The Basis for System Dynamics and Agent-based Modeling of Strategic Management of Intellectual Capital in Educational Organizations

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Abstract. This article discusses the problems of using simulation modeling to improve the management of intellectual capital of educational organizations based on the methodologies of system dynamics and agent-based modeling in the context of their impact on reaching strategic goals of an organization. Computer simulation methods using operational indicators and scenario variations provide management with a practical, adaptable and meaningful toolkit for the strategic management of the company's intellectual assets.

Keywords: Intellectual Capital, Educational Organizations, agent-based models.

1 Introduction

Methods of system dynamics and agent-based modeling can be used by educational organizations, as well as other companies and enterprises (hereinafter referred to as organizations) to make strategic decisions in order to achieve competitive advantages. To do this, a computer modeling system should be created and applied that can register, analyze and evaluate intangible assets, since these cases are not sufficient for accounting methods. In addition, this system will allow for an in-depth analysis of an organization's activities (in terms of intellectual capital) in order to identify potential opportunities for increasing the competitiveness of the organization.

2 Materials and methods

In modern international scientific literature, intellectual capital is defined as a set of intangible assets (resources, capabilities, and competencies) that drive an organization's performance and value creation [1]. According to the prevailing view in modern science, the structure of intellectual capital includes human, structural and relational (client) capital [2].

Accordingly, management of intellectual capital can be represented as a complex system of autonomous human and institutional agents, whose interaction is influenced by various stochastic and dynamic factors, which leads to the emergence of new phenomena in the activities of companies in the long term. Therefore, decision-making in this complex system can be problematic due to limited understanding of probabilistic and dynamic interactions, contradictions arising from competing goals and indicators, intermediate information generated by multiple variable feedback loops, etc.

3 Results and Discussion

In cases where strategic planning and cost research in organizations focus on economic performance and cost performance, they do not actually take into account the factors of intellectual capital (knowledge) in any form, which is unacceptable for strategic planning in knowledge-intensive organizations based on understanding and determining their perspective on the basis of available knowledge and intangible resources. Therefore, the scientific literature articulates the opinion that "understanding the potential and limitations of their own model of knowledge strategy, as well as its assessment and management is the key to developing an organization's competitive advantage" [3].

In this regard, systems thinking and its various variants are of particular interest and significance, since they consider the internal complexity of intangible assets and provide a holistic perspective. Intangible assets can be used as leverage to achieve business goals when viewed within the framework of a systems thinking paradigm. In particular, simulation is an effective approach, firstly, to understand and, secondly, to represent the complexity of an organization's intangible asset system.

For example, A. Nielsen classified three dynamic capabilities (possibilities) of the knowledge management process, each of which includes, respectively, several types of actions [4]:

- Development (creation, acquisition, collection);
- Combination (assembly, exchange, integration);
- Use (application, exploitation) of knowledge.

In other words, he presented a diagram of the relationship between dynamic capabilities and knowledge-based resources, stocks and flows of knowledge in a firm, which is considered as means of creating or updating organizational capabilities of a firm, contribing to the realization of the existing potential for creating value.

The mathematical principles of system-dynamic modeling make it possible to give a simple representation of this scheme, since the dynamics of a complex system is determined by its structural elements (stocks), the main of which, according to A. Nielsen's terminology, is the “stock of knowledge”. System dynamics equations represent the evolution of the system over time, the calculation of rates that determine this evolution, the intermediate results needed to calculate the indicators, and the initialization of the system.

According to standard practice, the system dynamics (SD) method aggregates discrete processes, representing them in the form of continuous flows. System dynamics technology was originally developed for the systems whose states change continuously over time. The SD model typically aggregates discrete events of the main system at a level where events can be considered as parts of a continuous flow. For example, individual events can be considered as a flow of similar events over a certain period of time.

In the context of SD, intellectual capital can be represented as an accumulated and expendable "level" (also called a fund or stock in SD models). For example, a project of UNSW Centre for Business Dynamics combines the groundbreaking work on "intangible assets" by Karl-Erik Sveiby with human capital modeling based on system dynamics [5].

If the system is represented as a network of "storages" and "flows", then the corresponding system-dynamic model can be implemented as a computer program. Such a program can be used to conduct pilot testing of proposed management policy changes. Using the modeling language, systems of linear and nonlinear algebraic and differential equations containing up to several thousand variables can be effectively solved.

Quantitatively, each "storage" is determined by the level of its content, and each "flow" is determined by the rate (speed) of movement. The rate of movement is calculated based on information about the content levels of the "levels". Thus, the simulated object is represented as an information system with feedback. "Storage" describes quantities that are continuous in their range of values and discrete in time. They can be defined as system state variables whose values are formed by accumulating differences between incoming and outgoing flows. "Flows" are analogs of accumulation transformation processes in the system; they move the contents of "storages" and reflect either material or informational processes. Their intensity (pace) is determined by management decisions, which are formed on the basis of information about the state of the levels. Decision functions (or rate equations) are a formalization of rules that determine how information about levels leads to the selection of current flow rates.

Flow-type models are dynamic feedback models. Since real systems have inertia, their structure contains elements that determine the delays in the transfer of changes along the feedback loop. In each model of system dynamics there is a special discrete variable − time, the choice of the unit of measurement, which (the time step of modeling) is carried out by the developer of the model as well as the modeling interval. Simulation research is characterized by internal logic, which is expressed in the sequence of a number of stages and allows combining the features of the experimental approach and the specifics of using computer support tools. Simulation research is sequential and iterative in nature, connected, on the one hand, with a clear order of changing stages, and on the other − with the cyclicity of individual stages (within individual stages and between stages).

Visual programming is used when developing models. A model that includes various elements is built on a conceptual level.

The cause-and-effect diagram shows how the model variables are related to each other. It is a marked-up graph whose elements are variables represented by their identifiers or full names, and arrows go from cause variables to effect variables.

The values of all variables included in the simulation model are calculated at each moment of the model time. Then, at a certain interval, new values of variables are calculated based on the old values, etc. Thus, the simulation model develops along a certain trajectory during a given period of model time.

The variable "time" is primary for the simulation model of a dynamic system: its value is generated by the system timer and changes discretely, that is, starting from a certain value, the time for each cycle increases by a predetermined value, which serves as a unit of model time. The number of cycles and the unit of time are parameters of the model "run" and are determined by the model designer.

From the point of view of the presented approach, it is impossible to study the processes in the system separately – only the study of the dynamics of the entire system with all its connections gives a correct understanding of the problem under study. All systems, no matter how complex they are, are built on closed feedback loops of the dependencies of variables in the structure of the simulation model.

To display the set of cause-and-effect relationships, which we call the basic scheme of the theory of intellectual capital, algorithms of the Powersim Studio Enterprise computer program can be used, which serves as an add-on for strategic analysis in the well-known complex of automated management of large firms and corporations SAP. The representation of cause-and-effect relationships in the form of connectors (arrows) that connect subsystems and system elements in a closed loop is displayed on the computer program interface, which is shown in Figure 1.

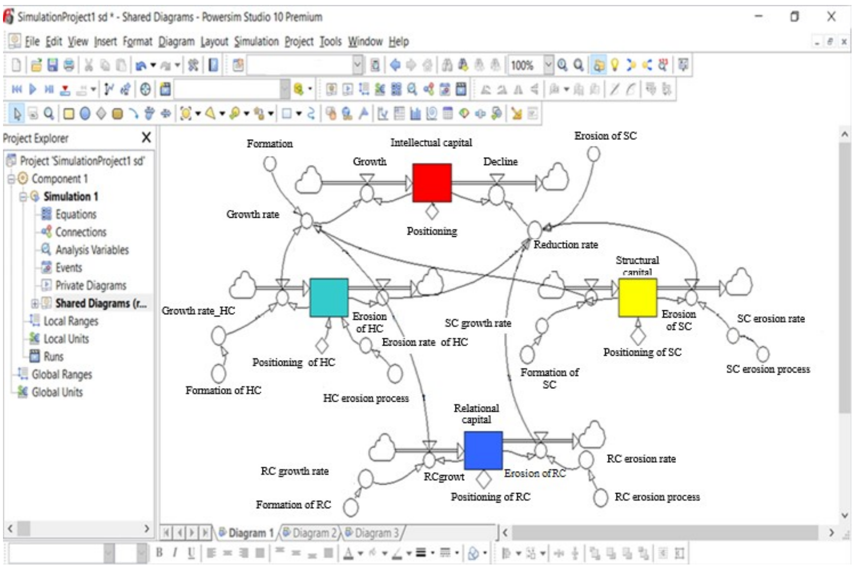

Fig. 1. Structure of a fragment of the SD model of intellectual capital Source: Compiled by the author.

Depending on the characteristics of specific industries and the research and management tasks put forward, the subsystems of the developed model of intellectual capital can include as many subsystems and variables as are considered optimal, and mathematical calculations of varying degrees of complexity can be performed with these variables.

For example, K. E. Sveiby's system-dynamic model of intellectual capital is based on his theory of measuring a company's intangible assets [6]. Three "families" of intangible assets act as "levels" of the model: external structure, internal structure and individual competence. The combination of internal structure and individual competence together can be called the "knowledge capital" of a firm. The external structure is formed by intangible relationships with customers and suppliers, which form the basis of a company's reputation (image). The internal structure contains patents, concepts, models, templates, computer systems, and other more or less explicit administrative tools and processes. The structure of individual competencies consists, on the one hand, of the competencies of professional and technical personnel, and on the other hand, of support and management personnel, including employees of the research and development department, employees of the enterprise, sales and marketing department.

The comparison criteria for choosing and applying system dynamics (SD) or agent-based methods (ABM) in the field of intellectual capital and intangible assets analysis may differ depending on the strategic goals.

The scientific literature notes that "one of the undeniable advantages of using ABM to study the dynamics of a certain system is that you are not limited to defining the behavior of the system in a mathematically solvable form. First, it allows complex behaviors to be built using multiple "if-then" rules. This is important because behaviors are captured by flowcharts much more easily and naturally than by systems of equations. Second, the simulation may contain many random elements controlled by different probability distributions. Applications in economics and finance, unlike some other areas where ABM is applied, almost always require randomness in the behavior specifications of the agent or system. Mathematical modeling in such conditions quickly becomes excessively cumbersome [7].

Since the model is created as a computer program, the behavior of agents can be easily described using a set of "if-then" rules, in fact by placing a flowchart describing an agent's behavior in the computer code. A behavioral model is clearly easier and more natural to capture with the help of flowcharts than through systems of mathematical equations. Simulations can also contain many random elements driven by different probability distributions. Social and economic applications almost always contain randomness in the behavior of agents, and this behavior may not always fall under well-studied analytically distributions such as the normal distribution.

Agents are reactive, active, autonomous and social software objects, a computer program or an isolated computer system that is located in a certain environment and is capable to act flexibly and autonomously in it. Agents have the following properties:

- are clearly identifiable (have clearly defined borders and interfaces);

- are located in a certain environment (receive data through sensors and act through effectors);
- are capable of flexible actions (react to changes and act ahead of time);
- have autonomy (control both their internal state and their own behavior);
- are created to achieve certain goals (try to achieve a goal or solve a problem).

Since an agent consists of both “states” and “rules”, it can perform actions on itself, other agents, and the environment, and receive input from other agents and the environment. An agent's "state" is a specific set of parameters that defines an agent or all relevant information about it at a given time. The internal, local and global states of each agent, static or dynamic, affect its overall state. Agent “rules” describe how agent states are converted into actions or new states. Rules are understood as mechanical rules of decision-making or transformation functions, rather than as generally accepted social concepts of rules as regulations or agreements (Figure 2).

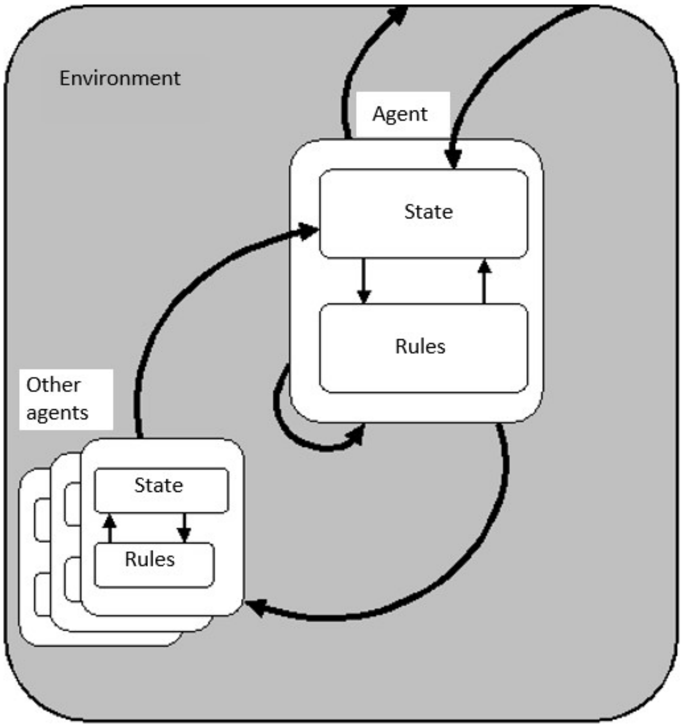

Fig. 2. Structure of an agent-based model. Source: Adapted diagram from the work [8].

When constructing full-scale agent-based models of innovation capital, the specific mechanisms included in the model structure (agents, their behavior, interactions, environmental structures, etc.) depend crucially on the goal and concept of the model. In our case, we consider two types of agents: agents representing real people, and agents representing real organizations and/or their divisions, which add several more complex levels to the model.

If we return to the fragment of the system-dynamic model of intellectual capital from this point of view (see the chart), the difference between system dynamics and the agent-based approach becomes more obvious. In the first case, a decisive role is played by the structure of the IC; in the second case, the behavior of these types of agents in the sectors of formation, positioning, and erosion of intellectual capital and its components – human, structural, and relational capital is of great importance.

When modeling IC, it is necessary to consider organizations as a set of management positions, and, more importantly, as a set of management agents. In any case, an organization must be a well-defined structure. The organizational design of a company, its strategy for developing intellectual capital, and mechanisms for managing intellectual capital are modeled.

The most important aspect of agent-based modeling is the design and inclusion of social networks in the IC model, since they influence the decisions and behavior of individual agents, and, consequently, the company in relation to intellectual capital at both the micro and macro levels. Theoretically, there are two ways to create social networks in an agent-based model: use existing software to create graphs with specified characteristics, or write the necessary codes using algorithms for creating network packets in Java or other General-purpose programming languages, if the model is created in an environment that uses this language (for example, REPAST Symphony [9]).

Networked agent-based modeling algorithms make it possible to deal with the long-term effects of stochastic and dynamic interactions and trade-offs arising from conflicting goals. Traditional optimization algorithms that search for optimal analytical solutions are less effective when analyzing complex real-world systems, since they do not take into account uncertainties, intangible factors, and dynamic factors of the decision-making environment, and homogeneous assumptions in conventional statistical models are not true for a system of heterogeneous agents.

Potentially, modeling allows management to better understand the complexities of real organizational systems by integrating organizational structure, tangible and intangible aspects of organizational behavior, resources and policies so that a holistic view of system development can be used. Most importantly, non-material behavioral aspects can be displayed and modeled, and the impact of feedback loops on system behavior can be included in analysis that cannot otherwise be reflected in traditional analytical models. In addition, organizational knowledge is consolidated during the model conceptualization stage by encouraging stakeholder participation, identifying structural relationships, analyzing basic assumptions and theories, and evaluating the values of modeling parameters.

In this context, agent-based modeling is an imitation of a complex human system as an artificial system of autonomous agents that interact based on a set of theories, rules, or assumptions. Macro-level behavior of a system arises as a result of repeated interactions of its subjects at the micro-level of the system. Agent-based modeling is a microanalysis technique that can be used as a learning tool in decision-making based on comparing emerging scenarios, rather than as an optimization tool for finding optimal analytical solutions.

Current approaches to decision support rely heavily on aggregates, assuming homogeneity in human resources, and focus on organizational performance at the macro level. Both static and dynamic assessments are performed using analytical and statistical methods, but the assumption of uniformity and the use of aggregated indicators limit the ability of such methods to reflect the qualitative heterogeneity of an organization's staff groups and the actual micro-level of their interaction. In addition, their behavior may be determined by dynamic internal and external factors of the organization itself.

In modern scientific literature, it is believed that approaches based on the methods of systems dynamics and agent-based modeling provide a more creative understanding of intellectual capital and intangible assets in general. In the usual sense, intangible assets are passive elements that are not included in the general statements of the results of operations and balance sheets of companies. Through these systematic approaches, intangible assets can be presented and reinterpreted as natural elements with active behavior. This leads to "significant improvements and new contributions to the area of knowledge management, as well as to the full range of applications of simulation approaches" [10].

4 Conclusion

Detailed, calibrated models using systems dynamics techniques, combined with agent-based modeling techniques, are powerful tools to support business strategy. They correspond to modern approaches to planning organizations, serve as a test for the adequacy of the model as a representation of the intellectual capital system, and provide accurate estimates of costs and benefits in the trade-offs of alternative strategies

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References

1. Li-Chang H., Chao-Hung W.: Clarifying the Effect of Intellectual Capital on Performance: The Mediating Role of Dynamic Capability. British Journal of Management, 23, 179–205 (2012).
2. Gogan L.M., Draghici A.A.: model to evaluate the intellectual capital. Procedia Technology, 9, 867-875 (2013).
3. De Toni A. et al.: The nature and value of knowledge. Kybernetes, 46(6), 976 (2017).
4. Nielsen A. P.: Understanding dynamic capabilities through knowledge management. Journal of Knowledge Management, 10(4), 67-68 (2006).
5. Sveiby K-E et al.: Report for the Australian Federal Public Service by the UNSW Centre for Business Dynamics (2006).
6. Sveiby K-E: Sveiby Knowledge Associates, 1-2 (2018).

7. Tarvid A.: Agent-Based Modelling of Social Networks in Labour–Education Market System. London: Springer, 24 (2016).
8. Van Dam K H et al.: Agent-Based Modelling of Socio-Technical Systems. Netherlands, Springer, 57 (2013).
9. Yakimov I.M., Kirpichnikov A.P., Trusfus M.V.: Bulletin of the technological University, 19(22), 143-6 (2016).
10. Sanchez-Segura M - I et al.: System dynamics and agent-based modelling to represent intangible process assets characterization. Kybernetes, 47(2), 289-306 (2018).
11. Tyulin A., Chursin A.: The New Economy of the Product Life Cycle, Springer International Publishing, 400 (2020).
12. Chursin A.A., Grosheva P.Yu., Yudin A.V.: IOP Conference Series: Fundamentals of the economic growth of engineering enterprises in the face of challenges of the xxi century. Materials Science and Engineering, 862(4), 42049 (2020).
13. Filippov V.M., Chusin A.A., Ragulina Yu.V. et al.: The Cyber Economy: Opportunities and Challenges for Artificial Intelligence in the Digital Workplace. Swutzeland: Springer Nature, 337 (2020).