is not able to embrace all modes of system functioning: normal, emergency (crisis reaction) and post-emergency (elimination of consequences). At the same time, in these modes and at other phases of the threat life-cycle of regional security, the information on behavior of the system and its elements can be obtained in the course of running series of simulation experiments with composite computer models built on the basis of the conceptual model (1)-(2) and its extensions. Thus, the formal analysis and substantiation of the security of a regional system using model (1)-(2) is carried out by dynamic modeling of interaction of the system elements with the external environment in time and under the influence of control, internal and external disturbances.

The principal components of the security of regional socio-economic systems are stability, controllability, observability, reliability and survivability.

Talking about the analysis of system stability, the conceptual model (1)-(2) allows obtaining a family of phase trajectories characteristic to the system subject to the entry conditions values $y(t_0) = y_0$, type and level of internal $\psi \in \Psi$ and external $\xi \in \Xi$ influences and their combinations. The stability theory statements [14] are widely used in problem-solving of regional security, since it allows discovering the causes of fluctuations in the system behavior occurring as a result of the multiple threats implementation of various natures.

From the standpoint of this theory application, the problem-solving of ensuring regional security comes down to stability delimiting of the regional socio-economic system. Overrunning these stability limits means that the system or its backbone elements lose dynamic balance due to the influence of negative factors on them (the development of disproportions and dysfunctions within the system, the entropy increment, external impacts, the destruction of internal connections, defect accumulation, etc.), i.e. the system transition from an equilibrium state to a critical one, in which the system resilience, its structural integrity or functionality may be violated.

In terms of stability theory, regional security is defined as such a protective attribute of the socio-economic system called self-preservation, when a set of preventive anti-crisis measures is implemented under the impact of internal and external threats that are uncertain in composition, type and level on its critical elements. In an effort to ensure and support system self-preservation, these protective actions provide sufficient remoteness of the system balance states and development trajectories from critical situations with a given margin of safety (survivability).

The stability theory is extremely useful and urgent for the general understanding of regional security theory, its scope, purposes and the range of problems it solves. Thus, classical studies in the field of stability theory [14] examine balance states of complex systems and carry out analysis of system dynamics in a small neighborhood of these states. Herein, the stability problems in case, when the system development is a result of external environment factors changing and not the system itself, are solved. Studying the nature of arising disturbances in the initial system state or at its primary input, is especially urgent to the protection of critical facilities of the regional systems. State-of-the-art studies on stability theory [14] are vice versa focused on structural stability [15] and "coarse systems" [16]. These research works examine perturbations in the system structure itself and consider problem-solving of qualitative changes identification in system functioning trajectories in case of violations of the system structure (parameters) itself. Hence, the stability theory makes it possible to estimate the behavior changes dynamics of socio-economic system (phase trajectories) under emergence of multi-type critical situations and various random events in the context of system normal functioning, as well as to determine the nature, conditions and mechanism of system transition to an emergency operating mode, when adverse or unknown events occur.

The further ideological development of the structural stability conception is the theory of bifurcations [17, 18] and the theory of catastrophes [19, 20] based on it. Bifurcation theory studies qualitative changes in the dynamics of system behavior that are sensitive to some of their parameters under an infinitesimal variation in these parameters, i.e. it examines the nature of system equilibrium positions in the phase space when these parameters change. Thereto, the methods of perturbation theory are used [21]. The system parameters, the change of which leads to a situation of bifurcation, are called bifurcation points. Catastrophe theory also studies the conditions under which there is a abrupt qualitative change in the dynamic system attributes as a result of a uniform quantitative change of its parameters on which it depends. On the basis of catastrophe theory methods, the critical domains of system parameters, that cause the initial system position transition in the equilibrium state space (changing of stability attraction domains), are determined.

Certain difficulties in the process of system analysis for stability arise when finding all points characterizing the system equilibrium states, and when constructing all possible system behavior trajectories in the neighborhood of these points over an infinite time interval. These problems may have rather high dimension and computational complexity. To simplify the solving method of these problems, ad hoc frequency, matrix and integral stability criteria are applied [14], which are also suitable for analyzing the risk-sustainable development of regional socio-economic systems for security and resilience. At once, the issues of studying the practical stability of regional socio-economic systems deserve special attention in terms of assessing the permissible limits of the macrosystem trajectories on a finite time interval [3, 5], as well as identifying the prerequisites for the unstable system behavior due to spontaneous or unforeseen failure of its critical elements.

The system controllability is essentially similar to the reachability concept and characterizes the possibility of achieving the control objective, which is fixed in the system state parameters. From the system controllability point of view, the application of control theory [8, 22-24] in the problem-solving of regional security ensuring pursues generation and maintenance of conditions for the system dynamic equilibrium, since the system utility function reaches its maximum only in the domain of stable states.

The traditional approach to problem-solving of socio-economic system stabilization under conditions of parametric disturbances (internal and external threats) using control theory methods [8] lie in the application of control action function $u(t)$ within the framework of model (1)-(2) and engineering the regional security management system of the "object – regulator" type. Thereto, three typical classical control circuits, which are considered in detail in [25] and shown in Fig. 2, are used. There are (a) closed-loop, (b) open-loop and (c) combined control schemes, differing in the principles of control implementation: "by disturbance" and "by deviation".

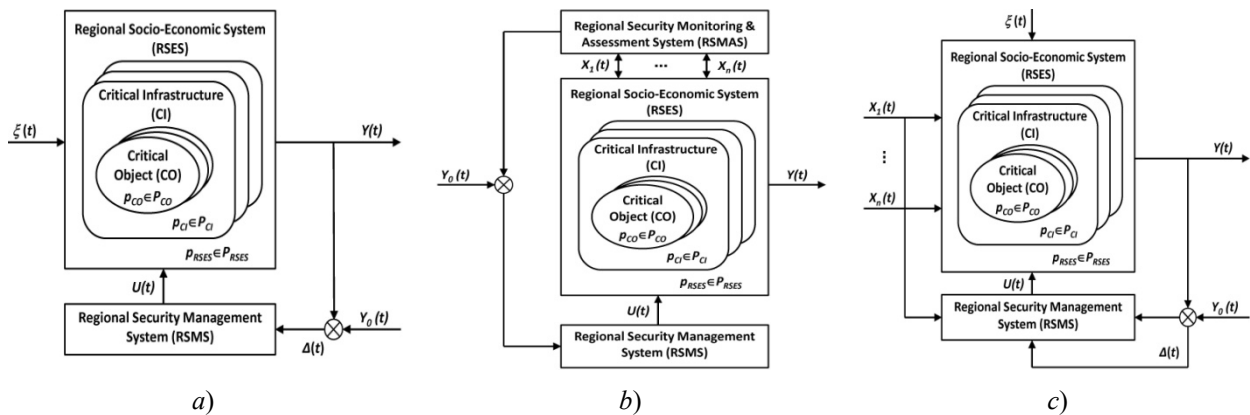


Fig. 2. The engineering circuit diagrams of the regional security control systems:
 a – closed-loop; b – open loop; c – combined

Key symbols in Fig. 2: $X_i(t), i = \overline{1, n}$ is a set of identifiable (measured) external disturbances (threats); $U(t)$ is a set of control actions generated by the regulator according to a certain program (control law) and compensating for the negative impact of external disturbances; $\Delta(t)$ is a deviation of state variables $Y(t)$ from the given values $Y_0(t)$; $\xi(t)$ is a set of random nature parametric disturbances of the external environment.

The synthesis of regulators for managing complex socio-economic objects and systems is a laborious multi-aspect problem in the development of integrated automated systems for control of regional security and ensuring of critical infrastructure resilience. For the theory and practice of regional security, of particular interest is a problem of finding and substantiating universal feedback control laws that guarantee the

stability of functioning in the chosen development cycle, the global stability and adaptability of regional macrosystems under any limited disturbances and impacts, regardless of their nature and scale.

In the practice of engineering and organizing regional security support systems, along with the fundamental ideas of control theory [26], methods of reliability theory [27, 28] are also used, aimed at operational reliability enhancement of critical facilities and infrastructures of the region. It is terminologically known that the concepts of security and reliability are not similar, since security is a system status when there are no negative impacts on the system elements or on other objects that are in the system operation environment. Meanwhile, reliability is a system status when, over a selected time interval, the system is able to perform its predefined functions in the specified modes and operating conditions while retention the values of all operating technological parameters, quality indices and dynamic characteristics within these permissible limits.

Traditionally in practice, methods of probability theory and mathematical statistics are used to reliability indices estimation of the system [29]. This is stipulated by the fact that the events characterizing the quantitative and qualitative reliability indices are random in nature. The system state is assigned by a multi-dimensional point y in the phase space Y , and the y state transition in time is defined by a random process $y(t)$. The subset of critical states $Y_c \subseteq Y$ that correspond to the failure occurrence is allocated in the phase space Y . Such failures initiate critical situations that are characterized by a gradual or sudden loss of system performance and functionality as a result of band fault, when system parameters overrunning the admitted region due to the impact of internal and external factors (threats). Thus, using the methods of reliability theory (e.g. the "event trees" or "failure trees" techniques), the estimation of the regional security level is derived through the emergence probability of critical situations at the facilities and infrastructures of the region and involves indentifying the set of infeasible values of the critical element parameters of the regional system and the vector of its phase coordinates that are unacceptable in respect to the functioning and development of the system.

The probabilistic approach to risk assessment of the critical situations (failures) emergence undoubtedly draws the theory of reliability closer to the theory of regional security when carrying out a probabilistic scenario analysis of the system unstable behavior characteristics. However, there are some limitations in application of the reliability theory to problem-solving of regional security ensuring. Firstly, for the probabilistic interpretation of risks and critical situations, a presence of the mass character of homogeneous events is important, while for the theory of regional security this is not always reachable, since regional crisis situations, like sources of threats, are heterogeneous by their nature and do not always emerge in statistically uniform conditions. Therefore, the probability statistical interpretation is not always applicable to the set of such events. Secondly, the theory of reliability was mainly focused on the failure analysis of complex technical systems from its origins, whereas failures of individual elements of the socio-economic systems do not lead to violation of the entire system functioning as a rule. At the same time, socio-economic systems require taking into account the active influence of the controlled system on the security management process and are characterized by a variety of macro-states such as dynamic equilibrium, sustainable development, transient phenomenon (bifurcation), crisis, absorption, adaptation to changes, recovery and others. At the same time, attempts to take into account the human factor are also made in the modern theory of reliability [5] on the basis of the well-known methods – on-line monitoring, precaution, preventive-treatment and diagnostics of complex socio-technical systems.

Despite the considered limitations, it is worth to mention that the relationship between the theory of reliability and the theory of regional security is quite obvious. Reliability theory explores the whole set of probable states of the system functioning: normal (stable), limiting, critical (emergency) and other types. The criteria for these states are regulated by technological normative, operational and experimental-design documentation. In turn, the theory of regional security, from the standpoint of acceptable risk, studies ways to minimize and mitigate the consequences (damages and losses) from the impact of potential threats and hazards on critical facilities and regional critical infrastructures located directly in the space of these states and having their own stability limits and security domains. However, not all objects of the theory of regional security have a developed legal framework and security certificates have been designed that establish the modes and requirements for performance and operation of these objects. The security certification of critical facilities and regional critical infrastructures is an independent applied problem and needs detailed scientific substantiation and consideration. Thus, the goals of the reliability theory and the theory of regional security coincide in maintaining the system resilience and retention its performance at the lowest cost, damage and loss in conditions of both stable and critical situations.

The concept of survivability [30, 31] is fundamentally different from the reliability theory. The survivability of socio-economic systems takes into consideration a wider range of destabilizing factors, the accumulation of internal dangers (e.g. structural changes) leading to fatigue, aging and subsequent degrada-

tion of system elements, and global threats from the external environment (crisis phenomena in the global economy, natural disasters, military-political international conflicts, etc.). The survivability of socio-economic systems is often understood as the conservation property of the full or partial performance of critical system elements under the influence of destabilizing factors on them, which ensures the structural integrity and connectivity of system elements with the minimum tolerable loss of system controllability and performance quality, as well as the possibility of system functions recovery.

Unlike security and reliability, the attribute of system survivability is actually considered in relation to the entire system and not to its components individually. Meanwhile, the methods of the survivability theory should ensure that the system fulfills its goals, functions and tasks under the influence of negative factors, and not support its full recovery after the threats are implemented. A system that possesses survivability attribute is capable, first of all, to respond to threats and seeks to mitigate (eliminate) the consequences of destabilizing impacts until the moment of complete failure of the system operation, regardless of the deterioration in the performance of the system elements.

Thus, the survivability of socio-economic systems, as a component of regional security, should be achieved not only through higher state of readiness and protection of critical facilities and infrastructures of the region (timely detection of potential hazards and implementation of preventive anti-crisis measures), but also through mechanisms for recovering and adapting the system to new operating conditions in the process of counteracting multiple threats.

A modern version of the survivability theory is the dynamically developing mainstream conception of socio-technical, cyber-physical and organizational system resilience [32]. Currently, this novel concept is popular mainly abroad. Meanwhile, as shown in [33-34], this is a relatively new research direction in the domestic science, which can be positioned as a logical continuation (evolution) of the ideas and postulates of the general theory of security of complex socio-economic objects and systems at the present stage of development of the risk and security sciences.

Results and Discussion

The theory of regional security as a science of protectability and resilience of the regional level socio-economic systems is based on the following main statements and conditions. The theory of regional security uses its own mathematical and conceptual-categorical apparatus developed on the basis of research concepts discussed in the previous section of the work and taking into account the specificity of objects and problems being solved in the field of regional socio-economic system management. To these problem-solving, the regional security theory encapsulates the entire arsenal of methods and tools used by scientific disciplines adjacent in goal-setting and phenomenology. In particular, the methodology of regional security is based on the concept of "acceptable risk" [5] and the principles of sustainable development [1], which allow systemic examination and definition of the concepts of risk, threat, hazard, damage and losses in resilience management of socio-economic systems from a unified position.

Since the occurrence of emergency and crisis situations in various areas of socio-economic system development is an imminent objective reality, the theory of regional security should operate with model toolset that provide the possibility of scenario analysis and forecasting of the behavior dynamics of critical facilities of the region under the impact of multiple threats. In this case, risk assessment, identification of trends, mechanisms and patterns is carried out using the methods of simulation, cognitive, logical-probabilistic and fuzzy modeling, as well as expert methods. In terms of minimizing the consequences of threat implementation, such an approach in the theory and practice of regional security management provides the principle of "anticipate – prevent – adapt", which is relevant to the research objectives in this subject domain. Based on this approach, not only the problems of risk assessment and prediction of the critical situations are solved, but also the problems of identifying sources of hazards, analyzing scenarios for the possible behavior of critical facilities, estimating their stability limits and impact tolerance to external and internal disturbances (threats), organizing or configuring (optimizing) the streamlined security systems, formation of an information structure for making managerial decisions.

A distinctive feature of regional security studies is the need to solve multi-objective optimization problems with stochastic or fuzzy target (criterion) functions under deterministic, probabilistic or fuzzy constraints in the context of data incompleteness on the origination causes and development dynamics of the regional crisis situations. An example of such a problem can be mentioned the estimation of the optimal configuration of program-technical assets (decision support system) of the regional situational center or the efficiency evaluation of the control program (project) of comprehensive security for the groups of critical facilities by regional economy sectors taking into account the costs of protection measures and current legislation.

A special place in the methodology of regional security is assigned to expert evaluation of random threats and dangers operating in a latent, background or active manner within the critical domains of the re-

gional socio-economic system functioning, since the sources and nature of hazard manifestation are not known in advance as a rule. At the same time, in some cases, the subjectivity of experts and judgement methods in the anticipation of adverse events may negatively affect the quality of prevention of the critical situation development and be accompanied by additional costs for goal-oriented planning and implementation of measures to security ensuring and support of the regional critical infrastructures and their elements.

From a methodological point of view, the theory of regional security corresponds a body of scientific knowledge, mechanisms and laws, methods and principles, terms and definitions in the field of risk and security management of complex systems that provide estimation of protectability criteria and indices of the regional socio-economic systems at the quantitative and qualitative level, studying the behavioral trends of this class of systems in the threat life-cycle of regional security, conducting the scenario analysis and forecasting of the regional crisis situations development, synthesis the comprehensive programs for situational management of the critical facilities security in the region and the regional critical infrastructures resilience. In a generalized form, the proposed methodology of regional security is schematically represented in Fig. 3.

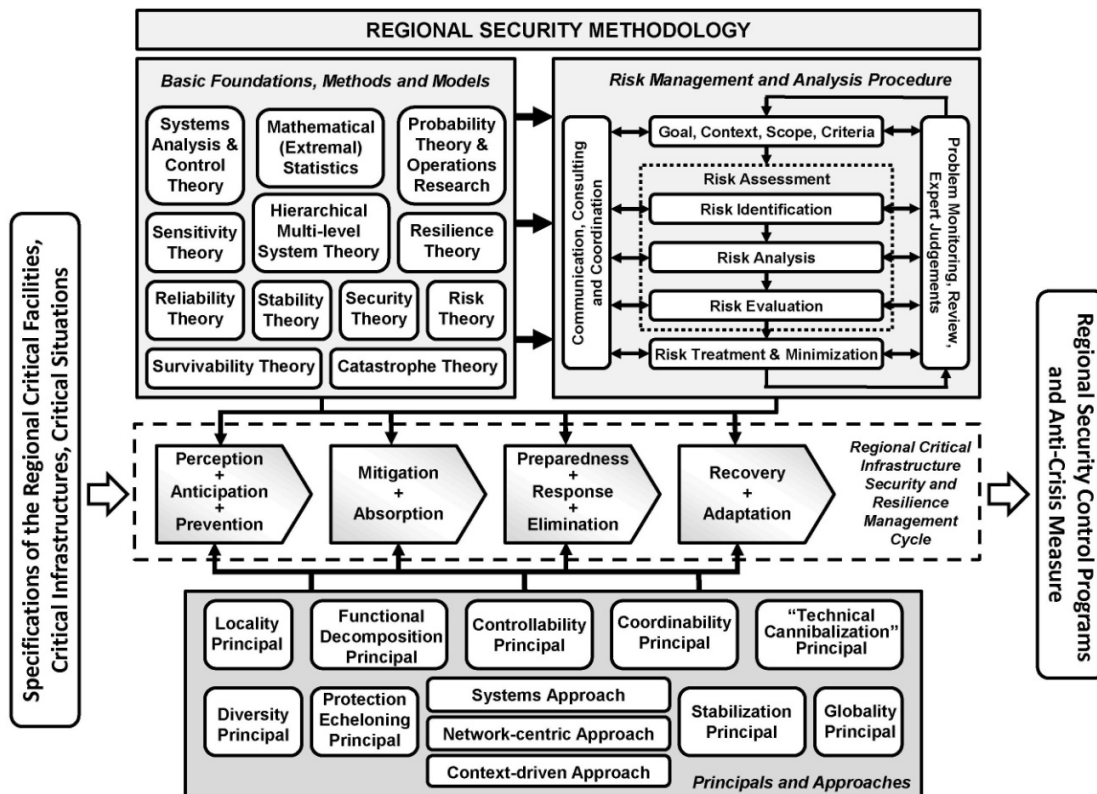


Fig. 3. The unified methodological base (methodology) of the theory of regional security

Let us state the basic principles of organizing security systems that underlie the theory and methodology of regional security (Fig. 3):

1. *The principle of locality.* This principle consists in parrying and localizing possible threats and hazards at the initial phase of their inception (before diffusion) by arranging special conditions that prevent the emergence and spreading of negative factors and trends and that are beneficial from an economic point of view at the same time. This principle is applied once or repeatedly subject to the specificity of problem statement to be solved on regional security ensuring.

2. *The principle of globality.* This principle consists in a broader multi-level organization of regional security management and is implemented in cases when the principle of locality is violated or the application of the latter is not efficient enough. This principle is a superstructure over the principle of locality and is designed to support favorable conditions for the system (region) existence and functioning under emergence of the global threats by streamlining and regulating the interaction between elements of the regional socio-economic system and the external environment.

3. *The principle of functional decomposition.* The application of this principle expects the implementation of two protective mechanisms (special measures built according to the systems concept): an internal mechanism for security ensuring of the region integrated into critical areas of regional socio-economic sys-

tem and an external mechanism for counteracting the security threats. The external protection mechanism implements models and methods that provide acceptable conditions for the normal functioning and progressive development of the regional system, i.e. the minimum permissible level of impact on the system of negative factors leading to the deviation of regional security indices from the standard values. The external security ensuring mechanism is aimed at achieving a protectability state of the regional system under the impact of multiple threats and their penetration into critical facilities and infrastructure of the region. The internal protection mechanism provides parrying and localization of internal security threats (structural transformations and disturbances generated by the system elements as a result of their self-organization), as well as external security threats (impacts produced by the environment and overcoming the external protective mechanism). In other words, the internal security ensuring mechanism is focused by its measures on maintaining the dynamic balance of the system elements (systemic homeostasis) and retention their critical parameters in the security domain by means of self-regulation and adaptation of the system. The use of the principle based on the considered protection mechanisms in the theory of regional security provides the major in-depth analysis of the origination nature of the internal and external threats, as well as recognizing and distinguishing between them when solving the problems of security control of regional socio-economic systems.

4. *The principle of stabilization.* This principle can be considered in respect both to the system we are examining and to a specific situation in the interaction of individual system elements with each other and with the external environment under the actuation of parametric disturbances. Regional socio-economic systems belong to the class of complex developing purposeful systems, the structure and functions of which change over time. Meanwhile, from the standpoint of general theory of systems and control theory, in the process of these system stability analysis over a certain fixed time interval, such systems can be considered as stabilizer systems of the "object – regulator" type owing to the presence of controls that counteract internal and external disturbances. Then the problems of the theory of regional security become the problems of stabilization. The principle of stabilization involves the implementation of a set of measures to preserve and process the system in the space of stable states (security domains), the observed characteristics of which can dynamically change and predetermine the manner of system behavior under critical conditions. As a rule, in practice, one has to deal with several, functionally related security domains in the state space of regional systems, corresponding to a variety of sources and channels of threat initialization in these systems.

As a regulator to compensate for disturbances, control mechanisms are used that ensure the formation of favorable conditions for the purposeful behavior of the control object (regional socio-economic system). Following [10], there are: "rigid" institutional management through the control of restrictions and norms of activity (control coordination at the metalevel); "soft" motivational management through changing the utility functions and preferences of control actors by introducing a system of penalties and rewards for choosing certain actions (stimulating the activities of actors); "flexible" information management through the change of control information structure (situational awareness), which is operated by the control actors in the process of preparing and generating decisions (decision-making information-analytical support appropriate to the situation). Violation of the system stability leads to malfunctions and collisions in its functioning, due to the development of critical situations and random processes, which in fact may not be amenable to compensating control actions (correcting signals).

5. The principle of controllability. This principle characterizes the set goal achievement by the regional security support system. As is known from practice, to implement this principle it is necessary that the security authorities of the region have the opportunity to purposefully influence on the state parameters of critical facilities and infrastructures of the regional system, as well as that the resource supply of the management process is sufficient to problem-solving on the way to the system goal and appropriate for it. At once, in order to implement system control, the system observability requirements must be met, which ensure the receipt and access to information on the system state. Thereto, tools for state monitoring and identification of the regional socio-economic system development are being designed. For nonlinear dynamic systems, the terms of controllability and control conditions are associated with great difficulties, while for linear systems it is known.

6. *The principle of echeloning protection.* This principle is based on the network-centric approach [10] and the implementation of the "in-depth" security ensuring mechanism by means of the deployment of the multi-level distributed security control systems of the region. Examples of such a network security infrastructure at the federal and regional levels are systems of distributed situational centers and regional management centers [35], respectively. The network is large-scale, there are many decisive centers, and each node (security manager or decision-maker) needs to be provided with information exactly corresponding to the current situation in order to coordinate managerial decisions and joint actions. Substantially, the principle of network-centricity in the theory of regional security implies the implementation of a fully or partially decentralized structure of security organizational management of the critical facilities in the region

with dedicated control centers, the interaction between which is carried out on the basis of their integration into a unified regional information space. Control centers perform the major functions of monitoring, preventive analysis, filtering and auditing of risks associated with a security violation of the regional critical infrastructures functioning, and on the basis of adverse event forecasts, it generates anti-crisis measures to minimize the possible consequences of the threat implementation in each domain of regional security and ensure an acceptable risk level of critical facilities protectability in the region.

7. *The principle of coordinability.* In the theory of regional security, this principle is implemented by controlling the restrictions on management. By this method of negotiation, the principles of coordination of the interactions and quality functions, as well as the postulate of compatibility of problems solved by the system elements with respect to the general problem of the system, must be fulfilled. Coordination is understood as the achievement of consistency in the operation of all system units by rational interfacing them that ensures obtaining the optimal solution to the general problem of the system under optimization the subproblems solved by the subsystems. The system is coordinated if there is a coordinating signal that ensures the consistency of the interfacing inputs and the consistency of the expected and actual values of local objective functions, respectively.

8. *The principle of diverse actuation (diversity).* The principle of diverse actuation security (protection) is one of the central ones in the theory of regional security and is implemented both at the object (local diverse actuation) and infrastructural (global diverse actuation) levels of regional socio-economic system organization. This principle is generally aimed at the rational combination and allocation of various types of resources and support tools to security ensuring at different levels of situational control of the region. This is necessary to reduce the disfunction probability (risk) of the group of critical facilities due to a common cause. When engineering regional security support systems, this principle implies the availability and actuation of the multi-version redundancy mechanisms (generation of two or more redundant systems) that optimize the functioning of critical facilities according to the criteria "reliability – cost" or "security (acceptable risk) – preparedness to parry", in the case of destructive impact of multiple internal and/or external threats, including those of an irreversible nature. The principle of diverse actuation protection is oriented to the adaptive support systems for ensuring regional security, capable of self-organization and operating according to non-programmable logic. The diversity in protection is achieved by means of the use of mutually redundant channels and security elements, or through expansion of the existing system by additional security support tools built on fundamentally diverse methods and approaches. As a rule, parametric diversity is programmable and expects the activation and actuation (launch) of control algorithms (regulators) appropriate to the situation based on monitoring data on the security parameters state of the controlled system and control of their permissible values and variations. The application of the diversity principle allows taking into account the influences of the human factor in problem-solving of security control of the socio-economic systems.

9. *The principle of "technical cannibalism".* This principle involves the use of resources of regional socio-economic system elements that have degraded or lost their functionality as a result of the impact of multiple threats in the interests of operability recovery of the other critical facilities of these systems and resilience support of the critical infrastructures of the region that integrate these objects. This principle is implemented in the process of transformation and evolution of regional critical infrastructures that is often caused by changes in their properties, system requirements, high dynamics of the external environment, etc., in order to adapt regional security systems to new challenges and changing operating conditions. This contributes to the rational choice of forces and means to security ensuring for the purposes of risk minimization of the functionality loss of critical facilities of the region.

Towards the end of our discussion, it is appropriate to assign a number of problem issues in the theory of regional security, which scientists and authorities have yet to comprehend in the process of developing this research streamline. Day by day, the requirements for technologies and support tools of security ensuring of the regional critical infrastructures are tightening and raising. The theory of regional security and its toolkit are not in time to keep abreast of the times with these requirements. That makes it difficult for the situational control systems to respond timely to new threats to sustainable regional development. At the same time, the latent or spontaneous character, the various nature and the slow growth of potential threats and dangers in all critical areas of the socio-economic system functioning provoke the emergence of crisis situations for which everything cannot be taken into account and planned in advance. Therefore, the models and methods of regional security management used today in practice and based on a logical-probabilistic approach to risk assessment and analysis need to be theoretically rethought in the focus on providing mechanisms for rapid recovery and adaptation of regional systems to the consequences of the impact on their critical elements of multiple negative factors. The transition to the theory of socio-economic system resilience [33], as a new comprehensive con-

cept of organizing the security of these systems, is one of the ways to solve this problem. In the course of interdisciplinary studies of the socio-economic system security, disagreements arise in the interpretation of the key concepts of this subject domain: threat, hazard, critical facility, incident, crisis situation, protection mechanism, forces and means, critical infrastructure, risk, and others. This indicates that the terminological and formal apparatus of the theory of regional security requires additional scientific research, analysis and interdisciplinary interfacing. Another problem of regional security methodology is the inability to control the forecast precision of crisis situations in real sectors of the socio-economic system development, while simulation experiments on individual object and critical infrastructure models are not able to predict the full picture of possible incidents in these systems. That is, forecasts are approximate nature, and this, in turn, affects the efficiency of the ongoing anti-crisis measures. Up to date, the development of digital twins and its combinations is one of the promising technological solutions to this problem.

The regional security methodology is focused on solving its own class of multi-objective optimization problems of risk assessment and analysis of the security violation of regional critical infrastructures functioning. These problems enclose local criteria (quality objective functions) that can be unmatched or fuzzy, and their parameters values can be characterized by randomness, high entropy, belonging to a multidimensional probability distribution, or error content. To efficient solving this class of problems, special mathematical methods and computer simulation tools are used [1, 3-5, 8].

The application of logical-probabilistic methods (e.g., "event tree" or "failure tree" methods) is of little use for regional security management and expects the statistical stability (homogeneity) analysis of the considered set of probable critical situations that are rare in recurrence and random. It has been experimentally founded that in practice a complete analysis of the statistical stability of critical situations is sometimes impossible and is highly laborious. In addition, this class of methods operates with conditional rather than true probabilities (risks) of the critical situations emergence. That reduces the accuracy of security estimate of the system when a threat or event is implemented. At the same time, only on the basis of the frequency stability analysis of adverse events occurrence, one can judge the nature and matter of certain crisis phenomena and evaluate their impact on the system functioning and its elements. Another contradiction, that arises when using statistical methods at the stages of security risks prediction of the system (risk assessment and consequences forecasting are subject to a probability law) and countermeasures planning to the consequences of critical situations, is due to the fact that the probabilistic problem of optimal choice of the regional security support system configuration options is in the final analysis reduced to a rigidly determined one. Even so, it is known that probability laws are irreducible to the principles of rigid determinacy [3].

For recent time past, in public policy and debates, there has been already a shift in emphasis from regional security (critical infrastructure protection) to that of resilience of the regional socio-economic systems. Comprehensive regional security ensuring by full protection of the critical facilities and infrastructure in the region can never be guaranteed, and achieving the desired guaranteed level of security is normally not cost-effective in relation to the actual threats. Therefore, one should put more focus on adaptive measures and quick recovery. Thus, the novel resilience approach in the theory of regional security should focus on both the pre-crisis phase and the during-crisis (response, adaptation) and even less to the after-crisis (recovery) phases. But this requires a developed legal and regulatory framework, as well as the positioning of a new methodology of regional security based on the principles of the digital economy, in the structure of public administration. This is a grand problem that has yet to be solved by researchers and specialists in regional security at a new historical stage in the development of the theoretical foundations of the security of socio-economic systems.

Conclusion

The study explores an important and promising research area – regional security. It is shown that regional security covers a variety of management aspects and scopes, which are essentially very diverse (economic, environmental, social, energy, military, industrial, personnel and other types of security). All of them are naturally interconnected and affect the functioning and development of regional socio-economic systems in different ways. These aspects need to be linked into a single whole. Thereto, a clearly-build and well-defined theory of regional security, which methodology considers all the diversity of security management aspects of the region from a unified standpoint of their influence on the stability and resilience of regional socio-economic systems, is needed. In our country and abroad, attempts to streamline and centralized control of the entire range of the regional security and resilience characteristics of socio-economic systems subject to the hierarchical design of the regional security support and evaluation system, have been re-

peatedly made. However, rigid centralized control did not provide the desired effect, even at the analysis level of the each regional security area separately, which has its own specific attributes and features.

To overcome these difficulties, the theory and methodology of regional security should be drawn on the general principles of network-centric (distributed) control of complex systems. The network-centric approach most sufficiently reflects the real nature of various level socio-economic system management and takes into account the decentralized nature of the ensuring processes of regional security both in terms of functional and organizational structure subject to the priori and posteriori information on the control object, the external environment and internal disturbances. In terms of the theory of socio-economic system management, such a flexible approach in the regional security methodology has not yet been implemented. The network structure of the organizational management of regional security provides the efficiency enhancement of the threat parrying measures implemented by the regional security support system at the expense of coordination and goal-oriented planning of the critical facilities security of the region within the unified information space. According to expert judgements, the application of such an approach to developing regional security support systems, for instance based on a system of distributed situational centers [36], is economically more costly than centralized solutions. However, the operability recovery costs of the critical elements and infrastructures of regional socio-economic systems and the consequences elimination costs of the critical situations are meanwhile much less than in the case of centralized control and support of regional security.

Despite the fact that today the theory of regional security is still in the phase of rapid development, it can be confidently asserted that it is an independent branch of the security science of complex systems. It has its own methodological base and formal apparatus built on the basis of knowledge domains already formed in the research agenda, namely control theory, stability theory, reliability theory, survivability theory, risk management, sensitivity theory, general system theory and quite a number of other scientific disciplines.

In perspective, further development of regional security fundamentals and methodology (theory and practice of security management of large-scale socio-economic systems) will be carried out in the following areas of basic and applied research:

- adaptation and spreading of the regional security theoretical apparatus to the management problems of the regional critical infrastructures resilience (resilience as a new comprehensive enveloping concept of security organization);
- shifting from "object-focused" models of the security situational control to the "function-focused" models, i.e. stealing the spotlight from goal-oriented planning of preventive measures for ensuring the security of socio-economic systems to targeted support of the flexible recovery of these systems functionality after multiple threats impact and adaptation to new operating conditions;
- engineering of models for the decentralized control coordination of regional security and methods for the situational awareness support at all levels of managerial decision-making;
- development of the theory of destructors (decomposers) that constitute implicit (hidden) sources of threats and dangers, accumulating over time within the socio-economic systems and that are able to randomly affect the normal functioning of individual elements and processes in these systems, as well as the system as a whole;
- toolkit design for problem monitoring and risk auditing of regional security, as well as the methods for risk analysis and potential threats and dangers identification at the initial stages of their life-cycle;
- development a set of the well-grounded and justified methods for scenario analysis of the behavior dynamics of the critical facilities under the destructive impact of internal and external threats for the purpose to estimate their stability limits, the recovery time of system functions and the options for adapting to parameters variations of the operating environment;
- engineering of computer-aided technologies for implementation and deployment of the intelligent information-management systems and network-centric digital platforms to situational control of regional security under uncertainty;
- optimization problems definition on the dynamic configuration of support tools (i.e. situational centers) for the ensuring of regional security and these problems step-by-step solving by methods that are appropriate to the efficiency target indices of anti-crisis management;
- regulatory and legal framework improvement of the theory of regional security, regional security methodology and management support tools;
- research substantiation of public administration digital transformation (virtualization) in the field of regional security ensuring under digital economy era.

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