International Journal of Evaluation and Research in Education (IJERE)
Vol. 13, No. 4, August 2024, pp. 2527~2535
ISSN: 2252-8822, DOI: 10.11591/ijere.v13i4.28856

The role of self-organization theory in the development of students' interdisciplinary research ability

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Article Info

Article history:

Received Oct 6, 2023
Revised Nov 21, 2023
Accepted Jan 19, 2024

Keywords:

Information theory
Integrative course
Interdisciplinary learning
Self-organization
Synergetic

ABSTRACT

Self-organization theory is an interdisciplinary scientific direction to improve the quality of acquired knowledge and skills. The article aims to study the development of interdisciplinary research activities among students based on self-organization theory. The study was conducted using an integrated approach, methods of analysis and synthesis, modeling, pedagogical experiments, and mathematical statistics. An elective course, "synergetic-interdisciplinary scientific theory", and a model for preparing students for interdisciplinary research activities were developed and implemented. The knowledge and skills of 272 physics students in the Republic of Kazakhstan universities in control and experimental groups improved after the training. The knowledge highest level is observed among the experimental group students while studying the natural experiments' theoretical aspects necessary for researching the natural objects' sustainability. Experimental group students demonstrated better results in completing the task based on the acquired knowledge and skills. They rated the education quality significantly better on a short educational assessment scale. The results-developed course and the students' preparing models for interdisciplinary research can be used in advanced courses for different specialties educators. Research perspectives could potentially contribute to the development of integrated subjects and interdisciplinary programs in natural sciences and humanities.

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1. INTRODUCTION

One of the leading trends in modern science is integrating and synthesizing knowledge from separate scientific disciplines. This approach is becoming more widespread in the educational process. It helps to combine various scientific areas to solve complex problems of modern science related to the practical needs of society [1]. Integrating scientific knowledge issues by the branches in educational and

research fields is particularly relevant in science and education development [2], [3]. Along with the existing disciplinary organization of subjects aimed at training graduates of narrow specialization institutions, there is targeted training of their interdisciplinary knowledge [4]. Organizing students' educational and research activities based on an interdisciplinary approach contributes to a fundamentally new scientific knowledge system at the intersection of different disciplines; new methods, tools, and instruments of various sciences supplement this knowledge [5], [6].

An interdisciplinary approach is a methodological approach to organizing scientific knowledge based on fundamental links between scientific fields, methods, and technologies [7]. One interdisciplinary primary manifestation is transferring ideas, tools, and research methods from one discipline to another [8], [9]. Interdisciplinary is based on the mutual impact, interaction, and interpenetration of two or more disciplines, which have their subject and object of study, conceptual apparatus, methods, and means of research [10]. An interdisciplinary pedagogical model enhances students' competencies while fostering the potential for a multitude of applications using the principles of self-organization theory (synergy) [11]. As a result, the interdisciplinary approach enables connections between various objects of study, thereby facilitating a comprehensive comprehension of the structure, mechanisms, and dynamics of phenomena and their interactions [12].

Synergetic aims to determine the general patterns in educational processes based on the study of sustainability and destruction of ordered structures in complex systems (physical, chemical, and biological) [3]. The intentional introduction of educational materials with the content of a research and experimental design nature into the educational process contributes to the development of students' scientific and research activities [13]. Thus, a systematic and intentional study by students of self-organization theory foundations can contribute to developing their interdisciplinary research activity. The primary work purpose is to explore the features of students' multidisciplinary research ability based on the self-organization theory study.

The interdisciplinary research development contributes to eliminating the current education system crisis, which combines interconnected pragmatic attitudes with a narrowly focused approach [14], [15]. Interdisciplinary is a pedagogical approach that involves synthesizing the various sciences methods (biology and physics, mathematics and linguistics), which fosters more detailed discipline analysis and helps to overcome the contradictions between the objective reality study and knowledge acquisition [16], [17]. An interdisciplinary learning approach is based on social learning processes (individual or group learning), social capital outcomes (interpersonal connections), knowledge outcomes, and human capital (new knowledge) [18]. An example of the development of interdisciplinary education is the science, technology, engineering, and mathematics (STEAM) education system [2], [19]. This approach helps to increase students' motivation to use creative techniques, which increases students' self-efficiency in the learning process [20]. The self-organization theory can be interconnected with the worldview function, which is aimed at the optimal application of synergetic ideas as one of the essential methods for forming a generalized student's worldview [21]. Learning processes provide the emergence of new knowledge that generates new knowledge, regardless of the owner's desire [22].

Trends toward interdisciplinary research are considered a means of finding innovative solutions for teaching different skills and their interrelationships by students [23]. Self-organization and information theories as an interdisciplinary approach have become widely used in studying complex systems objects [24]. The scientific articles analysis devoted to this study demonstrates that there needs to be a comprehensive technology for developing students' interdisciplinary research activities, identifying and assessing the structural element's formation level of this activity. The study hypothesizes that incorporating self-organization into the educational process of physics students will enhance their competence in conducting interdisciplinary research.

2. METHOD

The study was conducted using a combined approach. The first study stage was based on analyzing integrated education methods, which contributed to developing the elective course "Synergetic–an interdisciplinary scientific theory". This course aimed to teach students the basics of self-organization theory and to provide them with the skills and knowledge of interdisciplinary research activities. For this purpose, we analyzed the specifics of conducting classes in higher educational institutions (from now on, HEIs). A comparison and analysis of a holistic and integrated study of scientific materials were conducted [1], [8], [17]. The course elements elaboration was also based on the involvement of expert scientists from the pedagogical, psychological, humanitarian, and natural sciences. To this end, 15 expert educators were involved and provided materials to help prepare the model that became the basis for the curriculum development. The features of the curriculum are presented in the results.

The study was carried out in the first semester of the 2022/2023 academic year. It involved 272 final-year students divided into experimental and control groups. The experimental group was represented by 153 students in the elective course program. The control group (119 people) was introduced to the current education model. Nevertheless, they studied according to the traditional program within the framework of interdisciplinary research training. The sample size was determined based on the experimental conditions. According to Lakens [25], the study benefits from the size of the sample, which is explained by the chosen methodology.

In the second stage the model of a methodological system for preparing final-year students who studied the specialty "Physics" at some state universities in the Republic of Kazakhstan for multidisciplinary research activities aimed at self-organization was developed, and the levels of skills development among students was determined. The control task design was established on the completed training program, which included the provision of tests and detailed answers. The assessment was not included in the semester results of the sessions, and it had a generalized character (the task was completed in full, partially, or not completed). After the experiment, students rated six questionnaire suggestions on a Likert scale (1-strongly disagree, 5-strongly agree), characterizing the developed model's performance indicators for physics students to determine a design's impact on learning. The questionnaire's validity was established, as it was designed to evaluate the influence of skill development on interdisciplinary proficiency in students. Reliability was quantified by computing Cronbach's alpha coefficient from the respondents' answers, which resulted in 0.76. Students also evaluated the training using an interdisciplinary approach using the Brief-ACRA scales.

In the third stage, the obtained digital data was processed using Microsoft Excel. The obtained data were analyzed in percentage and using the Fisher criterion. To comply with the rules for the student's participation in the research, the work followed ethical standards in line with the guidelines for research ethics in science and technology [26].

3. RESULTS AND DISCUSSION

The first study stage was based on the structural elements' development of the elective course "Synergetic–an interdisciplinary scientific theory". The structural elements development of the elective course is grounded in the growth of student autonomy. This contributes to forming interdisciplinary knowledge and skills systems among students and exploratory mental actions based on the interaction of the different sciences. The learning process aims to use modern scientific approaches to solve professional issues following the specifics of the specialty profile. At the same time, the emphasis is on developing the skills of students' research activities. Structural elements of the elective course are presented in sub section.

3.1. Content component

The criteria of content component are availability of knowledge about the importance of self-organization for effective learning, well-formedness of the interdisciplinary knowledge system in the natural sciences. Furthermore, the indicators of content component are: i) the student possesses the basic concepts and patterns of self-organization in the process of learning and self-fulfillment of tasks; ii) the student understands the necessary and sufficient conditions for the implementation of self-organization of natural systems phenomenon (nonlinearity, openness, and nonequilibrium); and iii) the student can conduct the research required to study complex natural systems and interdisciplinary research.

3.2. Cognitive component

The criteria of cognitive component are striving for self-organization for effective learning and interdisciplinary activity, well-formedness of a thinking style focused on identifying common connections and relations of the surrounding world. Then, the indicators of cognitive component consist of: i) students are aware that self-organization is a principle of constructive world order; ii) the student is self-organized and self-learner; and iii) to analyze stochastic processes, the student utilizes probabilistic thinking techniques.

3.3. Operational component

The criteria of operational component: mastery of the methods and techniques necessary for the study of complex objects, mastery of interdisciplinary research skills. As a result, the student can model and diagnose socio-natural objects of the surrounding environment and predict their development trends. When learning complex processes, the student can generalize, draw analogies, compare, analyze, and synthesize; and students can transfer ideas, tools, and methods of research originating within one discipline to another. In addition, the modules of operational component consist of: i) self-organization characteristics of humans for efficient activities and interdisciplinary research; ii) the basics of self-organization; iii) mathematical apparatus of synergy; iv) computer simulation of natural processes self-organization; v) the doctrine of self-organization as a methodology for research; and vi) practical work on the study of self-organizing objects.

The course is thematically planned as: week 1-2–studying an introduction to methodological systems to comprehend the fundamental aspects of interdisciplinary learning, the importance of self-organization for learning, and incorporating these elements into the learning procedure. The program includes integrated lectures on mathematics and physics studies, as well as programming. For a period of three to five weeks, the students attended integrated lectures encompassing physics, chemistry, and mathematics. In addition, they accomplished independent assignments utilizing an interdisciplinary methodology in small groups (up to five people). From the sixth week until the 10th week, the students undertook programming tasks to model natural processes. The goal of these classes is to develop advanced competencies in software development for modeling natural phenomena and to utilize programming abilities to address scientific challenges. Programming tutorials and implementation assignments are organized to address practical challenges that learners might encounter. In weeks 11 to 13, students explored the interfaces between different phenomena and the visual techniques to explore these (e.g. video lectures, presentations, and coding). Lecturers were invited to supplement educational materials from various disciplines, while discussions were held with teachers and students. During weeks 14 to 18, the students worked independently on tasks with an interdisciplinary approach. They carried out independent research projects in specific scientific fields, created presentations, delivered them, and engaged in in-class discussions and debates. To determine the approaches to the study by students of self-organization theory basics, the work presented a model of the methodological system of their preparation for the possibility of organizing research activities as shown in Figure 1.

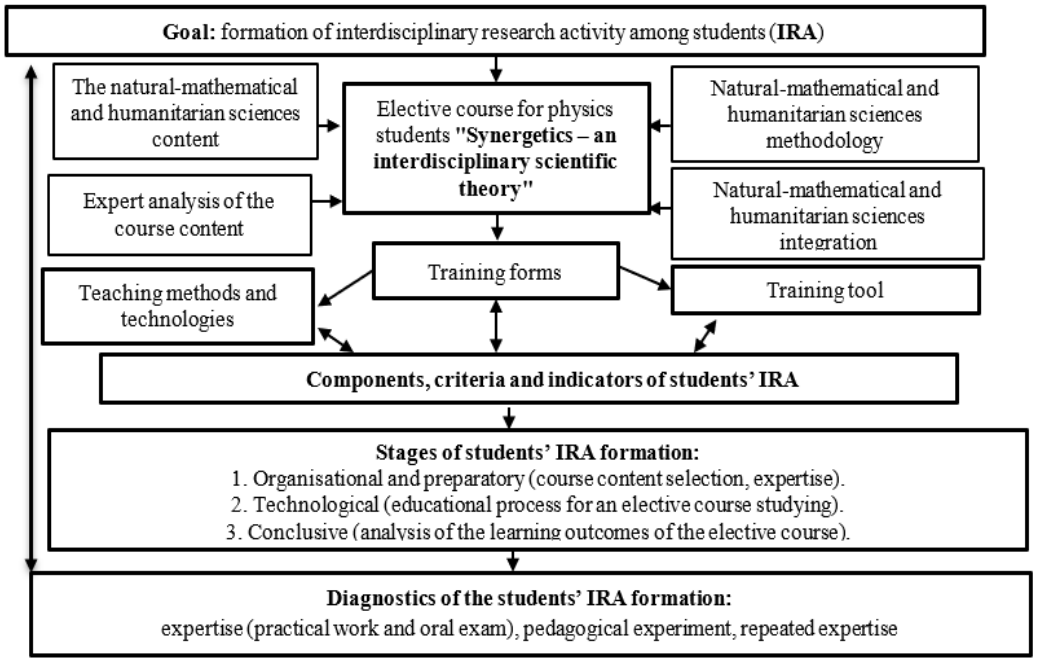

Figure 1. Model of the students preparing methodological system

Students completed various interdisciplinary tasks in different fields of physics, including biophysics (the study of physical principles), astrophysics (the physical properties of astronomical objects), computational physics (the development and application of computer algorithms and models for problem-solving in physics), quantum physics, environmental physics (atmospheric dynamics, ocean currents, and biogeochemical cycles), medical physics (the development of visualization methods in medicine and the study of physical processes for treatment), and cognitive science (the neural and cognitive processes underlying perception analysis, memory, and decision-making). Examples of student self-organization used in interdisciplinary teaching include initiating and completing research projects, collaborative problem-solving, problem-solving competitions, coding, and participating in interdisciplinary symposia where students present or share their research findings. Mutual evaluation of completed work is also encouraged. The completion of independent tasks has contributed to an improvement in students' interdisciplinary research skills. The majority of students in the experimental group were able to synthesize scientific knowledge from two or more disciplines, which has positively impacted their professional development. Table 1 displays the number of students who completed or partially completed the assigned tasks.

Table 1. Statistics of the completed tasks' quality distribution

Groups	Experimental (%)	Control (%)
The task was fully completed		
Students who completed the task based on the acquired knowledge	62	35
Students who completed the task based on the acquired skills	48	17.5
The task partially completed or not completed		
Students who partially completed the task based on the acquired knowledge	38	65
Students who completed the task based on the acquired skills	52	82.5
Students number	50	40

The experimental group students showed better results when performing the presented tasks, which confirms a higher knowledge and skill level in interdisciplinary research than the control group students. The results of students in the control and experimental groups completing the same task. It has been established that ϕ_1 for the experimental group students in terms of the formed knowledge level (62%) equals 1.813; for the control group students (35%), ϕ_2 equals 1.266. The percentage of students who completed the task in terms of the formed knowledge level in the experimental group was higher than in control one ($1.64<\phi_{emp}<3.31$, $\phi_{emp}=2.57$). Following the Fisher criterion calculation according to students' level of formed skills, it was also determined that the experimental group students showed higher results than the control group students ($1.64<\phi_{emp}<3.31$, $\phi_{emp}=3.14$). The student's assessment of the applied program efficiency indicators is presented in Table 2.

Table 2. The level of experimental group students' abilities development

No	Indicator of developed student abilities	Possibly agree (%)	Agree	Completely agree (%)
1	Cognitive horizons and methodological space in various sciences have been expanded.	4	32	64
2	A generalized interdisciplinary assessment of the surrounding world's socio-natural processes has been developed.	2	34	64
3	Self-organization phenomenon understanding helps me better navigate the laws and patterns of chemical, biological, and social objects described by a non-linear dependence.	6	32	62
4	Using the IRA increases students' interest in self-study.	4	30	66
5	Studying the synergetic fundamentals develops my critical thinking. It contributes to forming my personal qualities: flexibility of mind, perseverance, willingness to correct my mistakes, awareness, and the search for compromise solutions.	5	35	60
6	Acquiring the main issues of self-organization of socio-natural processes contributes to my self-development. I develop a readiness for reflection, creative activity, self-relevance, internal self-organization, self-esteem, and self-affirmation.	3	36	61

From the obtained calculation, students' understanding of physical phenomena and objects had increased significantly compared to when they started two years ago. Accordingly, the elective course influenced students' interest in mastering the necessary knowledge. Additionally, students were surveyed after the experiment regarding the impact of the model on the development of physics students' self-learning and self-organization skills to use it effectively in the future. The results are presented in Table 3.

Table 3. The student's assessment results of the strategies according to the scale the Brief-ACRA

Strategies	Experimental group	Control group	φ	p
Micro strategies	17.41±1.12	9.33±2.25	2.32	>0.05
Keys to memory and metacognition	15.28±2.22	10.20±1.35	2.11	
Emotional and social support	21.25±2.24	15.34±2.25	2.34	
Overall score	53.94±1.86	34.87±1.95	2.25	

The results of the application evaluation of the learning model with an interdisciplinary approach in the physics students' educational process revealed that experimental group students assess the quality of education significantly better than students from the control one. It demonstrates the effectiveness of the developed model. The students' interdisciplinary research activity is necessary for becoming competitive specialists, a means of professional development, and a form of a holistic and dynamic process of entering the profession. Interdisciplinary research combines two or more disciplines to achieve the same goal [16]. Modern research highlights the interdisciplinary research importance for students, especially within the natural sciences. Nevertheless, few empirical studies have been conducted on these topics [23].

Interdisciplinary research work is a professional and creative activity for students to master the knowledge, methods, and techniques system from various sciences. An interdisciplinary approach positively affects students who choose a common topic and explore it through a unified angle of interdisciplinary ideas to understand the subject better [27]. It also contributes to developing skills and abilities to solve problems at the intersection of multiple disciplines and develop crucial abilities for scientific search, independence, and initiative. Interdisciplinary can be considered both a didactic principle and a method of integrating knowledge from different disciplines. It also serves as a practical methodological approach for studying complex scientific problems across various fields [28]. Active engagement in learning is essential for the effectiveness of the education process as it enables learners to acquire relevant knowledge through involvement in internal and external activities [29]. The self-organization theory study and participation in interdisciplinary activities meet such effective learning requirements because they develop students' ability to self-learn, synthesize and critically comprehend information and its practical application.

Horn *et al.* [30] believed students can solve complex problems using interdisciplinary and transdisciplinary approaches. Implementing interdisciplinary strategies in student learning is difficult, especially in specific tasks [2], [31]. These approaches' implementation is possible by studying the presented strategies' features. This complements the research results of Englund [31], who developed an interdisciplinary activity method founded on the theoretical basis of the historical-cultural activity theory. Study by Carr *et al.* [18] focused on the use of a multidisciplinary method, guided by the process characteristics for the implementation of a training program that includes complementary training.

Research by Coleman *et al.* [32] indicated that preschool teacher training programs should be based on group learning, affecting knowledge and understanding from different educational disciplines. The effectiveness of this learning approach is established on the dialogue approach usage, which allows for studying the necessary information in the communication process. The present study emphasizes the students' analysis of the self-organization theory, which contributes to the development of interdisciplinary research activities. Researchers emphasize the importance of cultivating self-organizing skills and the capacity for self-directed learning as a foundation for the successful careers of emerging professionals [33]. At the same time, it is essential to consider the idiosyncrasies of the student's aptitude for self-directed education and the impact of the surroundings on their capacity to engage in self-learning [34]. However, it is necessary to consider the internal and external factors that influence the overall direction of the student population.

Education should be built on the direct participation of students and teachers, the search for new approaches to learning, collective responsibility and curiosity development [35]. Solving complex problems can be achieved by applying various knowledge in different subjects. The co-education of students who study architecture, business and art has led to an innovative approach to learning. This is related to the fact that students were required to transcend the boundaries of a single discipline and gain interdisciplinary collaborative experience [36]. These goals are met by using an interdisciplinary approach. The training was based on comparing knowledge from different disciplines and identifying similar vital points. This approach facilitates the creation of theoretical learning models, contributing to knowledge acquisition [37]. The teamwork formation facilitates student learning information discussion, affecting learning efficiency [38].

An interdisciplinary approach, with the rational organization of the learning process for different specialties students, can solve many education problems and contribute to a better knowledge understanding than the traditional one [23]. Further research is needed for meaningful study using an interdisciplinary method, which is problematic [18]. This research emphasizes developing a study model for physics students according to the interdisciplinary learning characteristics proposed by Carr [18] as an additional curriculum for students. The above allowed determining the tasks' quality based on the student's knowledge and skills. The development and testing of the training effectiveness in other learning types with an interdisciplinary approach proposed by Carr [18] (shared offices, research cluster meetings, passing a series of seminars, annual and semi-annual symposiums, and joint learning platforms) are relevant for future research.

The development of students' autonomy in interdisciplinary learning contributes to the formation of crucial knowledge and skills, comprehension of links between academic subjects, and overall self-organization. The findings demonstrate a favorable influence on the development of self-organization and autonomous learning abilities. Interdisciplinary study emphasizes the integration of theoretical knowledge into practical application, facilitating the efficient resolution of professional issues within the context of the subject profile. The adoption of an interdisciplinary approach to teaching enhances students' preparedness to tackle professional challenges, as it fosters self-directed learning and observation, which bolsters their understanding.

4. CONCLUSION

Whereas the authors determined physics students' knowledge and skills quality based on developing the self-organization theory foundations during training following the integrated course "Synergetic–an interdisciplinary scientific theory", the article's formed hypothesis was achieved. The study of the synergetic fundamentals aimed to develop their interdisciplinary research activities and abilities. The paper presents a model to prepare students for interdisciplinary research activities grounded on studying the self-organization theory basics. Priority in the learning process was given to the content, integration, and methodology of the natural sciences, mathematics, humanities, and course content expert analysis. The authors also point out that in the learning process, it is necessary to focus on the methods and technologies of teaching, forms, and means of education.

During the study, experimental data were used to determine students' knowledge and skill levels in the control and experimental groups. The results showed that the students of the two groups have more developed skills that contribute to the scientific knowledge synthesis of two or more disciplines. The highest knowledge level of the two groups' students was achieved by studying the theoretical aspects of natural experiments necessary to examine the natural objects' sustainability.

The study also determined the allocation statistics of the quality of student tasks' quality. The education quality was based on the tests and standard task performance, which involved the detailed answers provision. It also included practical and laboratory work. The number of fully and partially completed tasks was distributed among students in percentage using the observation method. Students from the experimental group rated the education quality significantly better on a short educational assessment scale. They also positively assessed the training impact on the developed model on the evolution of their abilities obtained in the elective course "Synergetic–an interdisciplinary scientific theory." The study's novelty is in solving the problems of developing interdisciplinary research activities of students in the purposeful reflection context of self-organization theory. This increases student engagement in active learning and therefore has a positive impact on learning outcomes.

The results of this study can be used in advanced training courses for natural sciences teachers and physics students' preparation in higher educational institutions. It can also be adapted and applied to training other specialties students. Research prospects may be related to improving the learning model, which will be aimed at developing the students' competence in interdisciplinary research through the self-organization theory and conducting an appropriate pedagogical experiment.

ACKNOWLEDGEMENTS

This study was carried out with the financial support of the Scientific Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AR14869376 "Development of Interdisciplinary Research Ability of Students in the Realization of Synergetic Education in Higher Education").

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