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Simulation of Innovative Systems under Industry 4.0 Conditions

Nestor Shpak [1], Mykola Odrekhivskyi [1,*], Kateryna Doroshkevych [1] and Włodzimierz Sroka [2]

[1] Institute of Economics and Management, Lviv Polytechnic National University, 79013 Lviv, Ukraine
[2] Management Department, Faculty of Applied Sciences, WSB University, 41-300 Dąbrowa Górnicza, Poland
* Correspondence: odr2002@ukr.net; Tel.: +38-0503-714-030

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Abstract: The world is at the threshold of the fourth industrial revolution, which has already begun. It requires enterprises and even sectors to move toward Industry 4.0. Innovative systems (IS) play an important role in this process. In the article, the innovative systems in Industry 4.0 are considered to be complex systems whose components have a lot of tasks; in particular, to produce innovative policy; to provide the subjects of innovative activity with the necessary resources; to participate directly in the process of creation, commercialization, and the practical use of new knowledge; to implement integration approaches between these processes, etc. The complexity of the innovation system leads to the development of modern approaches to their modeling, as a tool for further designing, creating, and modifying real innovative systems of different levels of organization under the conditions of Industry 4.0. In the simulation of IS under the conditions of Industry 4.0, the description of the subsystems by a number of sets is proposed. The model is described by the graph of relationships, including the abstract level of the hierarchical model of IS, its elements, indicators and their values, functions, actions and operations, their states and efficiency, and the tree of goals. In order to make optimal solutions, using the mathematical apparatus of the theory of Markov chains to study the dynamic and static characteristics of the states of the IS is proposed. This approach can be widely used in the simulation, designing, development, and rebuilding of IS at different levels of an organization.

Keywords: Industry 4.0; graph; relationship; innovative system; set; model

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1. Introduction

The world is at the threshold of the fourth industrial revolution, which has already begun. This fact changes all enterprises, regardless of their sector of activity. Therefore, all sectors have to move toward Industry 4.0 (Majerova et al. 2013; Hamid et al. 2018). Industry 4.0 significantly changes products and production systems concerning design, processes, operations, and services (Durana et al. 2019). It comprises a variety of technologies to enable the development of the value chain, resulting in reduced manufacturing lead times as well as improved product quality and organizational performance (Kamble et al. 2018). Interestingly, most studies that discuss technical aspects, e.g., Dalenogare et al. (2018), treat Industry 4.0 as a new industrial stage in which vertical and horizontal manufacturing process integration and product connectivity can help companies to achieve a higher level of industrial performance (Vochozka et al. 2018; Stefanovic 2018).

For a long time, the operation of Industry 4.0 has gone beyond simple deductibility and the acceleration of technological changes in the industrial sector. Today, it is also about changing the ways and means of doing business, improving business models, etc. which can effectively lead to increased economic development (Meyer and Danie 2017; Meyer and Jacques 2018).

Considering the trends of changes within Industry 4.0, the central issue in Economy 4.0 is to understand the impact of digital transformation, the creation of connection networks, and to adapt business models to increasingly demanding customers (Stverkova and Michal 2018; Nagy et al. 2018; Lazaroiu et al. 2018; Rajput and Prakash 2019). At the same time, the innovation orientation of these processes remains, which is expressed by developing the sphere of digital and information technologies, automation, and their effective application in industrial production, education, the social sphere, etc.

The operation of Industry 4.0 is also characterized by productive information provision of management processes in the manufacturing sector, where the prevailing volume of generated data which comes to the management subsystem is used for making management decisions, and the cost of storing and maintaining data in the enterprise management system is reduced. Effective implementation of these processes requires the development of innovative economic systems, which should ensure their modeling.

We propose considering the modeling of innovative economic systems, which are complicated systems under the conditions of Industry 4.0, as a process of streamlining organizational components by means of interconnection and interaction to improve their adaptability, sustainability, efficiency, and effectiveness (Androniceanu 2017; Meyer 2018). The same definition of innovation systems is used in the works of Eggink (2013), Pino and Maria (2018), Vaidya et al. (2018), Wixted (2009), and Warnke et al. (2016).

Since the subject of innovative systems (IS) modeling can be considered a system of their stable characteristics and goals, where both the process and the result of simulation are important, then the model of such systems should cover the forecasting and planning of the main variables, i.e., the means by which the managers should provide the necessary definition of the behavior of the IS staff and its influence on them. The inclusion of the following main organizational variable systems is proposed:

— A complex organizational structure (in the form of a tree of objectives, structural, and functional schemes);
— a dynamic system of indicators characterizing the state of the IS's activities, in particular the system of performance indicators provided by accounting and analysis systems;
— mathematical models and intelligent software and technical complexes for estimating and forecasting the results of the activity of innovative economic systems, making optimal decisions that can be implemented as an integrated management information system;
— compensation system (incentive and wages, career strategy, etc.).

The purpose of the research is the development, on the basis of system analysis, of an approach to modeling an innovation system for designing, creating, and reengineering real innovative systems of different levels of organization under the conditions of Industry 4.0.

All this determines the relevance of IS modeling under Industry 4.0, which would cover all levels of their organizations in their interaction with the environment.

Given the deliberations presented, the aim of this paper is to analyze IS and to implement its simulation under the conditions of Industry 4.0. Our paper is structured as follows. Firstly, we present the literature review, concentrating on analyses of different aspects associated with Industry 4.0 and especially the simulation of innovative systems. Secondly, we present the materials and methods that were applied in this research. The next part of our paper presents the research results and analyzes the results in detail. Finally, we present conclusions and future directions for research.

2. Literature Review

The topic of the simulation of innovative systems is a matter of interest for a number of scholars who have analyzed it from different points of view. Bolshakov (2000) studied the problems of modeling business processes and systems, for which he recommended the use of structural–mathematical and categorical–functural approaches. They should be implemented by constructing the qualimetry of models and multi-model complexes. In turn, Yevenko (1983) studied the issue of modeling business processes in forming the optimal organizational structure of the enterprise, taking into account factors of the external environment which influence it. This issue was also addressed in the works of

Milner (1975), who developed a systematic approach to enterprise management which involved the systematic development of organizational mechanisms, multivariate assessment of the requirements for a management system, etc. This formed the basis of a new approach to the construction of organizational management structures, which involved the structuring of goals, expert-analytical developments, and organizational modeling.

Lavinsky (1988, 1989) paid attention to the development of systems, as a result of quantitative, qualitative, and structural changes. Quantitative changes lead to a change in the state of component systems, structural changes influence the interconnection of parts without changing their quantity, moreover qualitative changes are associated with the emergence of new characteristics of matter and energy (Androniceanu and Popescu 2017). Methods of planning the resources required to make managerial decisions over a certain period of time and to calculate their optimal sizes are described in Fadel et al. (1994). Moreover, Gustas and Prima (2003) examined the modeling of business processes and their integration with enterprise information systems (Androniceanu et al. 2018). They suggest simulation at three levels: Pragmatic, semantic, and syntactic.

Krogstie et al. (2008) presented an approach to achieve the value obtained from activities on modeling activities to facilitate cooperation and coordination initiatives among stakeholders modeling and in all projects. They discussed it in the context of case projects and activities, and they stated that although work remains to be done both on the sophistication of the approach and on the validation of its general applicability and value, their results showed that it addresses recognized challenges in a useful way. Bergek et al. (2008) point out that the mechanisms and interactions of the actors of an innovation system, and the feedback loops between the different functions, need to be taken into account to properly understand the innovation process. These feedback mechanisms can induce an increase in innovations but also block further development. It is within these dynamic relationships that the development of an innovation system takes place. Thus, the feedback mechanisms between the functions provide for the internal dynamics.

Uriona and Sara (2017) focused their deliberations on a particular modeling and simulation approach known as system dynamics modeling. By analyzing a total of 34 studies, they presented the state-of-the-art use of system dynamics in the innovation systems field. They identified six main dynamics that have been modeled using system dynamics: (i) R&D, (ii) diffusion, (iii) absorptive capacity, (iv) science and technology, (v) learning processes, and (vi) regional agglomerations, both qualitatively (through causal loop diagrams) and quantitatively (through stock and flow diagrams).

Issues of producing innovative policy, providing the subjects of innovative activity with the necessary resources, participating directly in the process of creation, commercialization, and the practical use of new knowledge, intensifying the integration processes between the systems of creation, transformation, and the practical use of new knowledge, etc. were considered in the works of Abbas et al. (2019), Weber and Harald (2012), and Tidd et al. (2018).

This short review of the literature shows that the topic is multidimensional and analyzed on multi-level perspectives. One should then agree with Walz et al. (2016) that the development of innovation systems is a complex process, with many direct and indirect interdependencies of the different variables. Therefore, modern approaches to IS modeling are due to: Modeling the organizational and functional structure of such systems; studying options for their reengineering, flexibility, adaptation, and resistance to environmental conditions; development of directions and approaches to a situational choice of system characteristics. Thus, IS modeling under the conditions of Industry 4.0 should be based on the use of models of all component subsystems in their interaction with the external environment to achieve the set goals, which determines systematic modeling in general.

3. Methods

The article proposes approaches to the modeling of innovative economic systems in Industry 4.0, their states, functions, actions, and operations. Given the nature of the paper, the method of fuzzy logic and methods of structuring the components of IS and the corresponding mathematical apparatus were used. As is known, methods of fuzzy sets should be used in cases when the system operates under conditions of uncertainty. It is characterized by the lack of an exact mathematical model through which one can describe the functioning of the system. At the same time, under the structuring of the system, we understand the process of studying its internal structure. This will contribute to a deep understanding of the components of the system, the links between them, etc.

In particular, a graph of relationships, the system of Kolmogorov differential equations (Kolmogorov et al. 2015; Golinkevich 1985; Gnedenko et al. 2013), the numerical Runge–Kutta (Kiusalaas 2013; Babenko 1986) fourth order method, and a goals tree (Lutay 2014; Dettmer 2007) were used to describe the model. A tree of purpose serves as the basis for forming a graph of relationships. In accordance with the tasks of graph theory, it is used to formulate algorithms for solving the problem of IS modeling. Based on the current graph of IS business processes, Kolmogorov differential equations make it possible to determine the probable state of the system, taking into account the set of its possible states. To solve the system of differential equations, we used Runge–Kutta methods, namely the 4th order method. In terms of the practice of mathematical modeling, this is one of the most applicable, since it provides high precision and comparative simplicity. In order to study the dynamic and static characteristics of the states of the IS under the conditions of Industry 4.0, we had to use the apparatus of the theory of Markov's chains for decision making under uncertainty and resolve many management problems. Markov's chains of higher order should be used to increase the predictive efficiency.

4. Results and Discussion

Innovative economic systems are characterized by a set of interconnected structures (subsystems) involved in the production and commercialization of innovative products; they include, respectively, subsystems that produce innovative policies; aim to provide the subjects of innovative activity with the necessary resources; take part directly in the process of creating, commercializing, and practically using new knowledge; strengthen integration processes between systems of creation, transformation, and practical use of new knowledge under the conditions of globalization; carry out an analysis of international flows of knowledge; organize the export and import of technologies, patents, licenses, technological alliances between resident firms of different countries, international trade in consulting services, foreign direct investments, joint international innovation–investment projects, publications, etc.

The subsystems (SSi, $i = 1,2, \ldots, N$) proposed for the simulation of the IS (S) are to be described by eight sets of system components (Figure 1), namely: E—a plurality of elements; V—the set of indices inherent to the elements of Set E (for the set of V indices, it is expedient to select two subsets: Vj—a subset of the index names; Zj—a subset of values of indicators that change in time); W—the set of states of the system, whose elements are determined by the values of the indicators (Subset Zj), according to their names (Subset Vj), at a fixed time point—Set T; F—a set of functions (actions, operations) which ensure the transition of the system from the initial state to the main goal; C—the set of objectives of the system; R—a plurality of relations containing a subset of relations between the sets themselves and between the elements of each of these sets.

Between the given sets of the system model, there are the following types of relations: (E, Vj)—the relation of conformity, which corresponds to each element of Set E and some sampling from Vj; (Vj, Zj) is the relation of correspondence between the given index name and its specific values at Time t; (Zj, W) is the ratio that corresponds to each element of Set Zj—a subset of the values of elements of Set W at Time t; (W, F) is a relation of order, which defines a sequence of execution of functions (actions, operations) in the process of achieving the main goal C0.

The goal, in turn, can be formed as a requirement for the achievement of specific values of the indicators or performance levels of the IS subsystems and the effective performance of certain functions of the system as a whole (Ciobanu et al. 2019); that is, when modeling IS, it is necessary to allocate such compulsory sets of components (Lavinsky 1989; Milner 1975) which would ensure the completeness of the model (1):

$$M_S = \left\{ \begin{array}{c} E^{SS_1}, E^{SS_2}, \ldots, E^{SS_i}, E^{SS_N}, V^{SS_1}, V^{SS_2}, \ldots, V^{SS_i}, \ldots, V^{SS_N}, W^{SS_1}, W^{SS_2}, \ldots, W^{SS_i}, \ldots, W^{SS_N}, \\ F^{SS_1}, F^{SS_2}, \ldots, F^{SS_i}, F^{SS_N}, C^{SS_1}, C^{SS_2}, \ldots, C^{SS_i}, \ldots, C^{SS_N}, R^{SS_1}, R^{SS_2}, \ldots, R^{SS_i}, \ldots, R^{SS_N} \\ R(SS_1, SS_2), R(SS_1, SS_3), \ldots, R(SS_i, SS_{i+1}), \ldots, R(SS_{i+1}, SS_i), \ldots, R(SS_N, SS_{N-1}) \end{array} \right\} \quad (1)$$

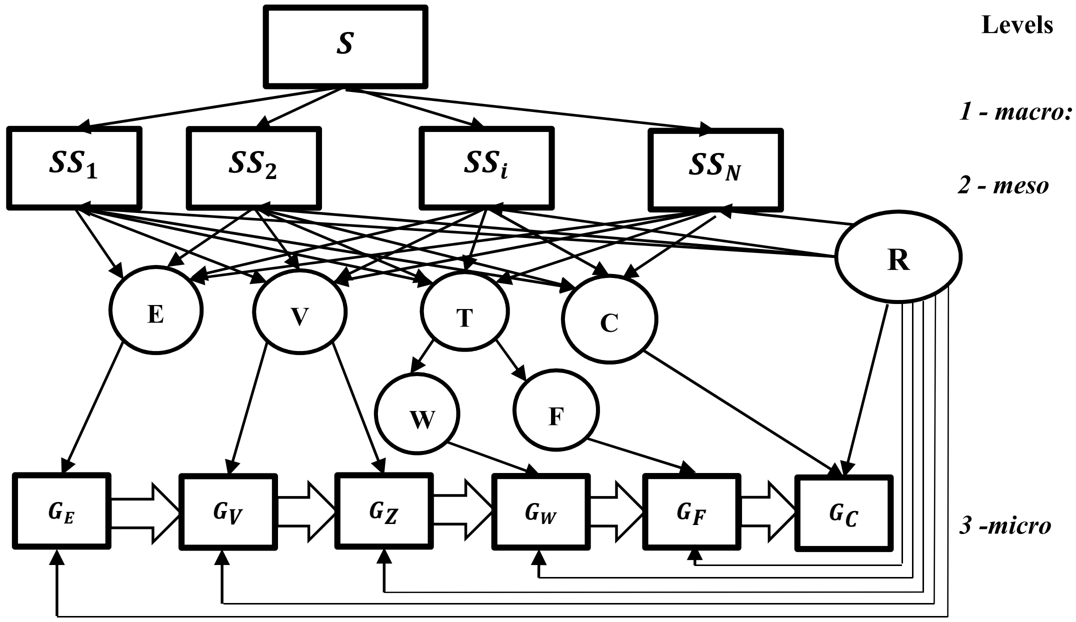

Figure 1. Graph of the decomposition of IS.

The given regularities of structuring and functioning of IS subsystems are the initial rules for the allocation of the system of elements and attributes of the model of the innovative economic system under the conditions of Industry 4.0. From the point of view of the completeness of the system model of such a system at the upper levels of decomposition, consideration of the interconnection of such objects is mandatory:

$$E = \left\{E^{SS_1}, E^{SS_2}, \ldots, E^{SS_i}, \ldots, E^{SS_N}\right\} \quad (2)$$

When decomposing elements of Set E, for each element of the set (2), selecting the entire set of system components $\{V, Z, W, F, C, R\}$ is proposed. The next decomposition of the elements (see Equation (2)) and their components depends on the type of subsystem SS_1 studied, where i = 1,2, . . . , N. A common feature throughout is the hierarchy of structuring. This can be formalized by a description in the theoretical–plural language in the form of a tree of relationships, which may be an abstract level of the hierarchical model of the IS, which defines the units of their characteristics and the relationship between them.

Therefore, it is a six-tier tree, where the first degree is Graph (G_E) (the graph of the elements), the second is Graph (G_V) (graph of the indicators), the third is Graph (G_Z) (graph of the values of the indicators), the fourth is Graph (G_W) (graph of states), the fifth is Graph (G_F) (graph of functions (actions and operations)), and the sixth is Graph (G_C) (tree (graph) goals).

This six-tier graph can specify the rules for the formation of a system model of national, sectoral, and regional innovative system; that is, an innovation system of any organization level (Kurinnyy 2007; Odrekhivskyi 2017). Therefore, it is proposed that the model of the IS under the conditions of Industry 4.0 be presented as a graph, where the hierarchical structures of all subsystems of such systems and environments can be placed on the first level. In order to graphically represent all stages of the graph of the IS, it is proposed that components of the system (macro), subsystem (meso), and micro level (element level) of the innovation system be used. Set elements $E^{SS_1}, E^{SS_2}, \ldots, E^{SS_i}, \ldots, E^{SS_N}\}$ (Graph G_E) indicate the upper level of IS decomposition and, accordingly, can be described by three-level graphs.

It is generally proposed that the evaluation of the efficiency of IS in the context of Industry 4.0 be based on the assessment of the following: Innovation potential, managerial personnel, management technologies, organizational structure and culture of management, personnel management and innovation activities (innovations, innovation projects, innovation process (R&D, production, and marketing operations), and economic relations in the market of innovations), investment and financial activities, and the efficiency of interaction of IS with the external environment according to indicators such as the balance of interests between the system and investors, suppliers, consumers, competitors, and structures that produce innovative policies and regulate innovation activities.

The second graph (G_V) is the graph of the indicators and the third graph is (G_Z)—the graph of the values of indicators can be, for example, the graph of IS's performance and, accordingly, the graph of the values of efficiency.

The fourth level (G_W Graph) can be the state of IS at different levels of the organization and, accordingly, the states of implementation of functions, actions, and operations and their effectiveness (Figure 2).

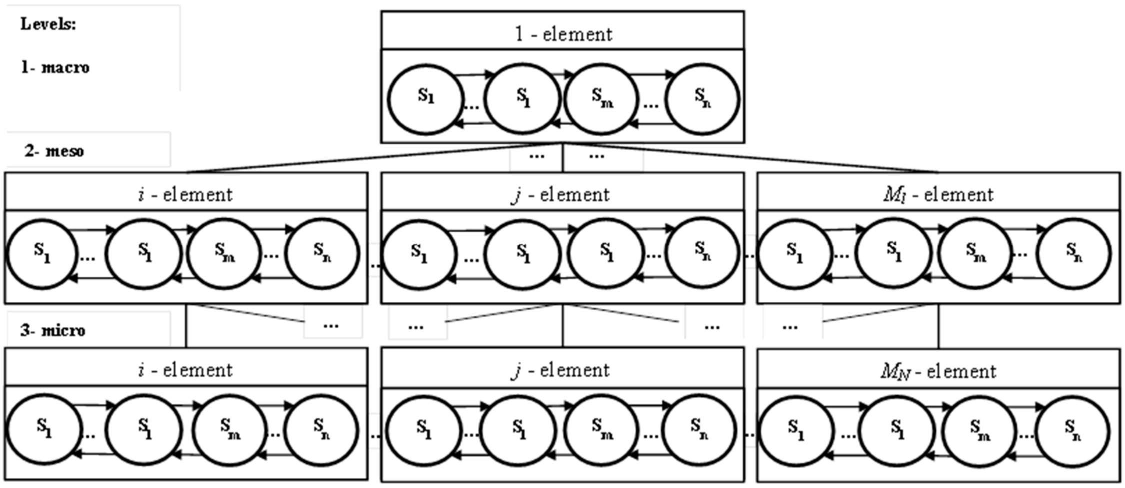

Figure 2. Graph of of states of IS.

This graph can be described using mathematical methods of the theory of Markov chains, for which the use of the system of Kolmogorov differential equations (Korn and M 1984) is proposed, where the description of the states of the j element of the i-th level of the hierarchy will thus appear as:

$$\frac{dP_{i,j,S_1}}{dt} = -\lambda_{i,j,S_1,S_2} \times P_{i,j,S_1} + \lambda_{i,j,S_1} \times P_{i,j,S_2}; \quad (3)$$

$$\frac{dP_{i,j,S_l}}{dt} = \lambda_{i,j,S_{l-1},S_l} \times P_{i,j,S_{l-1}} - \left(\lambda_{i,j,S_l,S_m} + \lambda_{i,j,S_l,S_m}\right) \times P_{i,j,S_l} + \lambda_{i,j,S_m,S_l} \times P_{i,j,S_m};$$

$$\frac{dP_{i,j,S_m}}{dt} = \lambda_{i,j,S_l,S_m} \times P_{i,j,S_l} - \left(\lambda_{i,j,S_m,S_l} + \lambda_{i,j,S_m,S_{m+1}}\right) \times P_{i,j,S_m} + \lambda_{i,j,S_{m+1},S_m} \times P_{i,j,S_{m+1}};$$

$$\frac{dP_{i,j,S_n}}{dt} = \lambda_{i,j,S_{n-1},S_n} \times P_{i,j,S_{n-1}} - \lambda_{i,j,S_{n-1},S_n} \times P_{i,j,S_n};$$

where $i = 1, 2, \ldots, N$—serial number of the level of the hierarchy, $N = 3$;
$j = 1, 2, \ldots, M_i$—serial number of the element of the i-th level of the hierarchy;
$S_1, \ldots, S_l, S_m, \ldots, S_n$—states of the elements of the researched system;
P_{i,j,S_l}—the probability of the S_l-th state of the j-th element of the i-th level of the hierarchy;
λ_{i,j,S_l,S_m}—the intensity of the transition of the studied system from the state S_l to the state S_m j-th element of the i-th level of the hierarchy.

The value of the transition strengths from state to state for each element of the hierarchical structure is statistical information that can be obtained as a result of the functioning of the investigated system. In order to evaluate and predict the states of these systems and their elements, collecting this information at the beginning, during, and after a certain period of operation of the IS is advisable. In order to automate the study of the dynamics of states of such systems and their elements, the numerical solution of the system of differential Equations (3) should be carried out using the numerical Runge–Kutta fourth order method (Korn and M 1984). The automated study of IS states in stationary mode, when t → ∞, a *dP/dt* = 0, is to be carried out on the basis of numerical methods of solving algebraic equations:

$$\begin{gathered}
-\lambda_{i,j,S_1,S_2} \times P_{i,j,S_1} + \lambda_{i,j,S_1} \times P_{i,j,S_2} = 0, \\
-\lambda_{i,j,S_{l-1},S_l} \times P_{i,j,S_{l-1}} - \left(\lambda_{i,j,S_l,\, S_{l-1}} + \lambda_{i,j,S_l,\, S_m}\right) \times P_{i,j,S_1} + \lambda_{i,j,\, S_m,S_l} \times P_{i,j,S_m} = 0, \\
-\lambda_{i,j,S_l,S_m} \times P_{i,j,S_l} + \left(\lambda_{i,j,S_m,\, S_l} + \lambda_{i,j,S_m,\, S_{m+1}}\right) \times P_{i,j,S_m} + \lambda_{i,j,S_{m+1},\, S_m} \times P_{i,j,S_m+1} = 0, \\
-\lambda_{i,j,S_{n-1},S_n} \times P_{i,j,S_{n-1}} + \lambda_{i,j,S_n,\, S_{n-1}} \times P_{i,j,S_n} = 0,
\end{gathered} \tag{4}$$

obtained for the *j*-th element of the *i*-th level of the hierarchy of the system of differential equations (3), since *dP/dt* = 0. Algorithms for the solution of systems of differential (3) and algebraic (4) equations can be used as the basis for the mathematical support of intellectual information systems of estimation and forecasting of states of innovative system and the adoption of optimal managerial decisions (Mints 2017). In the study of the efficiency of IS in terms of Industry 4.0, the effectiveness of the management subsystem *Ex (T)* can be considered the key efficiency, which is due to the effectiveness of management of innovation activities, the efficiency of personnel management, the efficiency of financial activity management, the effectiveness of management of marketing activities, and the efficiency of management of investment activities (Odrekhivskyi 2017). At the same time, the described subsystem of efficiency can be supplemented by the effectiveness of interaction and effectiveness component of potential of the enterprise (innovation potential, managerial potential, organizational structure, etc.) in the proposed system of efficiency of management of intellectual potential (Odrekhivskyi 2017).

In terms of the work of IS under the conditions of Industry 4.0, the efficiency of innovation activity can be considered the priority, which mainly determines the demand for IS goods and services and increases their economic efficiency as integral efficiency, which promotes the continuous development of such systems through their effective management.

The solution of differential equations (3) using computer technology makes it possible to capture dynamic characteristics of the indicators of economic efficiency of innovative systems and solution system algebraic equations (4) are static characteristics, making it possible to predict the state of the economic efficiency of these systems and on this basis, to support the adoption of optimal managerial decisions regarding its statuses and the choice of managerial influences for its improvement

For the effective operation of IS under the conditions of Industry 4.0, it is necessary to periodically or continuously compare the obtained integral efficiency and the efficiency of the controlled subsystem of such a system with planned ones, and if necessary, to correct the activity or planned indicators; that is, the control function in the management subsystem (Rabeea et al. 2019) and operational control of the managed subsystem innovation system.

The study of the economic efficiency of IS under the conditions of Industry 4.0 should be carried out by means of periodic collection of statistical material on the values of certain indicators, and with the help of the mathematical apparatus of the theory of Markov chains, carrying out its evaluation and forecasting is proposed. For this purpose, the value (state *S*) of the economic efficiency indicators should be submitted as: *S1* (*NC*)—"unsatisfactory"; that is, a state in which the basic economic indicators are lower than planned, but not lower than the previous year; *S2* (*S*)—"satisfactory"; that is, a state in which the main economic indicators correspond to the plan; *S3* (*D*)—"good"; that is, the state in which the main economic indicators are higher than planned; *S4* (*DD*)—"very good"; that is, a state in which the main economic indicators far exceed the planned outcome. This allows us to construct a graph of states of economic efficiency of IS (Figure 2) and to describe this graph by a system of Kolmogorov differential equations (3) and the corresponding system of algebraic equations (4), where $i, j = 1$; l, $m = 1, 2, 3, 4$; $l \neq m$. Solving the system of differential Equation (3) with the help of computer technology makes it possible to obtain the dynamic characteristics of the states of indicators of economic efficiency of IS, and solving the system of algebraic Equation (4)—static characteristics—makes it possible to predict the states of the economic efficiency of such systems.

The proposed approach to assessing and forecasting the state of development of IS is as follows. First, information on the results of experimental studies of the state of the innovation process at the appropriate level of its organization should be collected, based on the main economic indicators. The collection of information is carried out at the beginning, during, and after the research period. After this, the information collected is classified according to the states: *S1*, *S2*, *S3*, *S4*. Information was obtained from documents of the financial position of 23 sanatoriums and eight boarding houses of the resort poles of Truskavets as an innovation system (Law of Ukraine «On special economic zone of tourist-recreational type «Kurortopolis Truskavets» 1999). Next, the intensity of transitions from one state to another, which are the coefficients of systems of differential (3) and algebraic (4) equations, are determined. The data of the system of equations are solved and, thus, the probability values of the states of the innovation process in dynamics and statics are determined. According to the results of our calculations, it is possible to evaluate and predict the state of development of IS, the states of stability, and the efficiency of their development.

In order to test the proposed mathematical models for estimating and predicting the state of development of IS, a study was made of the status of the development of 23 sanatoriums and eight boarding houses in the resort town of Truskavets. Modern sanatoria are innovative systems that produce innovative products in the form of innovative sanatorium services that fall into the category of innovation systems. They have concentrated diagnostic and recovery systems, which are based on the use of appropriate equipment and the level of knowledge of specialists, etc.

Following these studies for the period 2016–2018, we obtained the following indicators: In the state of *S1*(*NZ*), there were six sanatoriums; in *S2* (*S*)—11 sanatoriums; in *S3* (*D*)—10 sanatoriums; *S4* (*DD*)—four sanatoriums. Thus, the probabilities of the conditions of the sanatoriums and resort complexes studied had the following initial values: $(S1) = 6/31 = 0.2$; $P_0(S2) = 11/31 = 0.35$; $P_0(S3) = 10/31 = 0.32$; $P_0(S4) = 4/31 = 0.13$.

During the period studied, the developmental conditions of the sanatorium complexes changed. The intensity of the transitions from state to state is represented by the corresponding values above the arcs of the graph transitions (Figure 3).

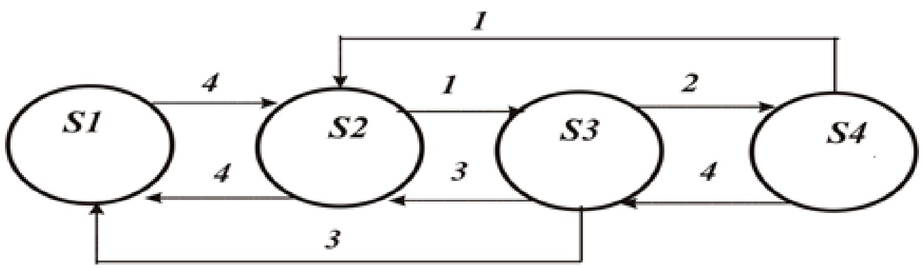

Figure 3. Graph of states of development sanatoriums and resort complexes in Truskavets.

To evaluate and predict the states of development of the studied complexes with the help of the proposed mathematical apparatus, we conducted a study on the probability dynamics of states by calculating Kolmogorov's differential equations with the help of computer technology (Korn and M 1984). The study of the statics of probabilities of states was carried out by calculating the corresponding system of differential Equation (3) of the system of algebraic Equation (4) with the help of computer technology.

In the study of the dynamic and static characteristics (Figure 4) of the probabilities of the conditions of development of the complexes studied on the main economic indicators, we can conclude that the most probable state for the sanatoriums and resort complexes studied is that in which the basic economic indicators are lower than planned, but not lower than the indicators of the previous year.

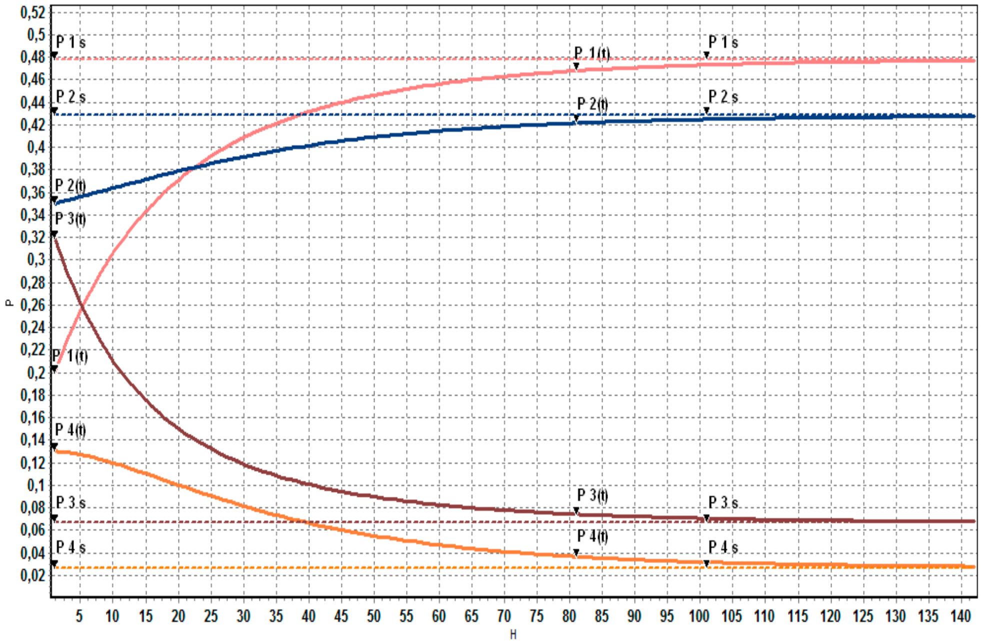

Figure 4. Characteristics of the probabilities of developmental conditions of the sanatoriums and resort complexes studied in Truskavets. $P_1(t)$, $P_2(t)$, $P_3(t)$, $P_4(t)$—value of probabilities of states in dynamics; P1s, P2s, P3s, P4s —the probability values of static states.

In other words, development can be considered unsatisfactory—with a probability of 0.48; satisfactory—with a probability of 0.42; good—with a probability of 0.08; or very good—with a probability of 0.02. The effectiveness of IS in Industry 4.0 also depends on the means of communication, since the exchange of information is directly integrated into all types of management activities and, accordingly, affects the efficiency of management.

The following types of communication are distinguished: Organization—external environment, between level (vertical), between divisions and other units (horizontal), subordinate leader, manager—working group, and informal communications; that is, in the organization of IS activity in Industry 4.0, there should be various types of communication provided that would increase the efficiency of IS management and thereby maximize the management of the managed subsystem of such a system and its integral efficiency. Therefore, it is relevant here to investigate the functions, actions, and operations of IS that contribute to the achievement of the goal, and such systems can be the fifth level (graph) when decomposing (Figure 5).

The inclusion of the management functions, actions, and operations of the IS (Bolshakov 2000; Yevenko 1983; Kuzmin and Olga 2003)—forecasting, formation of innovative goals, planning, organization, stimulation, control, and regulation—are suggested.

A six-level decomposition of the IS is proposed for the purpose tree (Figure 6).

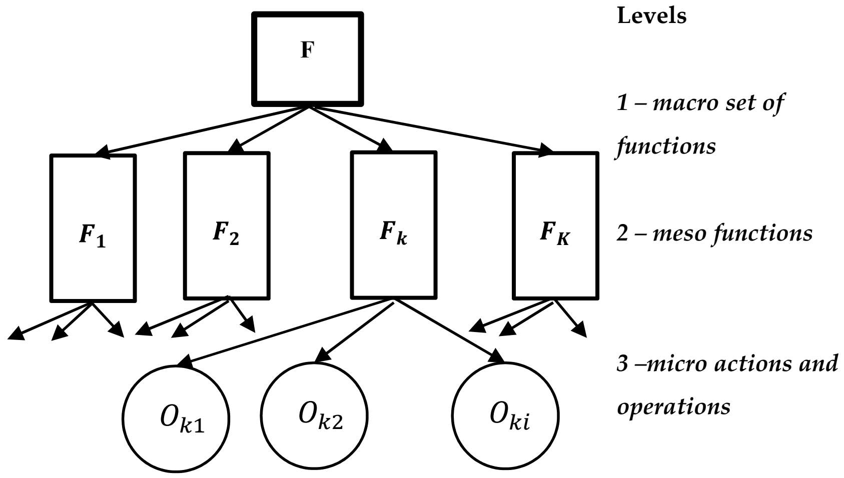

Figure 5. A graph of functions, actions and operations.

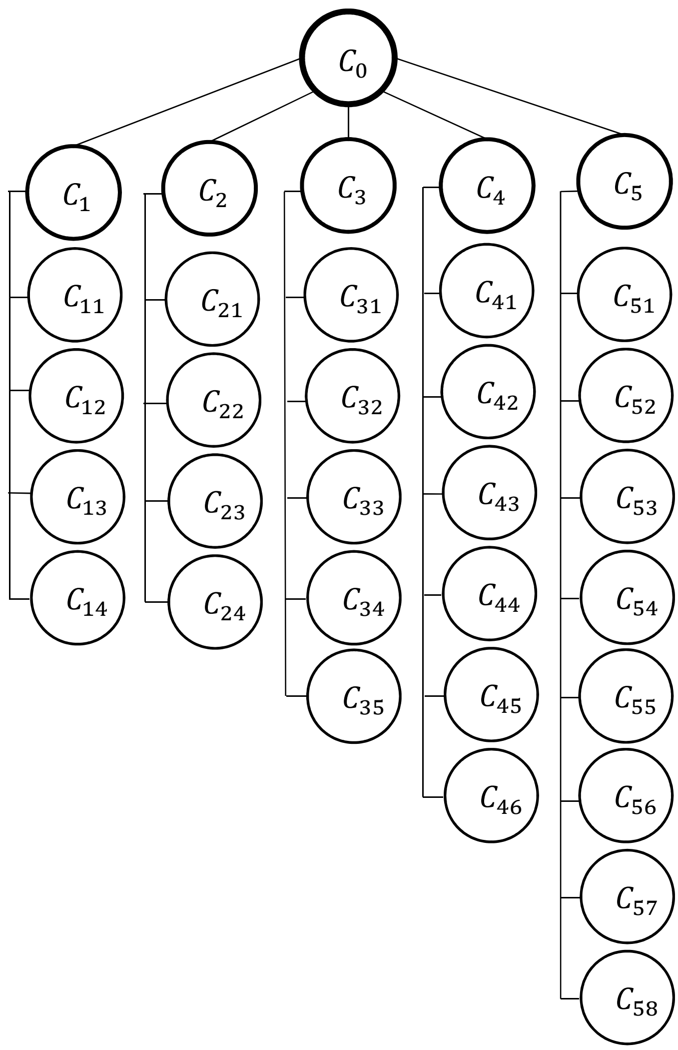

Figure 6. Tree of IS goals.

This tree defines the main purpose (C_0) of the IS and the ways to achieve it; that is, it includes the objectives of all elements and subsystems of the system, in particular:

C_1— production of intellectual products; C_{11}—generating ideas; C_{12}—research work; C_{13}—design and development work; C_{14}—experimental work;

C_2— production of intellectual products; C_{21}—development of production; C_{22}—production; C_{23}—sales;
C_3— training; C_{31}—knowledge; C_{32}—skills (actions and operations); C_{33}—Submission of submissions; C_{34}—use of innovative technologies; C_{35}—Study of the educational process and decision making on its condition;
C_4— introduction and use of innovations; C_{41}—resources; C_4—process; C_{43}—food products; C_{44}—market; C_{45}—managerial; C_{46}—organizational;
C_5— management; C_{51}—forecasting; C_{52}—the formation of goals; C_{53}—planning; C_{54}—coordination; C_{55}—organization; C_{56}—stimulation; C_{57}—control; C_{58}—regulation.

The main differences between the proposed approaches in assessing the efficiency of IS under the conditions of Industry 4.0, as complex systems, can be attributed to:

- The consideration of IS as open and controlled systems;
- the division and study of states of characteristics of their external and internal efficiency;
- a targeted approach to substantiating performance evaluations that cover all major components of the system (primarily inputs, transformations, outputs, and feedback);
- the transition from one-liter to multi-criterion (by verticals and horizontals of the hierarchy) of the evaluation of the performance standard;
- the use of system-wide and partial characteristics: Criteria and indicators of expected results (minimum, maximum, etc.), system status indicators, for example, on the development and achievement of the main objective of the IS, and the search for ways to harmonize the criteria for the effectiveness of such systems;
- a comparative analysis of the actual information and economic performance indicators of some IS with the characteristics of others, as well as subjective and cost-effective and documentary sources of performance information;
- a situational approach to the selection of criteria and performance indicators, according to which the type of organizational management system dictates the main type of performance standard.

5. Conclusions

In the article, the theoretical principles of management of enterprises under the conditions of innovative development are improved by means of a proposal to consider IS as complex systems with a set of interconnected subsystems and elements, structure, and strategic and operational activities, oriented towards the achievement of intermediate goals and the main goal in market conditions under the constant influence of the changing external environment. This interpretation allows us to develop IS modeling and to apply the approach proposed in the paper, which is based on the use of the mathematical apparatus of the theory of Markov chains and involves the use of the graph of relationships, the system of differential Kolmogorov equations, the numerical Runge-Kutti method of the fourth order and the tree of the goals.

In further research, the recommended approach to modeling for designing, constructing, and reorganizing IS of different levels of organization and various kinds of complex systems under the conditions of Industry 4.0 in general should be applied.

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