SYSTEMIC ASSESSMENT QUESTIONS FOR SYSTEMS THINKING DEVELOPMENT AND EVALUATION IN ORGANIC CHEMISTRY DOMAIN: A REVIEW OF APPLICATIONS AND FUTURE PROSPECTIVES

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ABSTRACT

The systems thinking is one of the fundamental 21st century thinking skills that our students should develop. Therefore, the value of systems thinking in chemistry education is increasingly recognized through developing efficient evaluation and/or instructional tools. This review investigated how the systems thinking skills were developed and evaluated in organic chemistry classes with the application of systemic approach to teaching and learning, SATL, and more precisely systemic assessment questions, SAQs. The empirical peer-reviewed articles indexed in SCOPUS database were analyzed. In order to analyze and compare included studies, four descriptors were formulated, and qualitative content analysis approach was further used. The results indicated that analyzed studies used DSRP (distinctions, systems, relations, perspectives) model in order to develop scoring rubric for assessing students' systems thinking skills after solving SAQs. SAQs were found to be efficient assessment tools with acceptable psychometric properties such as good validity and reliability. In the newest studies, SAQs were characterized as suitable instructional tools for enhancing students' systems thinking skills. The analyzed studies included additional factors that could be related to the construct of systems thinking, such as meaningful understanding of chemistry concepts and/or students' gender. At the end, the areas that need further investigation or improvement were highlighted. *[African Journal of Chemical Education—AJCE 13(4), December 2023]*

INTRODUCTION

The problems of „systems" were ancient and had been known for many centuries, but they remained philosophical and did not become „science" because of their complexity (von Berttalanffy [1, p. 411]).

It is well known fact that chemistry learned in schools is increasingly complex and abstract subject [2], often loaded with a large amount of information [3] that nowedays should be mastered in the environment of dynamic and fast changing world. Surly, this makes solving chemistry problems more demanding. The great power in solving complex problems that students cannot solve using conventional reductionist thinking has the concept of *systems thinking* [4] that is becoming more and more popular in science/chemistry education [5].

The brilliant, fundamental roots of the systems thinking can be found in *General Systems Theory* that has been firstly formulated in 1930's by von Berttalanffy [1]. A logico-mathematical General Systems Theory has been introduced within biological systems, but it is perfectly applicable in chemistry context too. Von Berttalanffy used mathematical descriptions of main systems properties such as wholeness, sum, growth, centralization, hierarchical order, etc. This theory has used the Aristotelian dictum "the whole is more than its parts" as investigation of the single parts and processes cannot provide a complete explanation and/or understanding of the system [1]. The properties of the system are not those that belong to the individual parts/components since the status of one component affects the status of other components of the system [6]. The parts/components need to work together in order the whole/system functions successfully [7]. Therefore, it could be said that the fundamental characteristic of the system is its *organization*, and to be able to understand the organized whole, we must know both its parts and relationships between them, i.e. interrelations between many but not infinitely many parts/components.

According to this, Salisbury [8] defined *systems thinking* as the ability to structure the relationships between the components in the system in an effective way. The person must think about all the components and the relationships that exist within a system, in order to effectively structure the relationships. To simplify this definition, it could be said that systems thinking is a way of thinking for a person to understand the system. However, systems thinking does not refer to the breaking down a system into its parts/components. Instead, systems thinking focuses on how the components act together in the networks, interactions, and interconnectedness [7].

Diverse interpretations of systems thinking lead to the diversity of systems approaches [9] that have offered not only the theoretical perspective, but also methodology to deal with the systems thinking [5]. The systems approaches will be considered in the following “Literature framework”.

LITERATURE FRAMEWORK

Systems Approaches: The DSRP Model

Despite diversities, in all systems approaches, the central construct is the term *system* that has been introduced earlier in this paper. It is obvious that the main building blocks of the system are not the parts/components but the relationships between them [9]. Why? Because components are not always clearly defined and often, they can be recognized through the many associations with other overlapping components [10]. In order to explain this, Cabrera and colleagues [9] proposed the four cognitive patterns that shape systems thinking: *D* (distinction), *S* (systems), *R* (relationships), *P* (perspective), or *DSRP* model. Distinction can be made between and among things and/or ideas, while things and/or ideas can be organized into the systems/wholes. The systems are made of the parts/components or/and sub-systems, between which the relationships can be made. At the end, things and ideas can be observed from the perspective of other things and ideas [9]. It is clear that these four patterns, *D*, *S*, *R*, and *P* (see Fig. 1) are in constant and dynamic interplay [11]. Therefore, systems thinking is an emergent property of the *DSRP* processing rules or cognitive patterns [9], that person needs to apply within the system of interest.

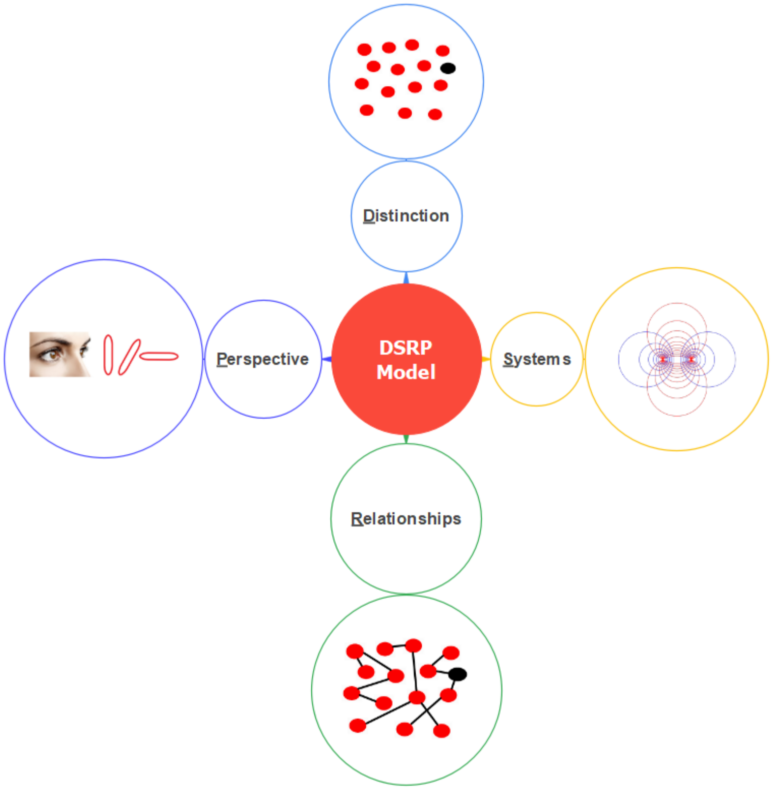

Fig. 1. Four cognitive paterns that shape systems thinking (DSRP model)

In the literature of chemistry education, there are several studies that focused on DSRP formalistic model in order to assess students' systems thinking [5, 12-16]. This model was chosen as it is suitable for the *closed systems* that possess clear boundaries that conceptually isolate the system under study [5]. The chemistry is rich of such systems that can be as complex as open systems are. In organic chemistry, there are a vast number of compounds, and each one should be observed as a concept with specific properties, such as the systematic name, functional group, molecular and structural formula, physical and chemical properties [12]. These properties *differentiate* (*DSRP*) the concept, i.e. organic compound from the others. For example, ethanoic acid is a concept that should be differentiated from the oxalic acid focusing on the number of carboxyl groups in the structures of two carboxylic acids. However, the ethanoic acid is the constituent part of the larger whole called “carboxylic acids”, that is a sub-system of the larger whole called „organic compounds with oxygen“, that is a sub-system of the „organic chemistry“ whole, and organic chemistry is a sub-system of the *system* (DSRP) of chemistry. In order to be properly understood, the ethanoic acid should be *related* (DSRP) with appropriate concepts from the sub-systems and/or system such as, for example, calcium acetate, acetone, diethyl ether, ethanol, etc. However, the system or sub-system of these concepts could be reoriented, perhaps, by determining another focal point or *perspective* (DSRP) of the system, e.g., from the acetone perspective.

Taking into account *DSRP* model, Vachliotis and colleagues [13] developed the initial Rubric for scoring students’ answers on *systemic assessment questions, SAQs,* in order to examine secondary school students’ systems thinking in an organic chemistry domain. Firstly, systemic assessment questions will be introduced.

Systemic Assessment Questions

Systemic assessment questions, SAQs, have been introduced as a sub-system of *systemic diagrams* or *systemics* which have a central role within a Systemic Approach to Teaching and learning (SATL) chemistry. The SATL was created in 1998 by professors Ameen Fahmy from the Ain Shams University in Cairo, Egypt and John Lagowski from the University of Texas at Austin [17]. For the last 25 years, chemistry has been in the focus of SATL, however, this approach was applied in teaching process of a variety of subjects like biology, physics, and mathematics [18]. Taking into account the basis of the SATL, two contributing concepts should be mentioned:

- Theory of meaningful verbal learning, and
- Concept mapping technique.

In the 1960s David Ausubel developed the theoretical approach of meaningful verbal learning as a contrast to the rote or mechanical learning [19]. Ausubel has highlighted that meaningful learning occurs if students connect new concepts with those already adopted, on essential and unarbitrary way [20]. It was pointed out that meaningful learning happens through the acquisition of new meaning from presented learning material, which must be connected with the relevant mental model. Therefore, student's mental model must possess the relevant fixed ideas to which new learning material can be connected [21]. It is well known that student's mental model is fundamental for learning science, mathematics, and logic, as the student "manipulates" with the mental model in order to find the true answer to the difficult, complex, and abstract problems as those seen in the chemistry [22, 23]. It must be recognized that the student's mental model is incomplete and unstable at the beginning of the learning process, but with time, it continues to change, grow, and improve because new information/concepts are integrated into it [22]. On the other hand, rote or mechanical learning occurs when presented leaning material does not have an established relation with those previously learned [23], so the rote memorization is inefficient and encourages students not to think systemically.

In order to promote meaningful learning, Joseph Novak introduced concept mapping technique. Concept maps are two dimensional diagrams consisting of nodes, i.e. circles or boxes and lines or arrows. Nodes represent the main elements or concepts, while lines or arrows are labeled with linking words explaining the relationships between these elements or concepts [25]. Selected elements or concepts closed into the circles or boxes can be represented by using words and/or symbols and are arranged hierarchically where more specific concepts are placed under more general ones [26]. For example, in concept map arrangement, starting from the top of the map and moving to the lower parts, the "carboxylic acid" is placed above the concepts of "ethanoic acid" and "oxalic acid". This provides linear relationships between the set of concepts, and these features, i.e., hierarchy and linearity are the main difference between concept maps and systemic diagrams [23].

Systemic diagrams have been described as a closed system of the set of selected elements or concepts while their arrangement corresponds to the "closed concept map cluster" [17]. It is crucial to note that all possible relationships between the set of selected concepts are made clear to the students in order to provide opportunity for the students to see topic, subject, or domain globally without missing its constituent parts [17].

Later, Fahmy and Lagowski [27, 28] have created a type of questions that were philosophically compatible for the SATL in order to assess the students' progress in learning chemistry topics [18] at secondary and tertiary levels [27, 28]. Depending on the number of the selected concepts and the size of the diagram, systemic assessment questions, SAQs, follows various geometrical shapes like triangular, quadrilateral, pentagonal, hexagonal, etc. Additionally, several types of SAQs have been proposed. In our studies, systemic synthesis questions, SSynQs, as one specific type of SAQs, were in the focus [12, 15, 21, 23, 29]. SSynQs were created to follow the structure in which the students were required to perceive defined relationships (i.e. "pyrolysis/500 ^{0}C", see Fig. 2) and initial concept (i.e. "pentane", see Fig. 2) in unfilled, or partially filled boxes in SSynQ, in order to identify concepts that were missing [21]. One example of SSynQ with nine concepts could be seen on Fig. 2.

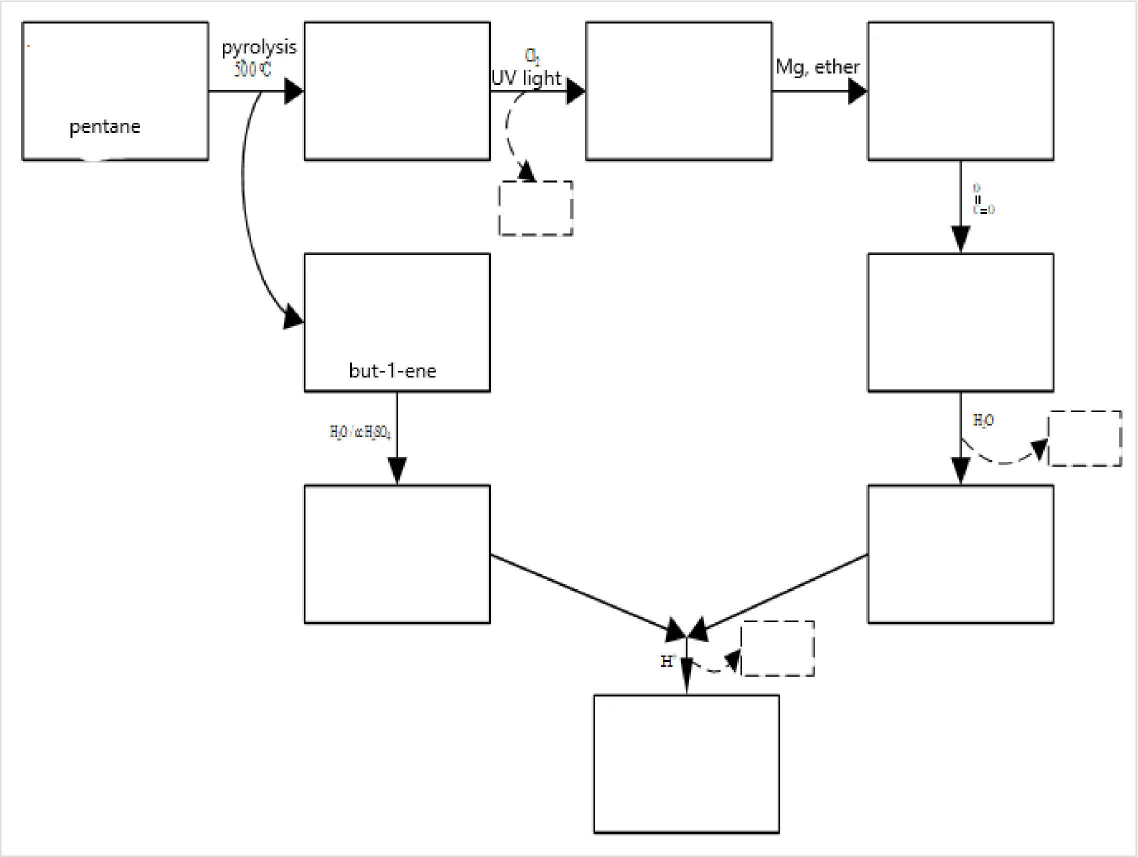

Fig. 2. SSynQ with nine concepts

The process of solving SAQs and/or SSynQs requires the following steps: (1) organize concepts, (2) define or perceive relationships between concepts, (3) synthesize concepts into sub-systems and further into coherent whole system, and (4) analyze system to the fundamental concepts

[13]. In line with this, SAQs and SSynQs were applied in the organic chemistry educational process in order to enhance and assess high school students' systems thinking skills [5, 12-15, 29]. Therefore, an appropriate Rubric for assessing students' systems thinking skills has been developed.

The Rubric for Assessing Students' Systems Thinking

The original systems thinking assessment rubric theoretically based on a formalistic system thinking conceptual model, i.e., *DSRP* model, which will be here abbreviated as STARubric was designed in order to assess Greek high school students' systems thinking using SAQs as assessment tools [13]. STARubric possessed three identification steps, where the first step, *S1*, included the identification of some individual and conceptually isolated concepts within the conceptual system. The second step, *S2*, observed two or more concepts linked together, forming a conceptual sub-system that is a part of the whole system of interest. The third step, *S3*, represented the identification and integration of all sub-systems in order to form a meaningful whole system. These three identification steps included five levels of skills that could be read in more details in the original publication [13].

In the following years, the modifications were made to the original STARubric. For example, in the later study of the same authors [5], the four steps STARubric with five scoring levels was designed. Therefore, *S1* included two levels of skills, "no connection" and "partial connection".

Furthermore, *S2*, included "sufficient connection" level, while *S3* "complex connection" level. The most desired *S4* referred to the level of skill called "system" where students were able to recognize all relevant concepts and possible relationships that form a meaningful conceptual whole. These levels of skills were made more comprehensive to capture all possible students' responses on SAQs [5].

In the two consecutive studies [12, 15], the modified version of STARubric with three identification steps were used:

- *S1* – Identifying concepts,
- *S2* – Identifying connection between concepts,
- *S3* – Examining the connection structure.

Also, five levels of skills were translated into four systems thinking levels. Firstly, if the student provided no answer or completely irrelevant answer on SSynQ, a value of zero, *0,* is assigned (no answer, or incorrect answer level). Furthermore, if the student demonstrated skills to identify the relevant concept of a selected system or a sub-system, a value of one, *1*, is assigned. It should be explained that identified concept was unrelated with any other concept, and, as such was isolated from a system and/or a sub-system. If the student recognized a proper relationship between two concepts, a value of two, *2*, was assigned. In addition, if the student was able to organize more than two concepts and at least two processes, a value of three, *3,* was assigned. In this way, the identified concepts formed the relationships with two or more specific links. The most desired outcome of the process of the systems thinking assessment was when the student managed to interconnect all the concepts, to recognize all the sub-systems that formed the whole system of interest. Such answer on the SSynQ was evaluated with the value four, *4* [12].

To clearly illustrate how this modified version of STARubric was used to assess students' systems thinking, we will consider an example student, Joy. Looking at Fig. 3 it could be seen that Joy managed to link several concepts, i.e. organic compounds into a sub-system. He/she successfully related *pentane* with *methane* that is produced through the process of pyrolysis. Additionally, he/she related *methane* with *chloromethane* through a chlorination reaction in the presence of UV light. Therefore, Joy's answer on SSynQ would be scored with the value *3* – multiple connections were observed. It should be mentioned that Joy identified additional two concepts – *buthane-2-ol* and *ethanoic acid*, with both correct formula and name, or, in the case of ethanoic acid, only with the name (see Fig. 3). However, these concepts were not related with the other concepts, i.e. they remained isolated within this particular SSynQs.

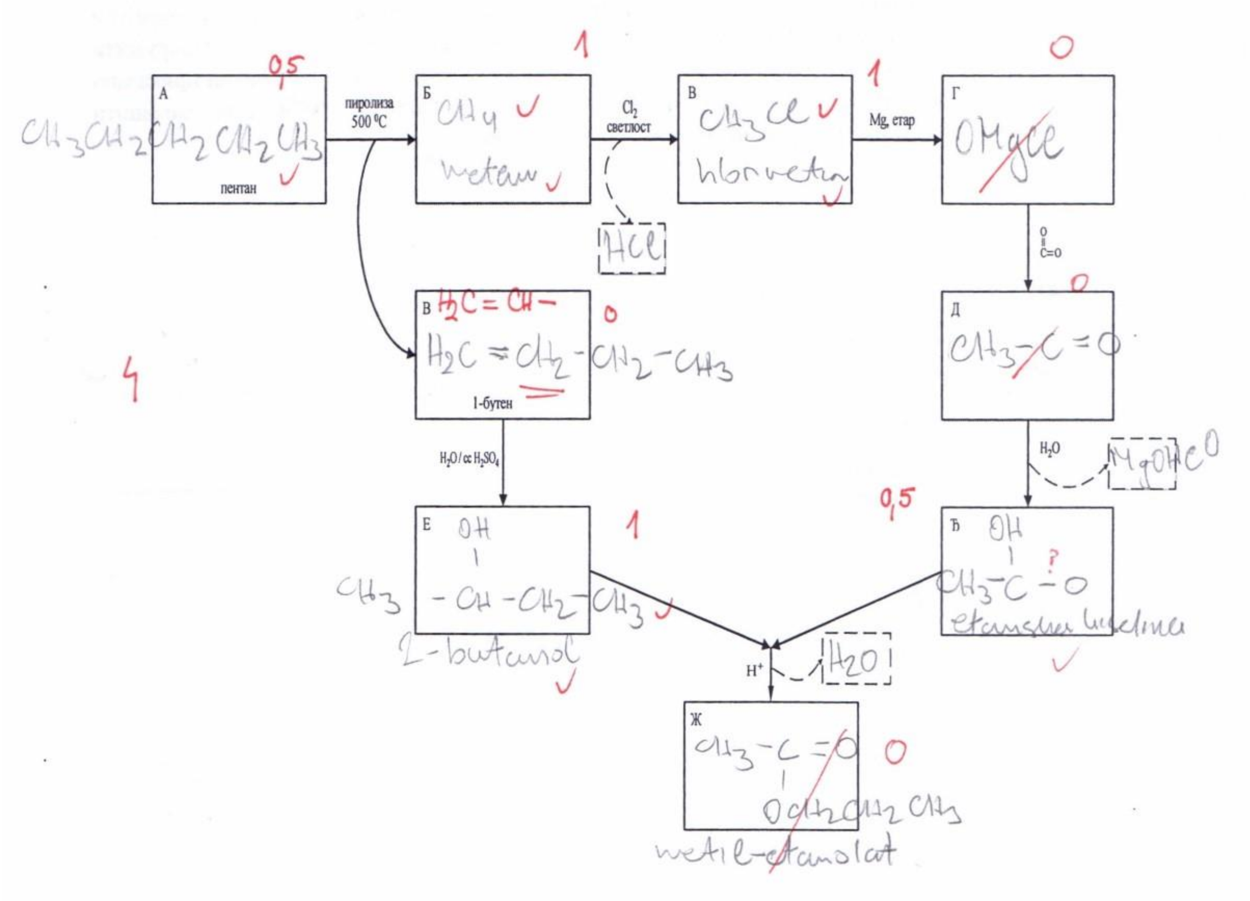

Fig. 3. The Joy's answer on SSynQ with nine concepts

METHOD

The aim of this study was not only to represent the STARubric, but also to review the articles related to students' systems thinking in chemistry education that were theoretically and methodologically related to SATL. In order to achieve this aim, the SCOPUS analytical tool was used for gathering descriptive statistics such as the year distribution of articles, publication journal, citation of articles, etc.

In the first stage of the analysis, the articles were searched on the SCOPUS database through the "systems thinking" and "chemistry" query in August 2023. Totally 118 SCOPUS-published articles in English were obtained. The first one was published in 1974, and the others between 2002 and 2023. In the second stage, we have added "SATL" in our query and 3 articles published between 2014 and 2021 were found. Two of these articles were published in the Thinking Skills and Creativity journal and one in the Research in Science Education journal. The most cited article has been published in Thinking Skills and Creativity journal in 2017 (see Table 1). The cumulative citation of all three articles is 42 (according to SCOPUS, August 2023). It is interesting to note that all three publications covered the contents of organic chemistry, and the studies were conducted in two countries, Greece and Serbia. Table 1 summarizes the basic descriptives about articles found in our analysis.

Table 1. The basic descriptives about selected articles

	Publication journal	**Publication year**	**Research area**	**Country**	**Citations**
Vachliotis and colleagues [13] - **A1**	Research in Science Education	2014	Organic chemistry	Greece	18
Vachliotis and colleagues [5] - **A2**	Thinking Skills and Creativity	2021	Organic chemistry	Greece	4
Hrin and colleagues [12] - **A3**	Thinking Skills and Creativity	2017	Organic chemistry	Serbia	20

This qualitative study used a content analysis approach to identify similarities and differences within selected articles. The common parts of the research within all three articles are the inclusion of the STARubric, the focus on high school students and organic chemistry contents. However, the articles marked as *A1*, *A2*, and *A3* (see Table 1) can be distinguished according to the following descriptors:

D1. Qualitative / quantitative exploration of suitability of new instruments and STARubric for systems thinking assessment.

D2. The validation of new instruments and rubric through validity and reliability analysis.

D3. The exploration of the relation between the students' systems thinking and other relevant constructs or factors (e.g. gender, or meaningful understanding);

D4. The examination of the impact of the SATL instructional strategy on the students' systems thinking development.

DISCUSSION

In order to compare the selected articles, firstly it should be said that all three articles satisfied descriptors *D1*, *D2*, and *D3*. Namely, the authors have designed new instruments, i.e. SAQs and their more specific sub-type – SSynQs that focus on synthesis reactions, in order to examine the effectiveness and suitability of instruments for systems thinking assessment (see descriptor *D1*). It must be highlighted that the great contribution of the study marked as *A1* (see Table 1) is the fact that SAQs were for the first time applied in an empirical study in order to examine high school students' systems thinking in the domain of organic chemistry. The constrained format of SAQs with a given, partially fulfilled diagrammatic form was used and the high school students were required to complete it by writing elements that were missing (e.g. names and formulas of missing organic compounds, types of organic chemistry reactions, reagents and the conditions of the reactions). In the next study of the same authors (marked as *A2* in the Table 1), the fill-in-the-blank SAQ items were also designed based on the results of the previous research [13] to capture high school students' systems thinking skills in organic chemistry domain (regarding the chemistry of alcohols and carboxylic acids). Even though in our study (marked as *A3* in Table 1), we also used constrained fill-in-the-blank format of SSynQs with given diagrammatic form, the main difference was in the fact that all concepts included in our diagrammatic form were directly included in the "closed cluster" (i.e. each concept was linked with at least two neighboring concepts, see Fig. 2). In the studies of Vachliotis and colleagues (marked as *A1* and *A2* in Table 1) the SAQs contained concepts that included multiple relationships, however, there where concepts that were related with only one additional concept, too. Therefore, our SSynQs contained fewer number of concepts integrated in "closed cluster" of SSynQs (i.e. from 5 to 9), in comparison to the SAQs used in *A1* and *A2* which included more than 10 concepts, while several of them were provide to the students. In all three studies, high school students' answers on SAQs / SSynQs were evaluated by using previously described STARubric, and the following was concluded:

- SAQs / SSynQs are useful instrument for assessing systems thinking skills in organic chemistry domain as, in order to be solved, they require skills such as making distinction between concepts, linking and organizing concepts, and taking multiple perspectives. The level of student's success in these processes determines the level of his/her level of systems thinking. Therefore, SAQs / SSynQs are appropriate tools for classifying students into different levels of systems thinking skills.

Additionally, the set of these instruments showed acceptable psychometric properties such as good validity and reliability (see descriptor *D2*). For example, the evidence of reliability in *A1* study was determined by calculating inter-rater reliability by using Cohen κ coefficients which were calculated to be sufficiently high (0.81 and 0.85). The reliability parameter in *A2* was determined by finding very strong positive correlation ($r = 0.95$) between systems thinking level scale and scoring method noted as “one point for each correctly written concept”. Additionally, the reliability of internal consistency, by calculating the Cronbach’s alpha coefficient, was performed in the study *A3* for all four levels of systems thinking. The Cronbach’s alpha coefficient was found to be high in the range from 0.773 to 0.797. In the same study, *A3*, the concurrent validity was estimated when regression analysis was conducted between variables: students’ performance scores on SSynQs and conventional questions. The significant values of Pearson’s r coefficient were found between students’ performance scores on conventional questions and lower levels of systems thinking (i.e. first and second levels).

The authors of the analyzed studies find in quite important to include additional construct or factor in order to correlate it with the systems thinking (see descriptor *D3*). More about that will be discussed in the continuation of this section. The associations between systems thinking construct and students’ meaningful understanding represented significant part of the investigation in *A1* and latter *A2*. Namely, SAQs were originally designed with the intention to capture students’ meaningful understanding in the chemistry. By analyzing students' answer on SAQs, the authors in *A1* found that systems thinking levels were strongly related with the students' deeper understanding of organic chemistry concepts, i.e. with their meaningful understanding. In addition, study within *A2* provided a continuing flow of the previous research *A1* about this issue. The main difference between *A1* and *A2* was in the research design, as now, within the *A2*, the authors implemented the pre-test/post-test nonequivalent control group design. The comparison between the experimental, *E* group (the implementation of SATL strategy in the teaching and learning process) and the control, *C* group (traditional classroom teaching) in *A2*, enabled the examination of the impact of the SATL instructional strategy on students' understanding in organic chemistry (fulfilled descriptor *D4*). An important influence of the SATL instructional strategy on students' meaningful understanding in organic chemistry was observed. However, the research design required only *E* group students to solve SAQs as validated instruments for assessing students' systems thinking skills. Then, the relationship between students' systems thinking skills and their understanding of chemistry concepts was explored only within *E* group students, and a strong positive correlation was found. The conclusion was that the level of systems thinking development is associated with the understanding of relative scientific concepts in the domain of chemistry. The SAQ test was not administered to the control group, because, according to the authors' opinion, these students were totally unfamiliar with the SATL strategy in chemistry.

The study marked as *A3* followed the experimental / control group research design, where *E* group students were trained in the SATL strategy similarly as in the *A2* (fulfilled descriptor *D4*). Before the research was conducted, the authors prepared both the learning sheets with fill-in-the-blank SSynQs, as well as final test with SSynQs and conventional (objective) questions (i.e. multiple-choice, open response, matching, and completion type questions). The C group students received short instruction about SATL strategy and SSynQs principles of solving before testing has started as they were not familiar with any of aspects of SATL strategy. Therefore, one of the differences between studies *A2* and *A3* was in the fact that *C* group students in A3 study solved both conventional and SSynQs on the final testing. Namely, the *E* and *C* groups were subjected to the exactly the same research instrument. The results showed that the students who were subjected to SATL approach and worked with [SSynQs] on classes developed all four levels of systems thinking in a more effective way that students who continued with traditional teaching and learning. Namely, the positive, high impact of SATL instructional strategy on students' systems thinking skills was highlighted, as students from the *E* group outperformed students from the *C* group in all four levels of systems thinking, and the *C* group students did not develop abilities of dynamic and cyclic relationships between elements of the organic chemistry systems and sub-systems (see descriptor *D4*).

In the same study *A3*, the issue of gender in regard to the construct of systems thinking was examined (fulfilled descriptor *D3*). No significant differences between male and female students were found in the *C* group. However, in the *E* group such difference was noted as *E* group female students outperformed male students in identification of dynamic and cyclic relations between concepts (III and IV levels of systems thinking). The conclusion about gender issue made in this study [12] was that application of SSynQs is more suitable for female students in order to develop higher order thinking skills such as systems thinking skills. It is interesting to note that in the next study of the same authors [15] one of the conclusions was that male students could benefit more from SATL instructional strategy if they receive longer lasting instruction with SSynQs.

SUMMARY AND FUTURE DIRECTIONS

This paper reported on our review of systems thinking construct in relation to the systemic approach to teaching and learning, SATL, chemistry. The SCOPUS database was used to find the empirical peer-reviewed articles that integrated both systems thinking and SATL approach in chemistry education. The qualitative content analysis applied to the selected studies indicated that all of them were conducted within high school organic chemistry domain and used scoring rubric developed on the theoretical and methodological bases of systems thinking framework called DSRP. The original and modified versions of scoring rubric (called STARubric for the purpose of this paper) was successfully used in three studies marked as *A1*, *A2*, and *A3* (see Table 1) in order to assess high school students' systems thinking skills through the defined levels. However, there are some challenges in implementing DSRP in developing process of STARubric. It seems like one aspect of DSRP model has been neglected. Namely, it is agreed that systems thinking refers to the application of four cognitive rules or skills to the given task or information. These are making distinctions, identifying systems, determining relationships, and making different perspectives, including awareness of our own thoughts which is also known as metacognition [30]. There are many theories how to develop metacognition, however, there is no study that examined the application of SALT instructional strategy in order to develop students' metacognition. This would provide the inclusion of additional variable to find valuable relations with students' systems thinking (noted here as descriptor *D3*).

Another interesting finding was in regard to the triangle between the students' gender, SATL instructional approach, and systems thinking construct. In the studies that used SATL instructional approach for the shorter period of the instructional time, e.g. within one or two teaching topic, female students scored higher observing the levels of systems thinking [12], or meaningful understanding [21]. However, when the students were exposed to the work with SSynQs for the longer period of class time, the male students benefited more from the SATL approach [15]. Perhaps there are sub-types of SAQs that are more suitable for the male students in order to develop higher order thinking skills. These could be systemic analysis questions, SAnQs, or systemic sequencing questions, SSQs. They should be examined together with the issue of students learning styles. Certainly, there are plenty of directions for future research in this approach that would be highly contributing.

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REFERENCES

1. L. Von Bertalanffy. The history and status of general systems theory. *Academy of Management Journal*, 1972, 15(4), 407-426.
2. D. Gabel. Improving Teaching and Learning through Chemistry Education Research: A Look to the Future. *Journal of Chemical Education*, 1999, 76(4), 548-554.
3. L. Cardellini. Chemistry: Why the Subject is Difficult? *Educación Química*, 2012, 23(2), 305-310.
4. J. P. Monat, T. F. Gannon. What is Systems Thinking? A Review of Selected Literature Plus Recommendations. *American Journal of Systems Science*, 2015, 4(1), 11-26.
5. T. Vachliotis, K. Salta, C. Tzougraki. Developing Basic Systems Thinking Skills for Deeper Understanding of Chemistry Concepts in High School Students. *Thinking Skills and Creativity*, 2021, 41, 100881.
6. O. Ben-Zvi Assaraf, A. Orion. Development of System Thinking Skills in the Context of Earth System Education. *Journal of Research in Science Teaching*, 2005, 42(5), 518-560.
7. H. Shaked, C. Schechter. Definitions and Development of Systems Thinking (Chapter 2). *Systems Thinking for School Leaders*. Springer International Publishing AG, 2017.
8. D. F. Salisbury. *Five technologies for educational change: Systems thinking, systems design, quality science, change management, industrial technology*. Educational Technology Publications, 1996.
9. D. Cabrera, L. Cabrera, E. Powers. A Unifying Theory of Systems Thinking with Psychosocial Applications. Systems Research and Behavioral Science, 2015, 32(5), 534-545.

10. D. Cabrera, L. Colosi. Distinctions, Systems, Relationships, and Perspectives (DSRP): A Theory of Thinking and of Things. *Evaluation and Program Planning*, 2008, 31, 311–334.
11. L. Cabrera, J. Sokolow, D. Cabrera. Developing and Validating a Measurement of Systems Thinking: The Systems Thinking and Metacognitive Inventory (STMI). In D. Cabrera, L. Cabrera, G. Midgley (Eds.), *The Routledge Handbook of Systems Thinking*. Routledge, 2023.
12. T. N. Hrin, D. D. Milenković, M. D. Segedinac, S. Horvat. Systems Thinking in Chemistry Classroom: The Influence of Systemic Synthesis Questions on its Development and Assessment. *Thinking Skills and Creativity*, 23, 175-187.
13. T. Vachliotis, K. Salta, C. Tzougraki. Meaningful Understanding and Systems Thinking in Organic Chemistry: Validating Measurement and Exploring Relationships. *Research in Science Education*, 2014, 44, 239-266.
14. C. Tzougraki, K. Salta, T. Vachliotis. Development and Evaluation of a Systemic Assessment Framework in Organic Chemistry. *African Journal of Chemical Education*, 2014, 4(2), Special Issue (Part I), 101-121.
15. T. N. Hrin, D. D. Milenković, M. D. Segedinac. Examining Systems Thinking Through the Application of Systemic Approach in the Secondary School Chemistry Teaching. *African Journal of Chemical Education*, 2017, 7(3), Special Issue, 66-81.
16. K. Paschalidou, K. Salta, D. Koulougliotis. Exploring the Connections Between Systems Thinking and Green Chemistry in the Context of Chemistry Education: A Scoping Review. *Sustainable Chemistry and Pharmacy*, 2022, 29, 100788.
17. A. F. M. Fahmy, J. J. Lagowski. The Use of a Systemic Approach in Teaching and Learning Chemistry for the 21st Century. *Pure and Applied Chemistry*, 1999, 71(5), 859–863.
18. J. J. Lagowski. Systemic Approach to Teaching and Learning. *Journal of Chemical Education*, 2005, 82(2), 211.
19. D. P. Ausubel. *The Acquisition and Retention of Knowledge: A Cognitive View*. Springer Science + Business Media, 2000.
20. D. P. Ausubel. The Facilitation of Meaningful Verbal Learning in the Classroom. *Educational Psychologist*, 1977, 12(2), 162-178.
21. T. N. Hrin, A. F. M. Fahmy, M. D. Segedinac, D. D. Milenković. Systemic Synthesis Questions [SSynQs] as Tools to Help Students to Build Their Cognitive Structures in a Systemic Manner. *Research in Science Education*, 2016, 46(4), 525-546.
22. I. M. Greca, M. A. Moreira. Mental Models, Conceptual Models, and Modelling. *International Journal of Science Education*, 2000, 22(1), 1-11.

23. T. Rončević, D. D. Rodić, S. A. Horvat. Investigation of Students' Conceptual Understanding in Organic Chemistry Through Systemic Synthesis Questions (chapter 13). In N. Graulich, G. Shultz (Eds.), *Student Reasoning in Organic Chemistry*. Royal Society of Chemistry, 2023.
24. D. P. Ausubel, M. Youssef. Role of Discriminability in Meaningful Paralleled Learning. *Journal of Educational Psychology*, 1963, 54(6), 331–336.
25. J. D. Novak. *Learning, Creating, and Using Knowledge. Concept Maps as Facilitative Tools in Schools and Corporations*. Routledge, Taylor & Francis Group, 2010.
26. J. D. Novak. Meaningful Learning: The Essential Factor for Conceptual Change in Limited or Inappropriate Propositional Hierarchies Leading to Empowerment of Learners. *Science Education*, 2002, 86(4), 548–571.
27. A. F. M. Fahmy, J. J. Lagowski. Systemic Assessment as a New Tool For Assessing Students Learning in Chemistry Using SATL Methods: Systemic True False [STFQs] and Systemic Sequencing [SSQs] Question Types. *African Journal of Chemical Education*, 2012, 2(2), 66-78.
28. A. F. M. Fahmy, J. J. Lagowski, (2014). Systemic Assessment as a New Tool for Assessing Students Learning in Chemistry Using SATL Methods: Systemic Matching [SMQs], Systemic Synthesis [SSynQs], Systemic Analysis [SAQs], Systemic-Analytic [SSyn-AnQs], as Systemic Questions Type. *African Journal of Chemical Education*, 2014, 4(4), 35-55.
29. T. N. Hrin, D. D. Milenković, M. D. Segedinac, S. Horvat. Enhancement and Assessment of Students' Systems Thinking Skills by Application of Systemic Synthesis Questions in the Organic Chemistry Course. *Journal of the Serbian Chemical Society*, 2016, 81(12), 1455–1471.
30. D. Cabrera, L. Cabrera. Complexity and Systems Thinking Models in Education: Applications for Leaders. In J. M. Spector et al. (Eds.), *Learning, Design, and Technology*. Springer Nature Switzerland AG, 2019.