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A HUMAN CAPITAL SIMULATION MODEL IN INNOVATION PROJECTS

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Abstract. The main aspects of three concepts—human capital, innovation projects, and simulation modeling—are considered, and a simulation model is proposed to describe the role of human capital in innovation projects. This high-level abstraction model is intended to study the role of the social component in the organizational structure of an innovation project in a general context (at the level of an economic sector, an enterprise, or part of an enterprise). It is treated primarily as a tool for tracking the dynamics of projects considering the state of human capital of the system. The model consists of two main components, namely, a basic simulation model in system dynamics terms and an agent-based component of the model describing human capital dynamics. The model is a conceptual tool that requires calibration and refinement when being implemented in a particular organization.

Keywords: simulation modeling, system dynamics, agent-based approach, human capital, innovation projects.

INTRODUCTION

Simulation modeling is actively used to study various socio-economic and social and technical systems [1, 2]. The advantage of this approach is the ability to represent a modeled system at different levels of abstraction, which allows the resulting models to perform descriptive, predictive, and prescriptive functions on different planning horizons.

The three main paradigms of simulation modeling––system dynamics, the discrete-event approach, and the agent-based approach—provide many applications due to differences in their principles and tools [3]. Considering the impact of human capital on innovation projects, it is necessary to study two paradigms: the agent-based approach and system dynamics.

System dynamics implies an exceptionally high level of abstraction: various systems are studied in terms of stocks and flows connecting them, and the individual entities within a system (within the agent-based approach, often represented by the individual actors of system processes) are specified by the nested characteristics of such stocks and flows [4]. System dynamics is useful when investigating global systems, e.g., demographic processes or epidemiological trends [4, 5]. The agent-based approach focuses on the behavior and interaction of individual actors in a system whose states together form the state of the entire system [6]. This approach is quite universal and allows modeling systems at various levels of abstraction: the abstractness of the model is bound to the object modeled as an agent and increases when passing from local particular agents (people, machines, devices, etc.) to global abstract agents (enterprises, regions, states, etc.) [7].

The transition to agent-based modeling is mainly due to the fact that the generality and strictness of the rules implied in other paradigms can be used to a limited extent when tracking trends boundedly dependent on human thinking (e.g., in epidemiology [4]) but appear less adequate in organized and controlled systems.

The need to track the dynamics of the mutual impact of the social component and the efficiency of an innovation project in project-oriented systems (project teams, enterprises and groups of enterprises implementing projects) is the main problem stated in this paper. Simulation modeling with the hybridization of the agent-based approach and system dynamics is chosen as a method to develop such a tracking tool. The results of this study also justify the value of human capital in the formation of a sustainable system for implementing innovation projects.

Thus, the goal of this study is to develop tracking tools for the dynamics of projects considering the state of the human capital of the system. When applied to a particular project-oriented system, the model under development should analyze the role of human capital in the implementation of innovation projects from two points of view. The first one is bottom-to-top, i.e., by analyzing the behavior of individual actors in innovation processes in the context of its impact on the projects under consideration. The second point of view is top-to-bottom, i.e., by analyzing the impact of global indicators of an enterprise's innovation activity (primarily the effectiveness and efficiency of innovation projects) on human capital.

1. BASIC CONCEPTS AND REQUIREMENTS FOR THE MODEL

1.1. Human Capital

The concept of human capital became widespread at the end of the twentieth century. According to the Oxford English Dictionary[1], human capital is defined as "a labour force, or the skills it possesses, regarded as a resource or asset." In addition to skills, more complete definitions include the concepts of knowledge, implicit knowledge [8], and intellectual property, as well as employee education and even health [9].

Human capital is often associated with knowledge management, i.e., a branch of organizational management in which human capital is considered primarily from the point of view of the expert knowledge, skills, and implicit knowledge of employees. In this context, some researchers treat human capital as part of intellectual capital [10], which is the main source of profit for an enterprise within the concept of a self-learning organization [11].

Human capital development is an important problem of modern organizations. In various conceptual versions of knowledge management, it is interpreted differently. For example, in the Japanese doctrine of knowledge development, human capital (still being expressed primarily through the knowledge and skills of employees) is a dynamically developing structure within an organization and is improved mainly due to the continuous exchange of knowledge [12]. This approach aims at incentivizing communication and knowledge transfer. The American concept, in turn, concentrates on direct knowledge management using organizational and financial decisions that stimulate the development of knowledge primarily within a limited circle of inventors who transfer outwards not so much knowledge as the result of intellectual activity, which is not always the same [13].

This study involves both concepts mentioned above. By assumption, human capital in the context of knowledge is replenished both through the transfer of knowledge from more experienced or knowledgeable employees to less experienced or knowledgeable ones and through the generation of new knowledge by the efforts of one employee or a limited group of employees. Terminologically, such knowledge generation processes can be called extensive and intensive, respectively. In the former case, the organization's human capital index will increase by disseminating current knowledge; in the latter case, by creating new knowledge. Obviously, these processes should be connected and coordinated; otherwise, the growth of human capital becomes impossible. Thus, knowledge, skills, and other forms of intellectual objects as part of human capital move in an organization, which provides a basis for forming its innovation potential [14].

Russian researchers are actively elaborating the competence-based approach. First of all, it is applied to education [15]. The competencies developed by students are fixed in educational standards, but logically this approach can also be applied to the human capital of organizations, at least because some competencies are designated as professional and, accordingly, are intended for use in the professional activities of graduates. Current Russian studies also establish a connection between the competence-based approach and human capital, particularly in innovation-oriented companies [16, 17]. The examination of competencies is also applicable to assessing the human capital of organizations. The feature distinguishing competencies from knowledge and skills (see the description above) is that the former cannot be transferred to other employees: they are the sovereign characteristic of an individual employee. The human capital model will need to link the competencies and knowledge of employees in order to adequately assess the impact of (transferable and non-transferable) knowledge on the organization's human capital.

It is necessary to consider other aspects of human capital, primarily related to the health of employees. The problems of physical [18] and mental [19] health of employees are being intensively investigated in the context of their impact on human capital. Note that the particular factors of working conditions or occupational risks are difficult to account for within a high-level research model since threats to the physical health of employees may vary significantly between organizations.

[1] The Oxford English Dictionary. URL: www.oed.com. (Accessed February 19, 2024.)

Therefore, when developing a model of human capital in innovation projects, it is to map the human capital of employees considering the following main components:

– knowledge, skills, etc., increasing human capital by transferring knowledge between employees (further called extensive knowledge);

– knowledge, skills, etc., increasing human capital due to their emergence and development in a limited circle of people or a person, including extensive knowledge, skills, etc. from the outside (further called intensive knowledge);

– health and other factors of human capital that are not related to knowledge but can be formalized at a general model level without binding to any organization.

Modern studies connect research projects and human capital [20], confirming the topical subject of this paper.

1.2. Innovation Projects

Project activity in modern entrepreneurship is relevant and widespread. For some problems, project management is more efficient than classical operational management. The principles of project management are applied in innovation activity, which is characterized by a traditionally high level of uncertainty, the absence of strict standards and regulations, the involvement of expert opinions, and, if successful, a significant impact on competition in a corresponding economic sector [21]. These features of innovation activity are connected with the fact that innovation projects often focus on obtaining fundamentally new technological, technical, or organizational-legal results, which have no generally accepted standards or widespread best practices. In such conditions, the project approach becomes appropriate as it allows achieving the uniqueness and flexibility of work activities. This paper neither provides unique definitions of an innovation project nor makes an emphasis on the precise boundaries of the corresponding notion. In what follows, innovation projects are systems of measures providing a technical and economic, legal, and organizational justification for applying the results of R&D activities to create fundamentally new products, services, and methods of exploiting products (in function or form) or organizing fundamentally new production processes for goods and services [22]. When considering this term, some peculiarities arise, to be accounted for in model building.

As has been mentioned, it is important to consider human capital in innovation-oriented companies and, consequently, in their innovation projects [16]. It allows justifying the application of the model proposed in this paper to innovation projects. In fact, human capital (expressed primarily in the potential for generating new scientific knowledge) plays an especially high role in the activities of innovation companies in general and the implementation of innovation projects in particular [23]. By assumption, such a characteristic of innovation projects imposes the following requirements on the model being developed:

– Human capital should affect the system of innovation projects at all stages of their implementation.

– Each implementation stage of innovation projects should have a probability of project refusal due to the impact of various factors, including those of the organization's human capital (the lack of knowledge, errors in development, etc.).

– Each project should affect the organization's human capital, replenishing the knowledge base of its employees.

These general requirements presumably cover the entire range of innovation projects and, therefore, are applicable to a high-level simulation model. The requirements have to be specified when building models for the innovation activities of particular organizations.

1.3. Simulation Modeling

The two commonly used simulation modeling paradigms—system dynamics and agent-based modeling––have been described in detail in the Introduction. The basic model in this study is implemented in system dynamics terms: this decision is due to the abstract high-level nature of the model. The model should adapt to the particular conditions of economic sectors and enterprises but, at the same time, reflect the general patterns of human capital development when implementing innovation projects. In this context, agent-based modeling turns out to be overly detailed. However, as one of the development prospects, hybrid modeling can be implemented by combining system dynamics and the agent-based approach to specify some system interactions.

Hybrid modeling is a distinct paradigm within simulation modeling. A hybrid model combines several separate basic approaches to simulation modeling, which provides coverage of an almost unlimited space of simulated systems. This method should be used only if the goals of modeling cannot be achieved within any basic paradigm [3].

The capabilities of a hybrid model vary depending on the combination of methods. The agent-based approach and modeling in system dynamics terms are combined to describe systems in which some global patterns without detail (market prices, large urban infrastructures, or general demographic patterns) are associated with the behavior of individuals or separate objects, such as organizations, enterprises, and municipal or state entities [24, 25]. When considering the role of human capital in the implementation of innovation projects, this combination of approaches is applicable due to the interaction of global factors and particular agents (the company's staff, the sector's employees, and social groups).

Thus, simulation modeling is an adequate tool for solving the problem stated and studying the systemic relationships of human capital in innovation projects. We pose two problems as follows:

– implement a basic model in system dynamics terms;

– supplement the basic model with an agent component to refine the dynamics of individual variables related to human capital.

2. MODEL DESCRIPTION

2.1. Basic Model in System Dynamics Terms

For high-level abstract modeling, we adopt a simplified perception of a modeled system. In the context of system dynamics, single projects have no unique features and separate attribute values, in contrast to discrete-event modeling, and act solely as the characteristics of stocks and flows within the model.

As the basic template for implementing the simulation model, we take the "Main Chain" structure model, representing a chain of stocks connected by intermediate flows. This model is commonly used to visualize production chains [26].

In view of the requirements for the system (the impact of human capital at all project implementation stages, the probability of project refusal at all stages, and the impact of each implemented project on the organization's human capital), the model is supplemented with numerous individual converters (variables) and flows that remove projects from the system before their implementation. The key output characteristics of the system are the profit obtained and the growth of human capital based on the successful implementation of an innovation project.

The basic model and its supplement (the agent component) were developed in *AnyLogic*, a widespread simulation environment. The model is shown in Fig. 1.

All flows in the model are specified by complex functions that combine the impact of factors associated

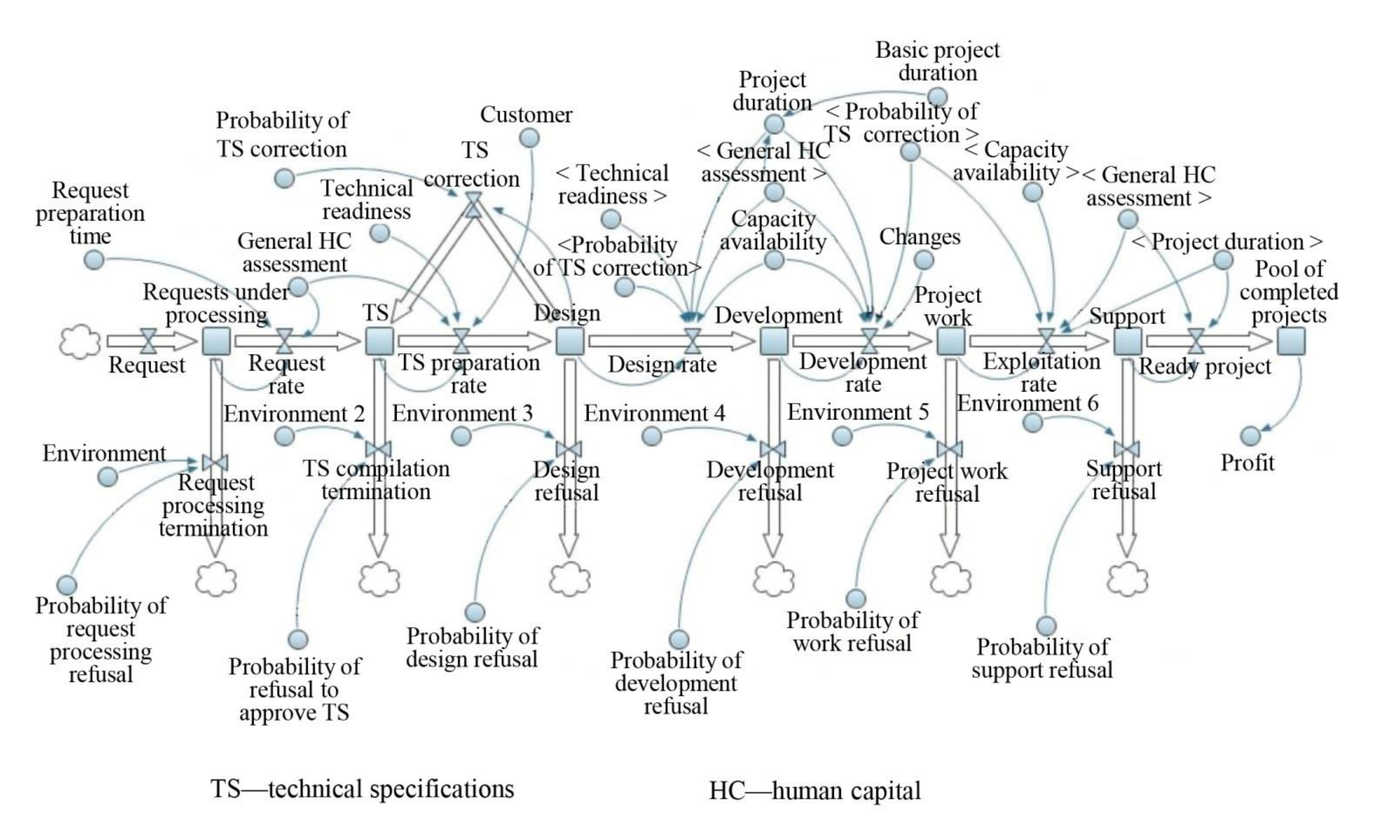

Fig. 1. The main module of the basic model in system dynamics terms.

with these flows. Most of the functions that determine transitions between the main stocks of the "Main Chain" structure are described by first-order delay functions with an acceleration correlating with the integrated assessment of human capital. The flow $f_1(t)$ is calculated using the typical formula

$$f_1(t) = \theta(t)\frac{I(t)}{\tau}, \quad (1)$$

where $\Theta(t)$ denotes the integrated (overall) assessment of human capital at a time instant t; $I(t)$ is the value of the stock ahead of the flow at a time instant t; τ is the delay.

Formula (1) with natural changes is applicable to the request rate, the TS preparation rate, the design rate, the development rate, the exploitation rate, and the ready project flow. The values of technical readiness and the customer's impact assessment are added to the integrated assessment of human capital to speed up the flow: the average value is taken as an accelerator. The impact of other factors is similar to that described for TS preparation.

The flows representing a refusal to further develop the model for any reason are modeled using the formula

$$f_2(t) = \varepsilon\, p\, I(t),$$

where ε denotes the integrated assessment of the impact of environment's factors (including the probability of customer's refusal) at a particular project implementation stage; p is the probability of refusal to develop the project by the executor at a particular project implementation stage.

This formula with different values of the input variables is applicable for the flows of request processing termination, TS compilation termination, design refusal, development refusal, project work refusal, and support refusal.

An additional component is required for the basic model to simulate human capital. This component models the dynamics of human knowledge, skills, and non-intellectual factors (e.g., health). By assumption, the basic model in system dynamics terms can model the entire human capital of an organization using one component of the simulation model. This component is demonstrated in Fig. 2.

The module in Fig. 2 generates a unified integrated assessment of human capital that affects the implementation stages of innovation projects (see Fig. 1). It reflects the professional and behavioral competencies (only the intensive factors of human capital growth), knowledge, and skills of employees (having intensive or extensive nature), the health level of employees,

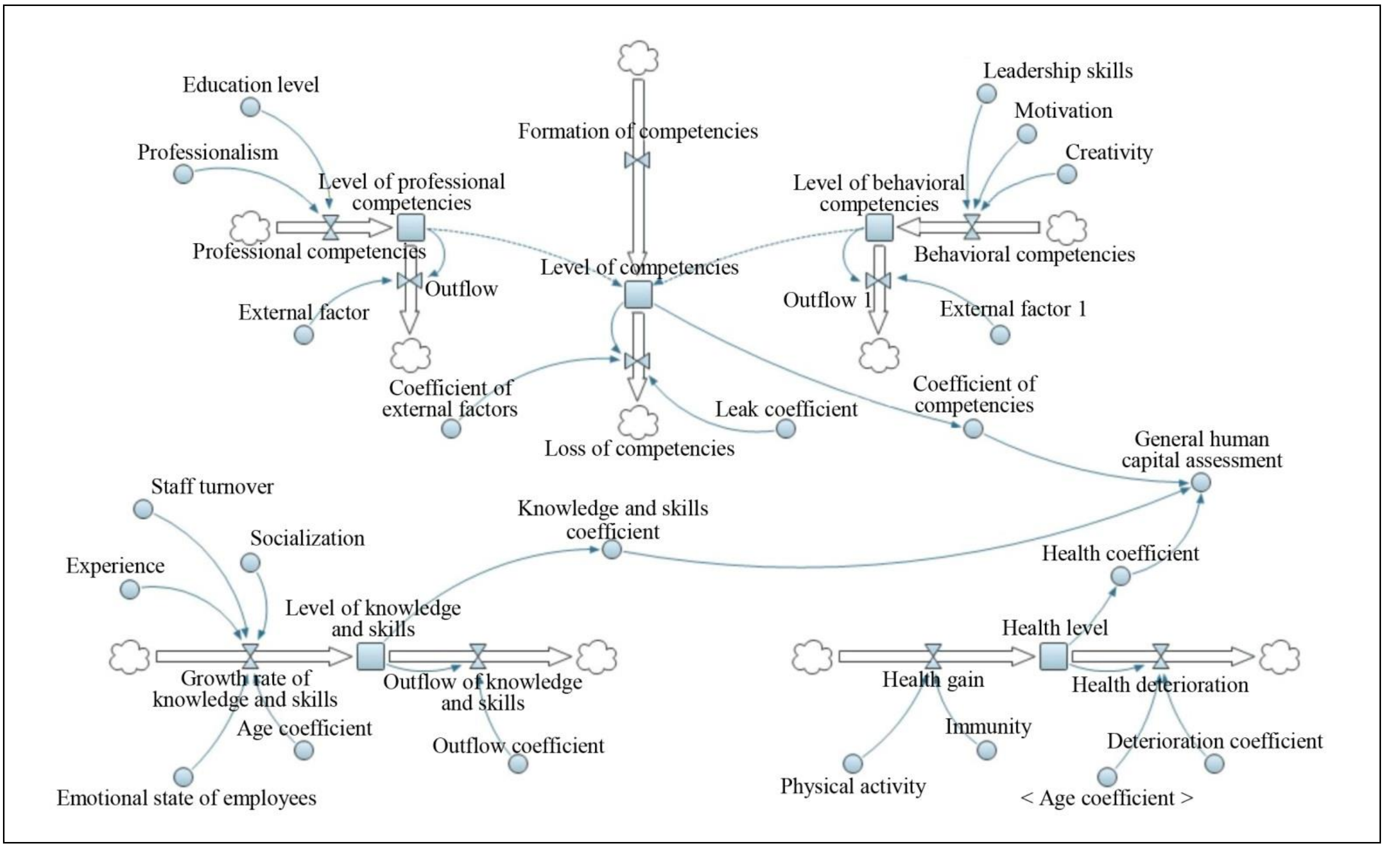

Fig. 2. The additional module of the basic model for assessing human capital in system dynamics terms.

and several simple factors assessed in this model by constants or continuously varying values (e.g., the emotional state of employees).

Flow modeling for the human capital assessment module is mainly based on calibration coefficients bound to a particular system being modeled. For example, health gain is described by the formula

$$f_3(t) = k_1 I + k_2 P,$$

where k_1 and k_2 ($k_1 + k_2 = 1$) are the calibration coefficients; I is the assessment of the immunity of the organization's employees; P is the assessment of the physical activity of the organization's employees.

For in-depth models of human capital impact, such assessments of immunity and physical activity can be variables that change according to the dynamics of the behavior and activity features of employees. However, in a high-level abstract model, such detailing seems to be unreasonable.

Some flows of this module are also described by first-order delays in their original form or with accelerators (see formula (1)). Such flows are the outflows of behavioral and professional competencies, the outflow of knowledge and health deterioration, and the loss of competencies. (The fundamental difference from an outflow is that the loss of competencies models the loss of competencies by employees due to their non-use, whereas outflows, including the outflows of competencies, describe the discharge of employees and the resulting decrease in human capital).

The other input flows of the model (the growth rate of knowledge and skills, the growth rate of behavioral and professional competencies, and the formation of employee competencies) are modeled as the aggregate assessment of factors positively affecting a given flow, divided by the aggregate assessment of factors negatively affecting the flow, with calibration coefficients if necessary.

The next modeling problem is to supplement the model with an agent component to refine human capital dynamics within the system.

2.2. The Agent Component as a Supplement to the Basic Model

Figure 3 shows a general behavioral algorithm for an agent (a person in a project-oriented system) in various simulated situations in terms of Business Process Model and Notation (BPMN).

The agent component is introduced by replacing the additional module for assessing human capital. In this case, the integrated assessment of human capital will be the sum of the human capital assessments of each employee. This logic is not absolutely correct since it neglects some probable latent patterns (e.g., a hidden optimum number of employees with a certain level of human capital), but it seems admissible for an abstract high-level model.

In the agent-based supplement to the basic model, an individual person—an employee of the organization being assessed—is taken as an agent. It has the same components with the same change patterns as in the additional module, but they are assessed for an individual person. Moreover, the increase in extensive knowledge and skills (i.e., in those growing through dissemination rather than generation) is determined by receiving corresponding messages from other agents.

Thus, the agent-based supplement has the following dynamic changes in the main parameters of the agents:

– Upon successful completion of projects, the knowledge and skills of the involved agents (random agents in the basic version) increase; the agents can exchange this knowledge. (The exchange occurs with a probability depending on the knowledge level and health of a given agent.)

– If projects are unsuccessfully completed, the health of the agents involved (random agents in the basic version) deteriorates due to their psychological stress after unsuccessful implementation.

– With each unit of the simulation time, part of the knowledge and skills of all employees is lost (due to long-term stagnation, which is leveled by successful projects or knowledge generation), and the competencies of all employees grow.

– At each sequential implementation stage of the project (increasing the stock of each sequential stage), knowledge is generated for the agents involved (random agents in the basic model) agents. They can acquire knowledge and skills with some probability; if successful, they can also exchange the generated knowledge. (The exchange occurs with a probability depending on the knowledge level and health of a given agent.)

– When an agent (a random agent in the basic model) receives an exchange message, his or her knowledge and skills increase.

Note that beyond the algorithm presented in Fig. 3, employees are hired and dismissed at certain intervals. Such a flow is specified by an additional module of the system dynamics model (Fig. 4). New employees entering the system have basic values for all characteristics (knowledge and skills, professional competencies, behavioral competencies, and health), whereas the characteristics of those dismissed are lost.

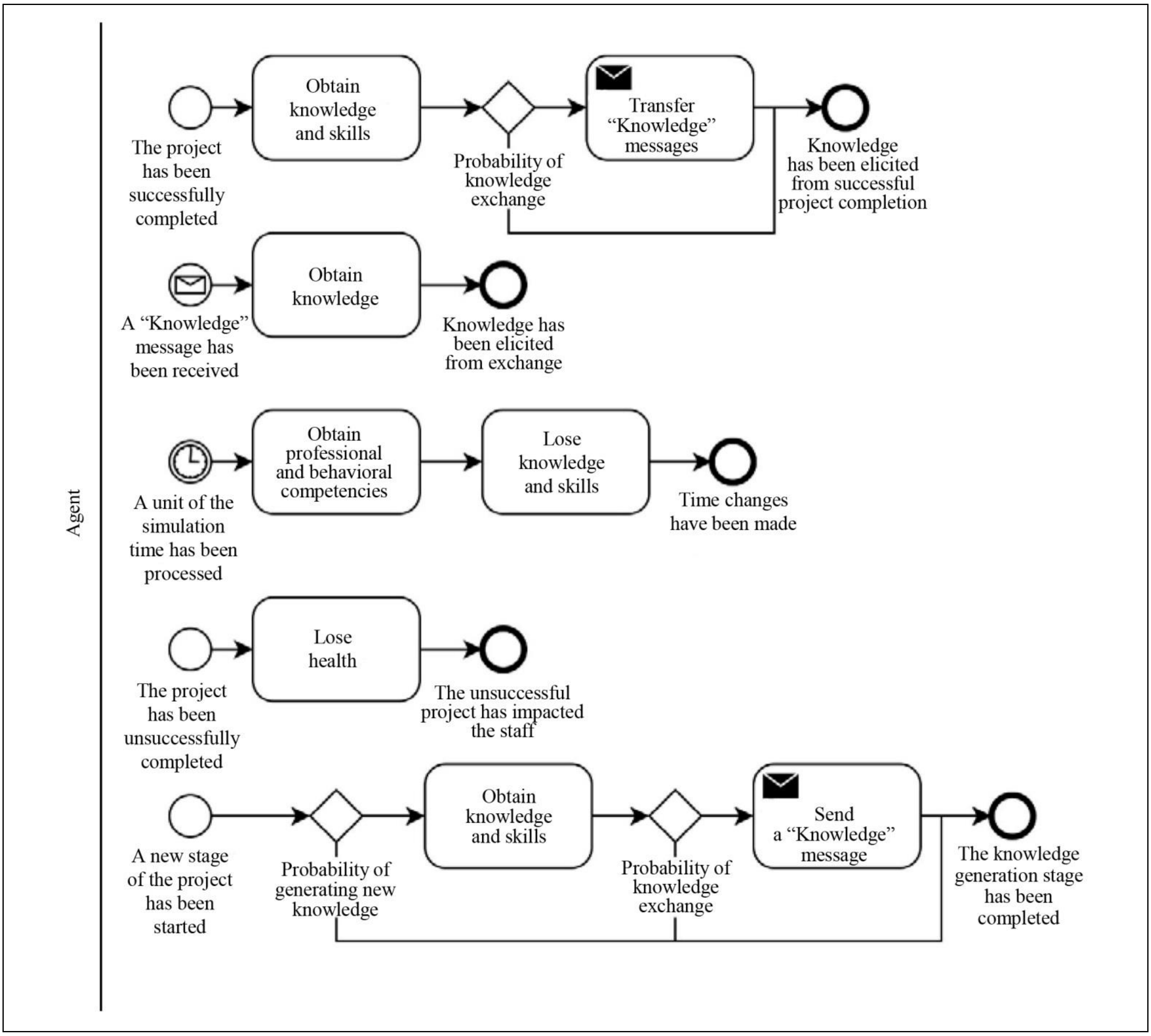

Fig. 3. The agent's behavioral algorithm in BPMN terms.

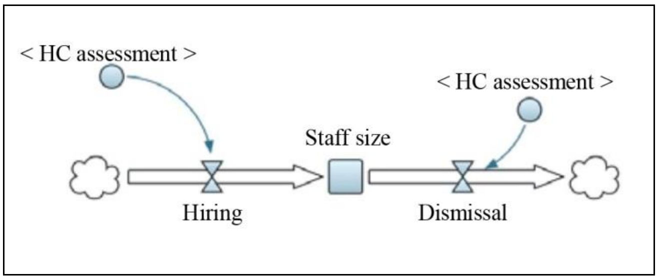

Fig. 4. The additional module for changing the staff size.

In Fig. 4, "HC assessment" is the integrated assessment of human capital in the system. This assessment is calculated based on the human capital assessments of individual employees using the formula

$$\theta(t) = \frac{\sum_{i=1}^{N} \frac{\sum_{j=1}^{4} \xi_{ij}}{4}}{N},$$

where ξ_{ij} denotes the value of human capital assessment criterion j (knowledge and skills, professional competencies, behavioral competencies, and health) for employee i; N is the number of employees (staff size).

Figure 5 presents the state diagrams of agents implemented in *AnyLogic* according to the algorithm (see Fig. 3).

These state diagrams taken in aggregate (for the entire population of agents) replace the additional hu-

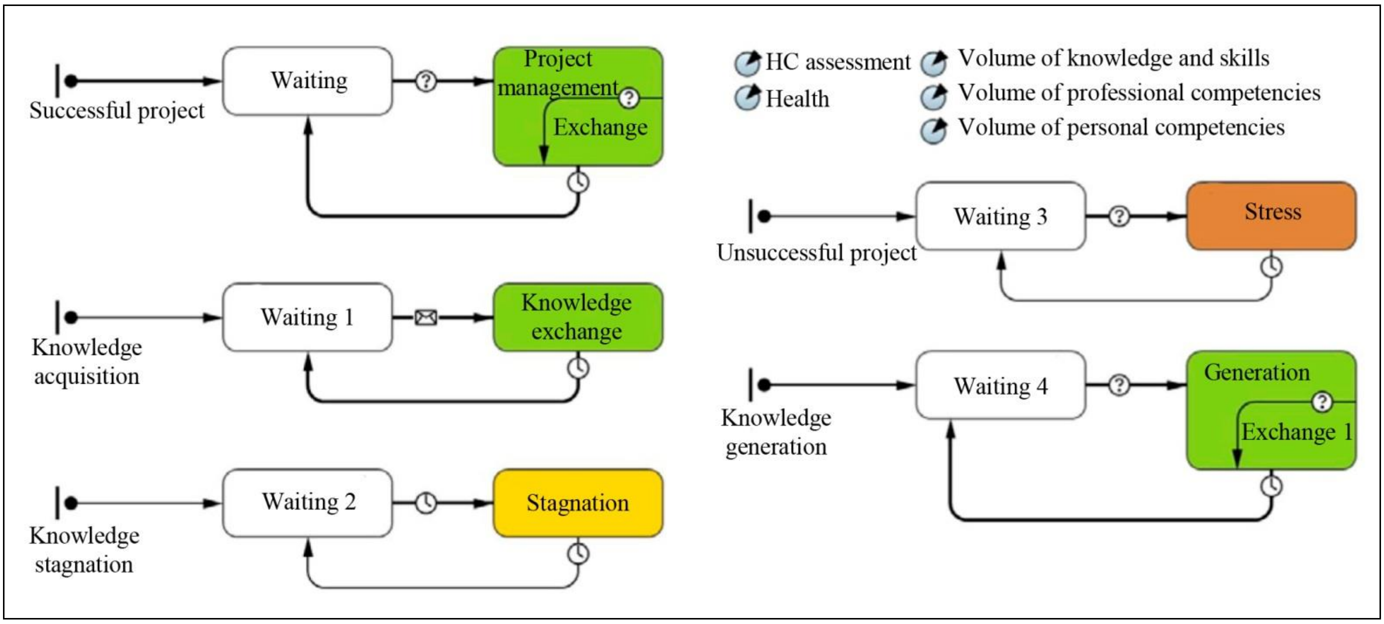

Fig. 5. The state diagrams of the agent component of the model.

man capital assessment module of the basic model in system dynamics terms (see the description above). The transitions in state diagrams are specified by message receipt conditions or the state of the system dynamics model.

2.3. Discussion of the Main Features of the Model

The model conceptually reflects the main factors of the mutual impact of human capital on the efficiency of ongoing innovation projects in a project-oriented system (firm, consortium, project team, etc.). These factors have been revealed based on the analysis of the sources and the authors' experience. Due to the conceptual nature of this model, we make some comments on its components, which may be revised when applying the model in particular project-oriented systems to assess the role of human capital:

• The set of factors influencing the parameters of the basic model of project dynamics can be reviewed and changed at the high level. (For example, the factors of health, the technical readiness of the enterprise, age, etc. can be reasonably excluded or replaced according to the goals of modeling; the model can be supplemented with other factors according to the requirements for a particular case of its application.)

• The main structure of the basic model can be complicated during model calibration: to better match a particular project-oriented system, it is possible to change the orders of delays describing the flow functions, the set of factors influencing a particular transition between states, etc.

• The rules for human capital dynamics can be revised at the high level of abstraction: a general or partial variation in human capital factors can be introduced as a result of various model states (e.g., improving the skills of individual agents in unsuccessfully implemented projects that have reached a certain stage, etc.).

• The mutual impact of factors can be changed, in particular, the nonlinear impact of individual factors on integrated assessments can be added. (For example, the health factor in the general model has a linear impact on an integrated assessment, in conformity with other factors, which seems correct for systems developing innovation IT projects. However, for systems with a risk of severe occupational diseases or those requiring exclusively on-site work without the possibility of remote employment, low values of the health factor can zero the integrated assessment of human capital.)

In its current form, the model has some limitations due to its structure. For example, the model does not allow assessing the unique dynamics of one project or a small group of projects. Therefore, its adequacy is low for systems with a small number of projects: the model is recommended for use in large project-oriented systems (firms, consortia, program committees, etc.). In addition, the model is a high-level abstraction and, hence, has low adequacy under a small set of empirical data for its validation and calibration. An additional limitation on adequacy is that the structure of this model is partially based on the experience of the authors and, therefore, the universality of the proposed concept is subject to discussion: such a system may be poorly applicable to some project-oriented systems, but the list of such systems remains uncertain at the current model development stage. According to the authors' point of view, promising lines for further research may be the concept's universalization and the applicability of the proposed tools to various systems.

Note also the advantage of this model compared to other tools for assessing the human capital factor in the activities of companies. There are known applications of agent-based modeling in knowledge exchange [27] and agent-based models for studying the impact of individual factors (e.g., the degree of mutual trust [28]) on knowledge transfer within an organization. Generally speaking, agent-based modeling is a fairly common tool for modeling the human capital of organizations [27–29]. (This logically follows from its ideology.) Therefore, the particular models listed above can supplement the general hybrid model described in this paper. Analogous studies, however, neither introduced the concepts of hybrid models nor focused on project activities. Hence, they appear less useful when applied to project-oriented systems. At the same time, the formal description of processes related to human capital in the considered examples of models is more accurate and deeper; therefore, integration with such models can seriously strengthen the proposed tool. The existing analogs focused on project management (e.g., see [30]) provide a much less particular approach to describing the project life cycle, also concentrating primarily on human capital. Thus, the proposed tool allows achieving the higher adequacy of modeling in project-oriented systems compared to these analogs. Moreover, it can be potentially improved by adding and clarifying the model components related to human capital.

CONCLUSIONS

This paper has proposed a simulation model reflecting the role of human capital in the implementation of innovation projects.

The analytical part of the study has considered the basic concepts of human capital, innovation projects, and simulation modeling, and has formulated the basic requirements for the model under development. The model has two implementations: a basic model, completely implemented in system dynamics terms, and a hybrid model, supplemented by an agent component to the basic module, still implemented in system dynamics terms. The model has been validated on a data set of an undisclosed organization, using two time series: a pool of successfully implemented projects and profits from the successful implementation of these projects. The validation results have confirmed the adequacy of the model.

The model is a high-level abstraction, and, therefore, can be supplemented and specified to model the processes of a particular sector or organization. The patterns and main factors of human capital reflected in the model can be adjusted when improving and refining the model.

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