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Models of Research, Development and Innovation Systems from the Perspective of Complexity Theory: A Case Study of the Republic of Moldova

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Abstract. Complexity Theory allows to better understand how some phenomena that surround us and are difficult to describe through traditional approaches of a single scientific domain appear, evolve and adapt. These phenomena have been called "complex systems". The objective of this paper is to analyse the *research-development-innovation* (RDI) system from the perspective of complex systems. The features of a complex RDI system are identified. It is argumented the importance of modelling RDI system for efficient management and decision-making under uncertainty. Several modelling approaches are reviewed with a view to setting the stage for proposing a comprehensive conceptual representation of the RDI system. The inputs, activities and various possible outputs, effects, and impact are described in details. Other possible models such as the Triple Helix and X-type, Y-type RDI models are described and their applicability is analysed. As a case study, a RDI system of the Republic of Moldova is analysed and modelled. A set of recommended decisions is presented together with a SWOT analysis.

Keywords: complex system, conceptual model, decision-making, methods of modelling, Triple Helix model

1. Introduction

A very large number of real-world systems are accepted as complex systems: the human body, the immune system, the financial market, social organizations, the road traffic system, the ecosystem, population dynamics and much more. There is no fixed and accepted-by-all definition of a "complex system", but this term is associated with an object or item composed of parts, elements or agents that interact closely and through mutual interaction produce non-trivial occurrences that cannot be explained by the behaviour of each individual element (Buslenko, 1978; Newman, 2011). Researchers that study complex systems have identified the features that characterize a complex system: large number of constituents; nonlinearity; feedback; spontaneous order or self-organization; robustness; hierarchical or network organization (Barabási & Albert, 1999; Filip & Leiviskä, 2009; Ladyman et al., 2013). These properties are not strictly necessary for a system to be qualified as a complex one, nor are they sufficient, but they are key features that differentiate complex systems from the simple ones (Zeng et al., 2017).

Out of these series of characteristics, one of the most essential and amazing feature both for complex systems and for their component parts (in the sense of structure), is the ability to self-organize. According to Heylighen (2009), self-organization is an unexpected emergence of the global structure, which arises from local interactions (internal environment). The word "spontaneous" means that no internal or external agents can control the process which is really collective, parallel and distributed among all the elements of the system. Thanks to this property, the organization of the system is very robust and resistant to destruction and disturbance. Because the interactions between the agents of the system (component parts) are non-linear, the evolution of the system is unpredictable and cannot be controlled. The interaction of agents and their self-organization at the local level results in global coordination and synergy.

2. RDI as complex system

Institutionally the RDI system consists of many interconnected entities: administrative and legislative institutions, funding organizations or bodies, research organizations and units, service subdivisions, libraries, etc. The network of all these entities with different type of connections form a complex system.

Any national RDI system is a component part of the global RDI system and should be examined in the context of global trends. At the same time, the national RDI system interacts with the educational, cultural, social, economic, political system, etc.; influences and is influenced by them. On the other hand, in the RDI system the key element is the human being. Based on this property, the RDI system is a complex social system: it represents a complex network of many people connected to each other institutionally, thematically, culturally through overlapping models of relationships.

Being a structure with many large-order chains and nonlinear feedback loops, any complex social system is characterized by unpredictable feedback reactions. This feature is the cause of the failure in attempts to radically improve the behaviour of a complex social system.

Sawyer (2005) identified three unique characteristics of complex social systems that are also applicable to any RDI system:

1. Social systems are more open compared to other complex systems.

2. In complex social systems the interconnections between individuals are more complex and not always physically visible. In natural systems they are always visible.

3. In social systems, unlike all other complex systems, components (individuals) have representations of emerging macromodels and thus, the emergence is the result of the specific communication of individuals.

Based on characteristics of complex social systems and specifics of science and innovation activity, we state that a RDI system has the following features:

1) It is self-organizing from two perspectives: researchers often self-organize into non-formal research groups to solve problems or present common ideas (collaboration, co-authorship); new knowledge appears and self-organizes in the process of scientific and technological activities;

2) It is illogical: the system behaves in a manner that contradicts to our expectations. The situation may worsen when its improvement is expected;

3) It is surprisingly insensitive to changes in many parameters of the system, resistant to administrative innovations; reacts "late" (long-term) to any administrative innovation when immediate (short-term) reaction is needed;

4) Contains powerful attractors (agents) of influence in unexpected places that can change the balance in the system;

5) Counteracts and compensates for external forces by reducing the rate of action that is generated inside the system.

According to complexity theory, the RDI complex system is open, non-linear, robust, emerging, self-organizing. The open state of the RDI system is maintained by the exchange of information with the external environment. The non-linearity of the RDI system is its unexpected reaction to external actions: an insignificant but well-organized action can have a greater impact on the evolution of the RDI system than a stronger but inadequately presented action in line with its own development trends. The robustness of the RDI system lies in the fact that no internal or external component parts can control the process which is truly collective, parallel and distributed among all parts of the system. Thanks to this property the system is very resistant to destruction and disturbance.

The emergent effect of the RDI system consists in the self-organization of informal scientific collaboration networks, the appearance and self-organization of new information and knowledge.

Thus, the efficient management of the complex RDI system is one of the biggest challenges.

3. Management and decision-making in a complex RDI system

The most important activity of the management process is decision-making. All other activities are carried-out to ensure that the right decisions are taken or, if the decision has already been taken, to implement and monitor its effectiveness. Depending on the degree of certainty of the possible results or consequences that the manager faces in the decision-making process, three types of methods can be applied:

- Decision making under certainty (classical model);
- Decision making under risky conditions;
- Decision making under uncertainty.

The classical decision-making model is applicable in those cases where the initial data for the calculations are clearly specified (defined or measurable) and the calculations themselves can be performed efficiently using classical mathematical methods (finding the exact solution) or numerical analysis (applying approximate methods with a predetermined accuracy).

The choice of a decision in risky conditions (partial uncertainty) applies if each action leads to one of the possible outcomes and each outcome has a probability of occurrence calculated or estimated by the decision maker or expert. It is assumed that the decision-maker is aware of these probabilities or they can be determined by expert estimates.

Decision making under conditions of uncertainty takes place when one or more actions result in several possible outcomes, but their probabilities depend on the state of the environment. In other words, uncertainty refers to situations in which events cannot be expressed in terms of precise mathematical probabilities (Mândru & Begu, 2009).

Because RDI systems are complex systems, most often the decision-maker does not have enough information or complete knowledge about the state of the system (environment). In this case, decisions are made under conditions of uncertainty.

Decision-making in conditions of uncertainty is always subjective, even if in these conditions, some mathematical methods can be applied with the view to elucidate the situation and provide reasoned advice to the decision maker. For example, in conditions of uncertainty, the manager or expert can apply the Wald Criterion, the Savage Criterion or the Hurwicz Criterion, which with a high probability will recommend different strategies. In such cases, the decision maker will choose the strategy based on personal experience and knowledge (Gaindric, 2017). In other words, it will be based on a prediction.

Prediction has become an integral part of managerial practice. Sometimes this

ability is called forecast, assumption, estimation or perspective. No matter how we call it, managerial decisions for short or long term, cannot be made without it. Any business investment decision requires the forecasting of key parameters, such as interest rates and / or demand. Any expenditure on research, development and innovation requires an estimate of future needs (Mandl, 2019). The range of qualitative and quantitative predictive methods is wide. Which of the methods is better remains an open question, since the decision-maker sees which prediction was more accurate only post-factum. Thus, the question of which method of prediction should be used is more an ideological one than a scientific one. It is to mention that any prediction method would be used, the first step in developing the management and control scheme of complex systems, including social ones, is to analyze and model them.

4. Models and methods of modelling of a complex RDI system

Modeling complex systems is a theory that describes the structure and interactions in the system. The very fact of modeling the process does not speak of a correct model. The model is only a representation of reality with which we can understand and analyze the phenomenon, the process, the system studied. At the bases of the structure of a model can be put the principles of the dynamic behavior of the system with the feedback loop or the model can be a simple description of the fragments, the processes of the system without describing its structure.

At the same time, whatever the selected model of the complex system is, let us remember that any model reflects different aspects of the essence of the system. Recall that, according to Turing's theorem of undercidability (Turing, 1954), creating a model that would describe all the properties of the system is impossible. Such a model would be more complex than the system itself. Thus, when describing a complex system, one tries to model only a part of the system or a limited set of aspects that characterize the behavior of the system. In this case there is a risk of omitting important or even crucial parts or aspects. To resolve the conflict between the need for simplification and the accepted accuracy, the complex system can be represented by a family of models. These models reflect the behavior of the system from different perspectives and are called levels of description or levels of influence (Filip & Leiviskä, 2009).

The main problem of a complex system consists in the difficulties that arise in formal modeling and simulation of its behavior. There are several classifications of models and modeling methods of complex systems. Four methods of modelling systems are proposed by Berinato (2016). He states that any model can be designed based on the type of the available information and the purpose of the model. And because there can be two types of information about the system (data or idea/concept), and two different purposes to model a system (to declare or to explore), after combining the type of information with the purpose of modeling we

obtain four types of models:

- Declarative and based on idea / concept.
- Declarative and data-based;
- Exploratory and data-based;
- Exploratory and based on idea / concept.

With reference to RDI system, Nalimov & Mul'chenko (1969) view science as a system in the broadest sense of the word and proposes a set of 9 models:

1. The informational model, in which science is viewed as a self-organizing system, managed by its own information flows. Within this model, the development of science is studied in terms of its information flows. This model uses bibliometric methods for analysis.

2. The logical model reflects the logical development of ideas. This approach is related to the problem of classifying scientific fields / disciplines.

3. The gnoseological model, in which the methodologies used in scientific research are studied. In this model the attention is given to the problems of argumentation of mathematics, hypothesis and experiment, mathematical theory of experiment.

4. The economic model studies the interaction of science with the economic development of the country, evaluates the economic effectiveness of scientific research.

5. The political model reflects the interaction of science with political ideology, the link between the development of science and the country's prestige, the country's military potential.

6. The social model, in which the multitude of people engaged in scientific research are studied through the prism of the social group. It interacts with other groups, defends their rights, and influences social life.

7. The demographic model, refers to the study of the human scientific potential of the country through the prism of the demographic problem. Particular attention in this model goes to the age of the researchers.

8. The model "Scientist - active creative individual" studies the psychology of scientific creativity.

9. The engineering model in which science is studied as a system that can be guided. The issue of the optimal organization of scientific research, the use of the "operations research" method in the organization of research, development and innovation activities are considered important.

Nalimov and Mul'chenko (1969) warns that each of the mentioned models reflects only one aspect of science, and the complex, multilateral study of the process of science development requires the combination of several studies, obtained by specialists in different fields, through various methods.

5. The conceptual model of RDI system

The conceptual model of RDI system in terms of inputs, activities, outputs, outcomes and impact was developed and proposed by Cujba (2021) and is presented in Fig. 1.

The main purpose of RDI system is to solve the problems or needs of society. Arising from the problems, the objectives for the RDI system are formulated.

The inputs to RDI system (financial, human, material/technical resources, knowledge) are used to perform RDI activities (experiments, hypothesis verifying, testing, analysis etc.) and RDI related activities (communication, data-collection, monitoring, reporting, and dissemination).

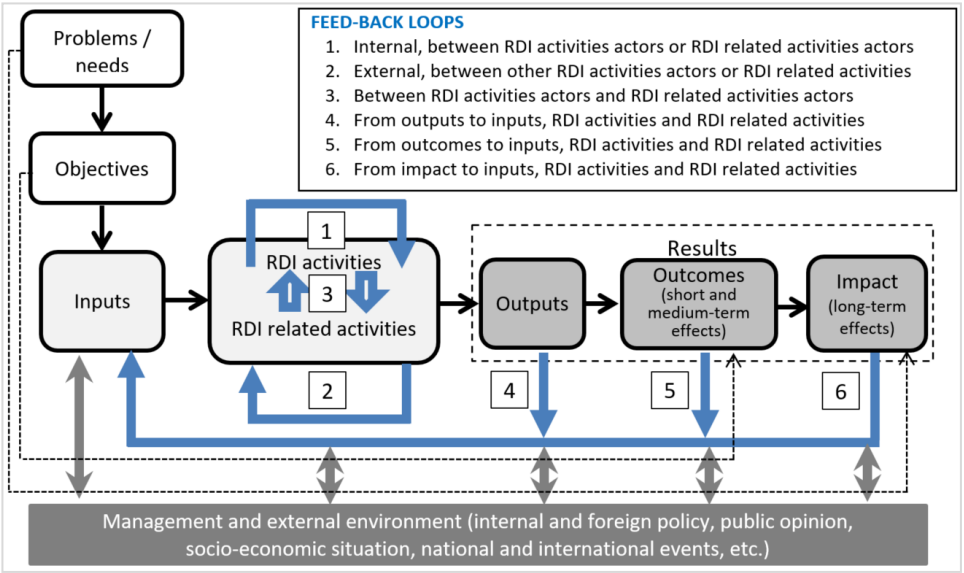

Fig. 1: Conceptual model of RDI system.

Most often RDI activities like experiments or tests are iterative in internal feed-back loop. RDI related activities are also iterative in the most actions like communication, data-collection, reporting. Between RDI activities actors and RDI related activities actors is a constant feed-back loop that lead to exchange of information and efficient RDI activity.

The outputs (publications, datasets, patents, reports, technics, methods, models, databases etc.) which result from RDI activities and RDI related activities start to bring short or medium-term effects or outcomes (services, processes, technologies, products, goods) through their implementation in economy, agriculture, education, culture, health system or, in a feed-back loop, used as inputs for RDI activities and RDI related activities (data-sets, knowledge, new ideas, hypothesis, databases etc.). In feed-back loop the outcomes (methods, models, technologies, and services) can also become inputs for RDI activities and RDI related activities. The outputs lead in

time to the impact like economic and social growth, population longevity, enhanced teaching level and literacy. The impact is the result of solving the problem or satisfying the need of society.

It is obvious that the effectiveness of the whole RDI system depends on each component of the system that interact with other and affect them in the loop of positive or negative feed-back.

6. The Triple Helix model based on innovation

The innovation is the main chain between science and technology transfer of research results to society. This transfer occurs only if the RDI system is open and collaborates with external environment.

The concept of *Triple Helix model (3H model)* that focuses on the collaboration of three spheres (academia-government-industry) to improve innovation is described by many authors (Leydesdorf & Etzkowitz, 1998; Etzkowitz, 2003; Filip & Vasiliu, 2009). This conceptual model was proposed for the first time in the late 90' by Leydesdorf & Etzkowitz (1998). They have shown that the *3H model* is the result of continuous conceptual evolution. They identify three successive forms that differ in how the relationships between the entities that compose the three spheres are realized. Thus, in the case of the first model, marked as *3H I*, the interactions made crossing the boundaries of the spheres are mediated by specialized organizations such as technology transfer centers, liaison offices, etc.

In the second model, *3H II*, the sheres are represented by the communication systems and the control mechanisms of the interfaces.

In the *3H III* model, the interactions are manifested on three levels. In the foreground, the three spheres (helices) evolve under the influence of endogenous factors. Alliances between companies are observed, and some universities are beginning to expand their economic activities. In the background, the effect of mutual interactions can be observed. Finally, the third level refers to the emergence of "trilateral networks" with components from the three institutional spheres that in turn take over the role of coordinator.

The three spheres (helices) of the *H3* system can be seen as subsystems (subdynamics). Each subsystem develops internally, but also interact and exchange knowledge, services and goods. Etzkowitz (2003) states the important role of the government programs that should be promoted not only on national level (top-down), but especially on local level (bottom-up). The main condition for an efficient *H3 model* mentioned by Etzkowitz is a free, open and democratic society.

Filip & Vasiliu (2009) systematized information on the *3H model* innovation processes and proposed actions in the context of phenomena generated by the global financial and economic crisis. The authors concluded that RDI activities can be one of the keys to recovering from the crisis and building a sustainable economy.

7. X-type and Y-type RDI systems

As presented above, the RDI system is characterized by strict institutionalization. At the same time, being a subsystem of the country's social system, the RDI system cannot be studied separately from the social context of the country.

Malkov (2009) distinguishes two types of institutionalizations of society - X-type society and Y-type society which differ considerably in form and content, but both effectively ensure the stability in siciety.

The institutionalization of the X-type society has developed according to the principle of collectivism, caused by limited resources and external military threats, in which the central power or a leader strengthens the population to counteract these threats. In these systems the administration structure is hierarchical, and social relations are regulated mainly by traditions, culture, religion and less by the formal law (Fig. 2, a).

In turn, the Y-type society is characterized by sufficient resources and individuality, in which the responsibility falls on all members of society, the basic principle being democracy and legislative regulation, with a strong society and a horizontal or network structure of the administration (Fig. 2, b).

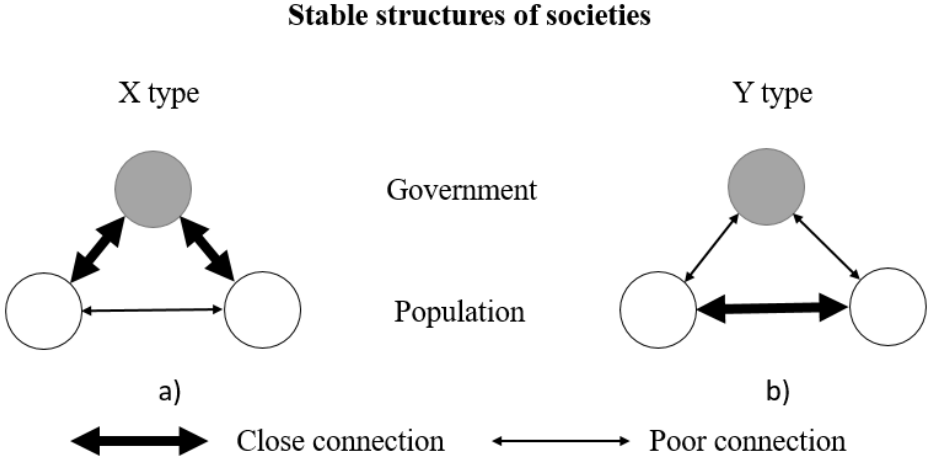

Fig. 2: Stable institutionalized social structures.

Social systems evolve and develop in relation to history, culture, traditions, climate conditions and got more or less characteristics of X or Y type society. The more features of one or another type social system posses, the more stable it is. In real life there are no pure X or Y-type systems. In X-type societies there are always Y type subsystems and vice versa, and the ratio between X and Y elements is not constant over time. For example, regardless of the type of institutionalization of the country's social system, its defence subsystem will always be of type X, because without a strict hierarchical subordination and authoritarian management the army

cannot exist.

Usually, the state of the system depends on the external changes: increase or decrease of resources, increase or decrease of the threats of existence of the society, a common goal, etc. However, in the end, an optimal balance of X and Y elements is established in the system. The internal stability and consolidation of society increases when contradictions and conflicts decrease and when a common external enemy appears (X-type system) or a common goal by most members of society is shared (Y-type system) (Malkov, 2009).

The RDI systems, being influenced by different type of the societies, are also different. The differences are presented in Table 1.

Table 1: The analysis of RDI systems in dependence of the type of institutionalization

Criterion	X-type RDI system	Y-type RDI system
The principle of institutionalization of the RDI system	• centralized management, in which policy development, distribution of funding, coordination and monitoring of RDI is performed by a single institution.	• decentralized management. Different institutions coordinate RDI activities, and are responsible for the development of policies, funding, coordination and monitoring.
RDI funding principles	• the funding is mainly governmental; • institutional funding of RDI predominates.	• 60-70% of RDI expendetures are from private sector / business enterprises; • it is mostly done through project competitions and grants.
Sector of performance	• most of RDI activities are performed by governmental / public organizations.	• fundamental and applied research is mainly concentrated in universities; • the RDI system is innovation-oriented, most of development and innovation activities are performed by the business environment.

Based on Fig. 2 and Table 1, we designed two conceptual models for each type of stable RDI systems (Fig. 3).

In transitional RDI systems, the principles of organizing and funding research are mixed and unstable. Identifying strengths is difficult, and among the weaknesses we will mention the decrease in RDI funding, instability of scientific career, dissatisfaction of researchers with policies and reforms in the field, teasing of many scientific schools, lack of motivation from young people to pursue research carrier.

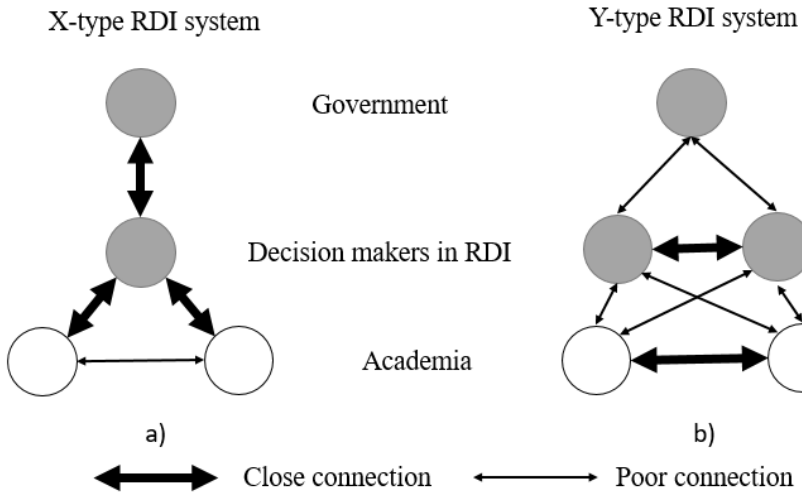

Fig. 3: Stable RDI systems.

As a consequence, countries with a transitional RDI systems face the problem of drain brain, the "aging" of human resources and research infrastructure.

8. RDI system in the Republic of Moldova

Most of post-soviet countries face the problem of transitional RDI systems. The Moldovan RDI system is not an exception and this is why:

1) The RDI system in the Republic of Moldova was organized as X-type system. In the past it was based on centralized administration through the Academy of Sciences, the lion's share of RDI works were and still continue to be performed by governmental research institutions.
2) Financial and human resources are limited; the research infrastructure is not renewed or is renewed very slowly.
3) The scientific community is influenced by the behaviour of society that has characteristics of X-type social systems.
4) The Republic of Moldova is on the border of two civilizations, and is organically linked to both Eastern and Western RDI systems, as confirmation being the active participation of the scientific community in European and bilateral project competitions, international conferences organized in West and East, co-publishing scientific papers with colleagues from the East and West;

5) At the end of the XXth – beginning of XXIst century, the procedure for obtaining financing for research through real competition was introduced;
6) The reform of the Academy of Sciences of Moldova implemented in 2018 decentralized the administration of the RDI system and limited its funding and expertise functions.

The organization scheme of RDI system in the Republic of Moldova is presented in Fig. 4.

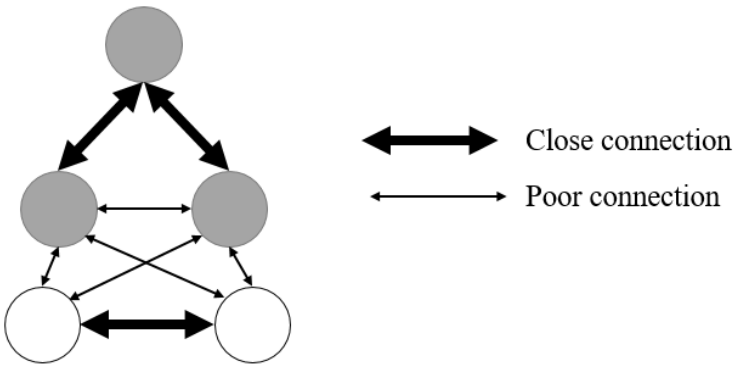

Fig. 4: Organization scheme of RDI in the Republic of Moldova.

Based on the above, we consider justified the following administrative decisions made in the field of RDI in the Republic of Moldova:

- Intensifying relations with European structures in the field of RDI by joining the EU's Research and Innovation Framework Programs, funding international and bilateral projects, promoting participation in scientific events organized abroad;
- Attracting European experts in evaluating research project proposals;
- Decentralization of the system by excluding the function of project expertise and distribution of funding by the Academy of Sciences.

If we treat the RDI system as a complex and self-organizing system, the administrative decisions set out above were strategically correct (without the awareness that the RDI system in the Republic of Moldova was designed by the X-type social system, but is influenced by Western processes by implementing European practices). But from a tactical point of view, they were counterproductive for the following reasons:

- National culture and traditions continue to influence significantly the organization and management of the RDI system in the country (passive

corruption, cumism, nepotism). Being a very small country with a limited number of researchers, especially in distinct scientific fields, in project expertise, defending doctoral dissertations, reviewing journals and articles, evaluating organizations can attract a small number of scientists, who they know each other personally, often being in collegial, friendship or kinship relationships of different levels. Under these conditions, the process of evaluation, expertise, review becomes very subjective.

- The non-functioning of the laws or their contradiction at state level negatively influences the socio-economic development of our country (Timuș, 2013). This is also reflected in the RDI system. For example, according to the Code on Science and Innovation (no. 259/2004) the evaluation procedure of organizations in the field of science and innovation had to be organized until the competition of projects within the State Programs organized in 2019 because according to art. 8 (2) of the Code "The purpose of evaluating organizations in the fields of research and innovation is to classify them by capacity level that determines differentiated access to funding according to the methodology of funding projects in the fields of research and innovation approved by the Government." At the same time, the mentioned Methodology (GD 382/2019) does not provide for differentiated financing depending on the results of the evaluation of RDI organizations.
- The RDI system is a complex system composed of the research, development and innovation subsystem. For the RDI system to have an economic impact, the reform had to provide for essential changes in the innovation subsystem as well, by creating mechanisms to massively attract the private sector to RDI activities.
- Because the RDI system is also a social system, it is flexible to procedural transformations, but resistant to administrative changes, to which it reacts late. Therefore, we should not expect an immediate result.

A SWOT analysis of the RDI system in the Republic of Moldova was conducted in 2013 by a group of experts (Stratan, 2013), which at that time have characterized the system. After a series of changes during last 8 years the new SWOT analysis of the current Moldovan RDI system was conducted by us and is presented in Table 2.

The analysis of the weaknesses and threats of the RDI system in the Republic of Moldova confirms that the state of the system is transitional (unstable) and requires further reforms in organization and management.

9. Conclusion

The RDI system, being composed of administrative institutions, funding organizations or bodies, centers, laboratories, enterprises that perform RDI activities, institutions and / or service subdivisions, it is a complex system organized from the

point of view of the institutionalization and regulation of its activity through legislative and normative acts. At the same time, because the RDI system is also a complex configuration of many people linked to each other institutionally, thematically, culturally by overlapping models of relationships, this is also a complex social system. We determined specific characteristics of any complex social RDI system: it is self-organizing; it is illogical; it is insensitive to changes; contains agents of influence; counteracts and compensates the external forces.

Table 2: SWOT analysis of the RDI system in the Republic of Moldova

Strengths:	**Weaknesses:**
1) Self-organization of the system in crisis conditions; 2) The existence of world-recognized researchers, who belong to the fundamental scientific schools; 3) Access to European research programs/funds; 4) The national priorities of the research and innovation sector correspond to the European research priorities; 5) Maintaining links with the scientific diaspora; 6) Financing RDI activities based on competitions; 7) Decentralization of the system and separation of the functions of organization, expertise, financing.	1) Non-compliance or contradiction of legislative and normative acts in the field; 2) Limited financial and human resources; 3) The exodus of highly qualified scientists and aging of intellectual potential; 4) Mass reproduction of qualified human potential in the socio-economic field to the detriment of natural, engineering and technical sciences; 5) Lack of motivating policies and strategies for the development of the innovation subsystem; 6) Weak scientific collaboration between research institutions, higher education and the business environment; 7) Insufficient promotion of scientific results.

Opportunities:	Threats:
1) Intensification of research and international visibility thanks to the e-Science paradigm; 2) Maintaining and strengthening science schools; 3) Participation in international programs and projects; 4) Carrying out scientific research that is part of European research priorities; 5) Attracting the scientific diaspora in establishing international scientific collaboration networks. 6) Obtaining funding based on skills and abilities; 7) Equal participation of universities and research institutions in national competitions for research projects.	1) Resistance to administrative changes and as a result the inefficiency of reforms in RDI system; 2) Further reducing the funding of the RDI system; 3) Low attractiveness of the research profession; 4) Reducing qualified human potential; 5) Apathy of researchers to participate in national and international projects; 6) Aging of the research infrastructure; 7) Lack of interest from the private sector to participate in RDI activities.

As soon as the most important activity in the management process of any complex social system is decision making, which are under uncertainty, predictability (forecast/ estimation) based on modeling of the system behavior is applied.

Based on the conceptual model of RDI system in terms of inputs, activities, outputs, outcomes and inpact we conclude that the effectiveness of the whole RDI system depends on each component that interact with others and affect them in the feed-back loop.

The Triple Helix model of RDI system examined in the paper can be applied for recovering from economic crisis and building a sustainable economy.

The conceptual model of RDI systems based on the type of instutionalization of society (X- or Y-type) was proposed and the strengths and weaknesses for each type of RDI systems were presented. It was determined that the RDI system in the Republic of Moldova is currently in a transient and unstable state. At the same time, the changes implemented in the last decade in the administration of the RDI system and the way of financing through competition of RDI activities are justified, but for the time being counterproductive. The SWOT analysis confirmed this conclusion.

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