Project Number: 2020-1-SE01-KA203-077872

Erasmus + Cooperation for innovation and the exchange of good practice
KA2 - Strategic Partnerships for Higher Education
Project Number: 2020-1-SE01-KA203-077872

REPORT ON LITERATURE REVIEW ON THE THEORY OF COMPLEX SYSTEMS APPLIED TO:

ARTIFICIAL INTELLIGENCE (COMPUTER SCIENCE AND MATHEMATICS)
SIMULATIONS OF PHYSICAL BEHAVIORS (COMPUTER SCIENCE, BIOMEDICINE, MATHEMATICS, MECHANICS)
POLITICAL SCIENCE (INTERNATIONAL RELATIONS, INTERNATIONAL GOVERNANCE)

Dalia Čalnerytė, Andrius Kriščiūnas, Stefano Corradi, Vida Drąsutė
Kaunas University of Technology
Kaunas, Lithuania

dalia.calneryte@ktu.lt, andrius.krisciunas@ktu.lt, corradis8@gmail.com, vida.drasute@ktu.lt

Co-funded by the Erasmus+ Programme of the European Union

ABSTRACT

Articles on complex systems, systems thinking and complexity management in the areas of artificial intelligence, simulations of physical behavior and political science were discussed in this review. The broad scope of topics resulted in a broad variety of aspects related to complex systems or systems thinking in educational process, namely, educational tools, description of educational process and examples. Although the conventional teaching / learning approach in some disciplines is designed to solve a specific problem with a set of assumptions, analyzing the problem from the point of complex systems enables students to understand the relations to other subjects and social, environmental or economic impact of their solutions. Moreover, solving complex problems motivate students to get specific knowledge, for example, using computational tools or programming. This also helps to develop "soft" skills, such as working in group, communication and critical thinking, which are highly valued in work market and cannot be replaced by robots or automatic processes. It is stated that these skills can be transferred to other disciplines, working environment and society and therefore prepare students to be socially responsible members of society.

1. Introduction

The literature review was carried on the topics of complex systems, systems thinking and complexity management in the areas of artificial intelligence (computer science and mathematics), simulation of physical behavior (computer science, biomedicine, mathematics, mechanics) and political science (international relations, international governance).

Artificial intelligence (AI) is an important part in solving complex problems or modelling complex systems nowadays. The authors of the reviewed articles emphasize the significance for students to be able to divide a problem into smaller problems, to formulate each problem in a way for computer to understand, to apply suitable computational tools, define causal relationships between parts of the system and provide reasoned conclusions [1][2]. These skills are of high importance in the 21st century as application of computers is increasing in learning and working environments [3][4]. It is stated that most of the repetitive jobs will be performed by the robots in a short time and students should develop the skills which would enable to create innovations and therefore would not be possible replace them by AI or robots [5][6]. Another application of AI is adaptive or personalized interactive learning environments, digital worlds and gamification of teaching process [7][8][9][10]. These learning approaches increase students' engagement in the subject, improve their abilities to relate interacting parts of the system and link the cause to the consequence in solving close-to-real problems.

Simulation of physical behavior usually combines areas of computer science, mathematics and mechanics. To solve specific problems, it is required to include knowledge and skills in other fields, such as medicine, biology, geology, economy, and social sciences. Most of the articles mention the importance of developing students' system- and critical thinking skills so that they would be prepared for the work environment and would be able to formulate problem, relate the interactive parts of the system and evaluate the feasibility of the results. There are three main groups of the articles, namely, ones which are dedicated to suggested educational tools [11][12][13][14][15], ones which describe the teaching / learning process in the field of numerical analysis and simulation of mechanical processes [16][17][18][19], and ones which define complex problems in real life and could be used as project tasks or examples in educational process [20][21][22]. In the analysis of the presented educational tools, most of the authors refer that it is important to encourage students to experiment so that they would detect and define the causal relationship between the different phenomena or variables. These tools include solving numerical simulation problems, demonstrational models or augmented reality equipment. The teaching / learning process described in the reviewed articles mostly present multidisciplinary approach and solving complex problems related to physical behavior as an extra-curriculum activity or a class project.

Within the field of political science, system thinking and complex systems theory are generally seen as a collection of tools capable of enhancing the explanatory power of traditional analytical practices. Many studies pinpoint how the typical adherence to linearity of the social sciences have resulted in analyses that provide a limited understanding of political, social and economic processes [23, 24, 25, 26]. To overcome this issue, numerous multidisciplinary approaches, often combining methodological practices of political science with computer science tools, are presented by almost all the authors identified. For instance, Furtado et al. [25] provide an introduction on how complex systems modelling can be used for the analysis and development of public policies. The authors present a list of methods

Co-funded by the Erasmus+ Programme of the European Union
The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

generally applied in natural sciences (e.g., network analysis, Cellular Automata, Agent-based modelling [ABM], etc.) that can be adopted also in the field of public policies analysis. These methods are described together with some software that can support researches when studying or developing public policies (e.g., Python, QGIS, NetLogo, R). Similarly, Dum and Johnson [27] define in their article the so-called *Global Systems Science* (GSS) an emerging and transdisciplinary field of study that, through the adoption of ABM, aims to model social, economic, political and environmental systems for the design of effective policies. The adoption of methodologies such as the one described would also bring substantial theoretical changes in the field of political science. Scott E. Page [28], one of the main advocates of integrating social sciences with complexity studies, claims that once the social sciences will have overcome the analyses based on linear regression and static equilibrium, they will be able to "*limit the damage of large events and to harness complexity to produce better social outcomes*". According to him, this goal will be reached by implementing the following four changes in social sciences' practices:

1. Advancing the methodologies for measuring and categorizing the complexity of social processes;
2. Promoting interdisciplinary research on specific problems (e.g., improving education);
3. Rethinking variation and diversity;
4. Advance computational agent-based modelling.

More or less, all studies analyzed provide similar accounts. Many also focused on the rejection of typical top-down approaches adopted when dealing with, for instance, conflict resolution, public policies, governance, etc. [29,30,31]. Similar changes are also suggested within the education sector, that, according to Davis et al. [32], should help students acquire:

1. A worldview when conceiving and posing problems;
2. The capacity of reasoning and inference within a worldview;
3. A stronger analytical style for conducting inquiry;
4. A broader and more firm understanding of the models used.

In summary, the developing systems thinking enables students to understand the complex world and relate different aspects and phenomena of various subjects and therefore become a socially responsible citizen.

2. Results Achieved

2.1 Complexity Science

There are several features of complex systems discussed in the reviewed articles. Firstly, the application of artificial intelligence (AI) to interactive elements of the analyzed systems, combining results and deriving reasonable conclusions based on assumptions are valuable skills in evaluating the connectivity of the complex systems. Secondly, if AI is used to create adaptive learning environment, it represents adaptivity of the complex systems to students' needs. Finally, AI is usually used as a tool to solve problems in various fields which possess non-linear or probabilistic relationships.

Similarly, the reviewed mechanic systems combine several interactive parts and should be analyzed in different aspects. Hence, modeling physical behavior is applied to solve problems in nonlinear dynamics to capture nonlinear relations and models.

Within the scope of political science, system thinking features and tools are adopted in a vast myriad of political areas. For instance, complexity theory can be applied in the analysis of public policies, international relations, political violence, peacebuilding, elections, etc. Scholars are realizing that phenomena related to these areas of studies present the typical characteristics of complex systems [33]:

1. They cannot be explained by its parts;
2. Their behavior is hard (or impossible) to predict;
3. They are sensitive to initial conditions (path dependence);
4. They exhibit emergent behaviors;
5. They often contain "strange attractors" (punctuated equilibria);
6. They require an interdisciplinary perspective to be understood.

By realizing this, scholars advocating for the use of complexity in political and social sciences are also suggesting the use of new tools and the rejection of traditional approaches, based on linear regression, reductionism and static equilibria. This fact brings a substantial change both at the theoretical and practical level.

From a theoretical perspective, researches will need to adopt different tools and accept the perspectives of other disciplines (e.g., computer science, mathematics, physics, etc.). Agent-based Modelling (ABM) appears to be the most

Co-funded by the Erasmus+ Programme of the European Union
The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

appreciated and effective tool for political analysis, as it is able to encapsulate the behavior of agents according to a well-defined set of rules to analyze emergent properties. The critical adoption of similar tools may help in overcoming old fashioned theories (such as behavioralism and rational choice theory) and establish a more fruitful discussion between the social and natural sciences. This same discussion might bring at the forefront of political research methodologies that already adopt the complexity approach without specifically referring to it (e.g., new institutionalism, path dependence, punctuated equilibria, world-system theory, panarchy, etc.).

On the other hand, from the practical point of view, complexity science can also support policy makers by providing them a new strategy for policy design. In fact, most studies claim that the insights provided by complexity science are a valuable proof for the adoption of a more grassroot/bottom-up approach (instead of the typical top-down methodology), one that takes into account the perspectives of populations and citizens in co-designing policies. Moreover, policymakers should also be aware that all policies are established in a highly complex environment, in which outcomes are not determined linearly. Thus, they should follow an approach of "trial and error" and be ready to modify their strategy when the situation requires so.

Hence, complexity science suggests considerable changes in current university curricula, especially for the social sciences. A more trans- and multidisciplinary approach is warranted to the training of students that are more conscious of world's complexities and how different systems react and evolve.

2.2 Sustainable development

The main aspect in the field of artificial intelligence is innovation, that is, students should develop creative thinking to avoid performing repetitive tasks as these tasks can be done by robots or computer applications [5]. Application of computers enable to dedicate human skills to create sustainable environment and therefore create ethical artificial intelligence tools.

Studying complex systems encourage students to assess a problem from various perspectives, for example, to solve flooding problem in a city by modeling physical behavior and to evaluate social, economic and environmental aspects of the flooding [15]. Developing complex problem-solving skills prepare students to be sustainability and socially responsible citizens.

Complexity science can also be successfully integrated in Socio-Technical Transition (STT) Models, which already explore path dependence, multi-actor systems and complexity [34]. The so-called "Dutch school" proposes 4 different STT models: (i) Transition management (TM), (ii) strategic niche management (SNM), technological innovation systems (TIS), Multi-level perspective (MLP). Building computational models with these theoretical bases can help researchers understand the emergent phenomena in complex system and advise policymakers in the design of ecological transitions. Hence, the study of these models in light of the perspectives coming from complexity science can support students in a wider understanding of how economic, political and social aspects interact in favor or against sustainable transitions.

2.3 Inter-disciplinarity and trans-disciplinarity

Students learn a particular skill by performing tasks in other fields, e.g. learning programming by developing a game [9] or learning to apply artificial intelligence by exercising tasks in STEM disciplines [2].

The interdisciplinary methods mentioned in the reviewed articles are collaborative work, research, experimenting, discussions. Although these methods also overlay the transdisciplinary concepts, this approach is mainly focused on solving reality-based problems using mechanical engineering, formulating and proving the concept, evaluating it with respect to various aspects.

In many instances, complexity science is presented and implemented as a bridge to overcome the old barriers between natural and social sciences [28, 35]. In this sense, system thinking is understood more as a set of tools instead of an actual theory. For this reason, students are called to adopt it as a problem-solving strategy and to learn how to construct computational models that can verify the reliability of theories. Some authors, like Bednar & Page [35], also propose their adoption to establish a connection between opposed schools of thought (such as rational choice theory and cultural/historical analysis) and build a synthesis between quantitative mathematic models and lengthy qualitative accounts.

2.4 Students´ understanding

Although AI is usually used as a tool to solve problems in other disciplines, students must understand how AI methods work and what problems or parts of the problems can be solved by applying them. Students' skills such as problem

solving, determining causal and conditional links between the interacting parts of the system, identifying solution and assessing its feasibility can be also transferred to other disciplines [10].
The systems thinking is important in the field of engineering to train socially, ethically and environmentally responsible citizens [19]. Despite solving mechanical engineering problems, they are also expected to evaluate the consequences and effect for the society and environment. The conventional learning approach in mechanical engineering is focused on analyzing a particular problem or situation. The systems thinking encourages students to identify relationships between the interactive parts of a system, to determine the causal links between the phenomena in other disciplines and modelled physical behavior.
In addition, complexity science should also encourage students of political science to renounce the limited perspectives of linearity and static equilibrium, accepting the high complexity of most phenomena studied. Teaching of statistical models should be substituted with diverse causal models, games and several other methods. It should also be taught to accept a certain level of error in analysis, taking into account the larger set of data and factors involved in complex systems tools. Finally, by understanding that systems are not stable, it should be taught to students of policy studies to adopt a humbler approach in policy design. Top-down, direct control should be substituted with an indirect, iterative and bottom-up approach [32].

2.5 Development of a toolbox

In case of creating interactive learning environments, it is important to define what features will be used as input to govern system behavior. The toolbox should have a simple interface to define problem formulation, experiment with various conditions and analyze results.
The reviewed articles emphasize the importance of students' interaction with the toolbox environment, for example, in modelling system of particles [14] or truss system, students should be able to change structures or initial conditions, interact with the model during simulation. It is even possible to include recent technologies such as augmented reality [12] to visualize modelling results and behavior of the structure in the real environment.
Computational modelling plays a central role when developing complex systems-based analysis. Network analysis, Cellular Automata, Agent-based Modelling, Information theory and Data mining can all contribute significantly in the study of social, political and economic phenomena. In the essential toolbox, it should also be included software like Python, QGIS, NetLogo and R to construct adequately the models previously presented. Thus, all students' digital skills (even for those who do not study computer science) should be significantly enhanced.

2.6 Discussions with teachers

The ideas to consider in discussion with the teachers:

- the benefit of application of augmented and virtual reality tools, interactive learning environments and gamification in the teaching / learning process;
- the skills that can be transferred between the disciplines (skills to formulate the problem for computer to understand, to assess the results, to determine links between the components of the system, etc.);
- the basic knowledge level of each discipline needed to start analyzing complex problems in educational process;
- advantages and disadvantages of combining conventional teaching and systems thinking approaches in teaching / learning STEM disciplines (by the means of teaching personnel, facilities, students' results, etc.);
- the benefit of the educational tools for numerical simulation (real-life problem) in developing students' creative and critical thinking, ability to relate different physical phenomena and interpretate results;
- ask the teacher to consider if they already address some features of complexity in their lessons even without using complex systems' terminology;
- the software they would suggest to use to analyze complex systems problems;
- how much would complex systems knowledge would change their teaching practices and educational goals.

2.7 Discussions with employers

The ideas to consider in discussion with employers:

- the jobs (skills) which can or cannot be replaced by the robots in near future;
- the importance of innovations and whether it is possible to create innovations continuously (the aspect of saturation);

Co-funded by the Erasmus+ Programme of the European Union

- the importance of employee’s skills to solve practical complex problems by using computational tools in working environment;
- the skills and knowledge which are needed in working environment (despite knowledge in the specific field) and their relationship to systems thinking;
- the application of complex system approach in the real life, the process of solving complex problem in working environment;
- how much complexity is addressed in their job on a daily basis;
- the software used in their job and their relation to complex systems;

References

[1] Estevez, J., Garate, G., Grana, M., 2019. Gentle Introduction to Artificial Intelligence for High-School Students Using Scratch. IEEE Access 7, 179027–179036. https://doi.org/10.1109/ACCESS.2019.2956136
[2] Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., Wilensky, U., 2016. Defining Computational Thinking for Mathematics and Science Classrooms. J Sci Educ Technol 25, 127–147. https://doi.org/10.1007/s10956-015-9581-5
[3] Wong, G.K.-W., Cheung, H.-Y., 2020. Exploring children’s perceptions of developing twenty-first century skills through computational thinking and programming. Interactive Learning Environments 28, 438–450. https://doi.org/10.1080/10494820.2018.1534245
[4] Yuen, T.T., Robbins, K.A., 2015. A Qualitative Study of Students’ Computational Thinking Skills in a Data-Driven Computing Class. ACM Trans. Comput. Educ. 14, 1–19. https://doi.org/10.1145/2676660
[5] Rampersad, G., 2020. Robot will take your job: Innovation for an era of artificial intelligence. Journal of Business Research 116, 68–74. https://doi.org/10.1016/j.jbusres.2020.05.019
[6] Crittenden, W.F., Biel, I.K., Lovely, W.A., 2019. Embracing Digitalization: Student Learning and New Technologies. Journal of Marketing Education 41, 5–14. https://doi.org/10.1177/0273475318820895
[7] Johnson, W.L., Lester, J.C., 2016. Face-to-Face Interaction with Pedagogical Agents, Twenty Years Later. Int J Artif Intell Educ 26, 25–36. https://doi.org/10.1007/s40593-015-0065-9
[8] Luan, H., Geczy, P., Lai, H., Gobert, J., Yang, S.J.H., Ogata, H., Baltes, J., Guerra, R., Li, P., Tsai, C.-C., 2020. Challenges and Future Directions of Big Data and Artificial Intelligence in Education. Front. Psychol. 11, 580820. https://doi.org/10.3389/fpsyg.2020.580820
[9] Seralidou, E., Douligeris, C., 2020. Learning programming by creating games through the use of structured activities in secondary education in Greece. Educ Inf Technol. https://doi.org/10.1007/s10639-020-10255-8
[10] Wong, G.K.-W., Cheung, H.-Y., 2020. Exploring children’s perceptions of developing twenty-first century skills through computational thinking and programming. Interactive Learning Environments 28, 438–450. https://doi.org/10.1080/10494820.2018.1534245
[11] Lee, J.Y., 2015. Interactive simulation of finite element equation processing for educational purposes: FINITE ELEMENT EQUATION PROCESSING. Comput Appl Eng Educ 23, 157–169. https://doi.org/10.1002/cae.21586
[12] Huang, J., Ong, S.K., Nee, A.Y., 2019. An approach for augmented learning of finite element analysis. Comput Appl Eng Educ 27, 921–933. https://doi.org/10.1002/cae.22125
[13] Sonparote, R.S., Mahajan, S.K., 2018. An educational tool to improve understanding of structural dynamics through idealization of physical structure to analytical model. Comput Appl Eng Educ 26, 1270–1278. https://doi.org/10.1002/cae.22006
[14] Langbeheim, E., Levy, S.T., 2019. Diving into the particle model: Examining the affordances of a single user participatory simulation. Computers & Education 139, 65–80. https://doi.org/10.1016/j.compedu.2019.05.006
[15] Valyrakis, M., Latessa, G., Koursari, E., Cheng, M., 2020. Floodopoly: Enhancing the Learning Experience of Students in Water Engineering Courses. Fluids 5, 21. https://doi.org/10.3390/fluids5010021
[16] Guo, Y., Yang, Lijuan, Chen, X., Yang, Lei, 2020. An Engineering-Problem-Based Short Experiment Project on Finite Element Method for Undergraduate Students. Education Sciences 10, 45. https://doi.org/10.3390/educsci10020045
[17] Zakharova, A.A., Chernysheva, T.Yu., Molnina, E.V., Telipenko, E.V., Tomilov, I.N., Min’kov, S.L., 2016. Complex system of developing information and communication competence, in: 2016 11th International Forum on

Strategic Technology (IFOST). Presented at the 2016 11th International Forum on Strategic Technology (IFOST), IEEE, Novosibirsk, Russia, pp. 276–280. https://doi.org/10.1109/IFOST.2016.7884105
[18] García-Macías, E., Castro-Triguero, R., Saavedra Flores, E.I., Yanez, S.J., Hinrechsen, K., 2019. An interactive computational strategy for teaching the analysis of silo structures in civil engineering. Comput Appl Eng Educ 27, 821–835. https://doi.org/10.1002/cae.22112
[19] Zoller, U., 2015. Research-Based Transformative Science/STEM/STES/STESEP Education for "Sustainability Thinking": From Teaching to "Know" to Learning to "Think." Sustainability 7, 4474–4491. https://doi.org/10.3390/su7044474
[20] Kuebler, W.M., Mertens, M., Pries, A.R., 2007. A two-component simulation model to teach respiratory mechanics. Advances in Physiology Education 31, 218–222. https://doi.org/10.1152/advan.00001.2007
[21] Ghayoor, F., Swanson, A., 2018. Modelling and analysis of electrodynamic suspension of an aluminium disc as a complex engineering problem. International Journal of Electrical Engineering Education 55, 91–108. https://doi.org/10.1177/0020720918754831
[22] Forsman, J., Linder, C., Moll, R., Fraser, D., Andersson, S., 2014. A new approach to modelling student retention through an application of complexity thinking. Studies in Higher Education 39, 68–86. https://doi.org/10.1080/03075079.2011.643298
[23] Scartozzi, C. 2018. A New Taxonomy for International Relations: Rethinking the International System as a Complex Adaptive System. *Journal on Policy and Complex Systems* 4 (1). doi: 10.18278/jpcs.6.1.7
[24] De Coning, C. 2020. Insights from Complexity Theory for Peace and Conflict Studies. In Richmond, O.; Visoka, G. (eds.) The Palgrave Encyclopedia of Peace and Conflict Studies. Doi: https://doi.org/10.1007/978-3-030-11795-5_134-1
[25] Furtado, B.A.; Sakowski, P.A.M.; Tovolli, M.H. (2015) A Complexity Approach for Public Policies, in Furtado et al. (eds) *Modelling Complex Systems for Public Policies*, Brasilia: Institute for Applied Economic Research, pp. 17-35
[26] Astill S. & Cairney P. (2015). Complexity theory and political science: do new theories require new methods? In Geyer R. & Cairney P. *Handbook on complexity and public policy*, Cheltenham: Edward Elgar Publishing, pp. 131-149
[27] Dum, R. & Johnson, J. (2017). Global Systems Science and Policy, in Jonhson, J. et al. (eds), *Non-equilibrium Social Science and Policy*, Cham: Springer Nature, pp. 209-225
[28] Page, Scott E., Complexity in Social, Political, and Economic Systems (2010). American Economic Association, Ten Years and Beyond: Economists Answer NSF's Call for Long-Term Research Agendas, Available at SSRN: https://ssrn.com/abstract=1889359 or http://
[29] Sandole, D. (2006). Complexity and Conflict Resolution, In Complexity in World Politics: Concepts and Methods of a New Paradigm, Neil E. Harrison (ed.). Albany: State University of New York (SUNY) Press, pp.43-71.
[30] Ricca, B. (2020). "No Child Left Behind" and the Predictable Failure of Education Policy. *Journal on Policy and Complex Systems,* 6-1, pp. 117-130. doi: 10.18278/jpcs.6.1.7
[31] Orsini A, et al (2019). Forum: Complex Systems and International Governance. *International Studies Review*, 22-3.
[32] Davis, P., McDonald, T., Pendleton-Jullian, A., O'Mahony, A. and Osoba, O., 2020. *A Complex Systems Agenda For Teaching And Conducting Policy Studies*. [online] Rand.org. Available at: <https://www.rand.org/pubs/working_papers/WR1326.html> [Accessed 15 October 2020].
[33] Cairney, P. (2012). Complexity Theory in Political Science and Public Policy. *Political Studies Review*, [online] 10(3), pp.346–358. Available at: https://pdfs.semanticscholar.org/6396/60fa8e616722adc9df7bf0f43e5e5fef803b.pdf
[34] Li, F.; Trutnevyte, E.; Strachan, N. (2015). A Review of Socio-Technical Energy Transition (STET) Models, *Technological Forecasting and Social Change*, 100, pp. 290-305
[35] Bednar & Page (2016). Complex Adaptive Systems and Comparative Politics: Modelling the Interaction between Institutions and Culture, *Chinese Political Science Review,* 1: 448-471.