**Design, Implementation and Evaluation of a Systems Thinking Course in an M.A. Program in Learning Sciences**

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**Abstract**

Although the Systems Thinking approach in education is not new worldwide, implementations in K12 education are in their 7th and the course in a MA program is in its 2nd year in Turkey. In the current study we present the first Systems Thinking course incorporated in a MA program in Learning Sciences. Our research aims to investigate the effectiveness of the developed Systems Thinking course curriculum on problem definition and analysis..

Study group consisted of 12 MA students who were also actively teaching in various grade levels ranging from preschool to secondary school. The 42-hour curriculum included lectures, practical applications and also games emphasising the system concept. All students were asked to define and to analyse a dynamic problem and also suggest solutions. The same application was repeated after the completion of the course. Problem analysis parts of the pre and posttest were further analysed comparatively. Seven criteria were used for the evaluation; definition of the problem, analysis percentage, the depth of the analysis, the width of the analysis, the number of relations, the number of loops, the use of ST/SD tools.

The results of the research demonstrated statistically significant ameliorations in the tested skills. Majority of the participants demonstrated progress in seven described skills corresponding to improvement in analysing a given subject with system point of view.

As a conclusion, the course curriculum is found to have an effect on the analysis capability. The persistency of the obtained skills should be evaluated in further studies.

**Key words:** system dynamics approach, problem analysis

## INTRODUCTION

Systems thinking approach has been advocated as a 21st-century skill for students (Hari, et al. 2013). The PISA 2021 assessment framework identifies critical thinking, creativity, research and inquiry, self-direction, initiative and persistence, information use, systems thinking, communication and reflection as critical 21st-century skills to be included in the assessment of mathematics.

System thinking approach is defined in different ways. Senge (2006) defines that the system thinking approach is a discipline for seeing wholes. It is a framework for seeing interrelations rather than things, for seeing patterns of change rather than static "snapshots". Cabrera, (2006) claims that systems thinking is not a discipline, but rather an interdisciplinary conceptual framework used in a wide range of areas; it is "an orientation to the world, and a model for thinking about and learning about systems of all kinds-scientific, organizational, personal, and public".

According to Meadows (2009), systems thinking consists of three kinds of things: elements (in this case, characteristics), interconnections (the way these characteristics relate to and/or feed back into each other), and a function or purpose. System thinking involves capturing a system as a 'whole through the interaction of its parts' (Ben-Zvi Assaraf & Orion, 2005) and understanding a system's stability as cause and effect loop related.

Systems thinking is not new to the field of education. In the mid-1960s the U.S. Department of Education contracted the School of Education at the University of Southern California to create a research report on how to apply systems thinking to instruction. Their findings were later developed into a book (Heinich, 1968).

Systems thinking approach is applied in different field of education, e.g. in geography (Cox, Steegen, and Elen 2018; Rempfler and Uphues 2012), sustainable development (Schuler et al. 2018), chemistry (Hrin et al. 2017), biology (Ben-Zvi Assaraf and Orion, 2005 and Orion and Basis, 2008), mathematics (English, 2006) and science education (Assaraf & Orion, 2010; Boersma, Waarlo, & Klaassen, 2011; Hogan, 2000; Penner, 2000; Lehrer and Schauble, 2005; Sommer & Lücken, 2010).

Forrester (2007) argues that developing a systems perspective takes less time when it begins with a young (elementary school) inquisitive, and open mind. Assaraf & Orion, 2010; Sommer & Lücken, 2010 emphasize the introduction of system thinking as early as possible like Forrester (2007). Sheehy, Wylie, Mcguinness, and Orchard (2000) pointed out that children can reach an appropriate level of sophistication thinking skills by adolescence. Boersma et al. (2011) recommend imparting system thinking in primary and secondary school education to provide students with basic cognitive structures such as causality, form function relation and part whole relation corresponding to systems concepts. Others argue that system thinking—as it is necessary to reconstruct complex systemic processes—implicates higher order thinking skills (Frank, 2000). These skills seem to be underdeveloped even at university-age. Jacobson and Wilensky (2006), for example, state that many university-age students also tend towards simple causal explanatory statements rather than towards the reconstruction of complex systemic processes. Sweeney & Sterman, (2000) studied with university age students.

The aim of this study is to investigate the effectiveness of the developed Systems Thinking course curriculum for MA students in the Learning Sciences Program on problem definition and analysis skills of MA students.

## METHODOLOGY

### *The models of research*

The single group experimental design with pre-post test without control group is applied in this research. The study group is not randomly selected.

### *Research sample*

The study was conducted in a university in Istanbul / Turkey in 2018-2019 summer semester. A total of 12 MA students in Learning Sciences were involved in the study. MA students were also actively teaching in various grade levels ranging from preschool to secondary school.

Details of the Systems Thinking course curriculum is given in Table 1.

### *Assessment tool*

In order to evaluate the effectiveness of the Systems Thinking course on MA students, two part, open-ended question was used:

> *Part 1*: Identify an ongoing problem that you think it is important. The problem can be at any level (personal, institutional, social, local, national, global). Write the problem in a few sentences:
> *Part 2:* Analyze the problem you have written with the information you have and write your solution suggestion if any.

MA students were asked to respond to the open-ended question before (pre-test) and after (post-test) the course. In the post-test phase, participants were allowed to review the problem description. Additionally they were asked to rewrite their analysis and solution suggestions in the light of the information they learned during the course.

An assessment tool, having 7 criteria, was developed to measure the effect of course instruction on problem definition of students.

Three of the criteria for assessment were based on scoring schemes of concept maps. Concept maps, like stock-flow and causal loop diagrams, are one of the many ways of visual representation of knowledge structure. They are used effectively for support and assessment of learning, organization and presentation of information (Canas, 2003). Anohina and Grundspenkis (2009) list 16 types of scoring schemes for concept maps and group these schemes into 3 approaches: Evaluation of components of a concept map, comparison with an expert and combination of both. We used evaluation of components method as the course was for beginner level and expected outcomes were not sophisticated models but simple models for adapting systems thinking approach to K-12 level. Concept map component evaluation is mostly based on criteria like number of propositions, hierarchy levels, depth of explanation, branching and cross links. (Strautmane, 2012) Three of the criteria, namely, depth of analysis, width of analysis and number of relations, were determined in analogy to criteria for scoring concept maps.

The other 4 criteria were determined by researchers as the effect to be measured had aspects specific to intervention. The very act of problem definition in terms of systems thinking has quantitative and qualitative dimensions, like jumping to a solution, solution as problem or quantifiability. On the other hand, the number of causal loops used (first step for endogenous behavior, the keystone of systems thinking) or utilization of st/sd tools were specific to systems thinking.

Analysis percentage is determined to be a criterion as all problem solving processes involve at least two interrelated stages: analysis (problem) and solution (solving). Allocation of resources for these stages is quite content dependent. Literature on basic skills of systems thinking places great emphasis on skills for analysis. (Waters Center for Systems Thinking; Richmond, 1990; Tu, 1999; Richmond, 2000; Assaraf & Orion, 2005; Sweeney & Sterman, 2000; Stave & Hopper, 2007; Hung, 2008; Hopper & Stave, 2008; Assaraf & Orion, 2010; Plate & Monroe, 2014; Dorani & others, 2015; Arnold & Wade, 2015; Schaffernicht & Groesser, 2016; Gilbert, Gross & Kreutz, 2019; Lee, Jones & Chesnutt, 2019). Among skills defined as systems thinking skills, about 90% are for analysis. So, analysis percentage in discourse seems to be a good indicator in measuring the effect of the systems thinking course.

The 7 criteria used in the analysis of problems are described below:

1. Problem Definition: Quality and quantity of the problem
    a. Quality: Is the problem really a problem or a solution in the form of a problem?
    b. Quantity: Is the problem defined as a variable that can increase or decrease? How will it be understood that the problem is solved?
2. Analysis Percentage: The ratio of the number of words for analysis to the total number of words in the given response

3. Depth of Analysis: The number of vertical cause-effect relations established in the given response (such as result, cause, cause, cause)

4. Width of Analysis: Horizontal cause-effect relations established in the given response (such as having multiple causes of the result)

5. Number of Relations: The number of relations in the entire analysis

6. Number of Causal Loops: The number of relations forming a loop pattern.

7. ST/SD Tools Used (posttest only): Which systems thinking tools were used? (Behavior Over Time, Stock-Flow Diagram, Causal Loop Diagram, and Inference Ladder)

***Implementation Steps of the Research***

1. The curriculum was designed by researchers working in three different disciplines in the field of education, medicine and industrial engineering. Details of the program are shown at Table 1.

Table 1. Curriculum of Systems Thinking Course for M.A. Program in Learning Sciences

| Lesson | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 | Day 7 | Day 8 | Day 9 | Day 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Welcome | HW1 evaluation | HW2 evaluation | HW3 evaluation | HW4 evaluation | HW5 evaluation | HW5 evaluation | HW7 evaluation | HW8 evaluation | HW9 evaluation |
| 1 | Identify, Analyze, Solution Pre-test | What a System? Simple, complicated, complex, static and dynamic systems. | Behavior Over Time Graph (Theory and Examples) | Causal Loop Diagrams (Theory and Examples) | Archetypes | | World Climate Game | Experience Sharing session | Story Deconstruction | Project Preperations |
| 2 | Introduction of Course Program<br>An Outlook of Systems Thinking | Habits of a Systems Thinker | | | | Dynamic Behavior | | | Experience Sharing Session | |
| 3 | | Iceber Visual - Theory | Stock-Flow Diagram (Theory and Examples) | Ladder of Inference (Theory and Examples) | Group Model Building | Simple Numeric Models | | | | Project Presentations |
| 4 | Systems Thinking Games | Iceber Visual - Examples | | | | | | | Identify, Analyze, Solution Post-test | |
| | | Evaluation | Evaluation | Evaluation | Evaluation | Evaluation | Evaluation | | | |
| | Reading 1 | Reading 2 | Reading 3 | Reading 4 | Reading 5 | Reading 6 | Reading 7 | Reading 8 | Reading 9 | Reading 10 |

2. Prior to the experimental study, problem analysis pre-test was applied.

3. Experimental research took in 2 weeks/10 days/42 hours.

4. On the 8$^{th}$ day of the course, analysis and solving post-test was applied.

5. The data received from the study group were evaluated by the researchers according to 7 criteria.

## RESULTS

Table 2 summarizes pre-test and post-test results for the assessment of the effect of systems thinking course. Details of the results according to each criterion are as follows.

Since 1 of 12 participants failed to attend the pre-test evaluation, in assessments where pre and post-tests are compared, 11 participants were taken into consideration. In assessments where only post-test results are rated, all 12 participants' data was used for the evaluation.

While 8 of 11 participants described a real dynamic problem in the pretest phase, 2 defined static problems which cannot be evaluated with the ST/SD approach. One of 12 participants reflected a solution rather than a problem. In the post-test phase, participants were allowed to review to and also change (if necessary) their problem description. At the post-test, all participants could correctly define their problem as a dynamic, real problem.

In terms of quantifiability of the problem, the pre-test and post-test results were significantly different. The rate of quantifiability increased from 0% to 66.7% following ST course (Figure 1).

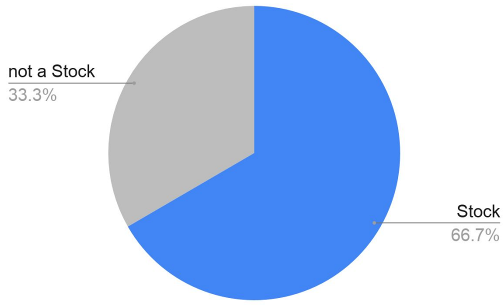


Figure 1. Problem Definition (post-test)

Analysis percentage was the second criterion evaluated. Graphs reflecting the change for each participant and also for the mean values of the study group is given in Figure 2. In 2 students, the analysis percentage was found to be decreased. In 1 of these 2 students the circumstance was caused by the misunderstanding of the instruction. Although participants were asked to re-write the whole problem and analysis in the post-test, this particular participant wrote only an addition to her initial work instead of writing a whole new analysis. In 9 students an improvement was observed in the analysis percentage. The difference between pre and post-tests was found to be significant ($p < 0.05$)

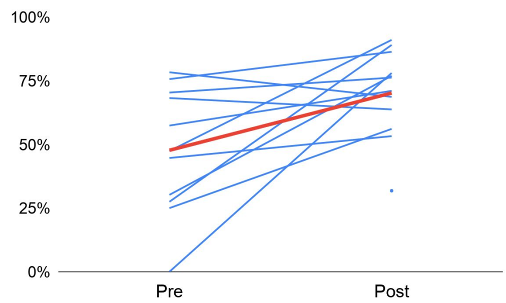


Figure 2. Analysis Percent

Thirdly the evaluation of the depth of the analysis was performed. In this criterion, the number of vertical cause-effect relations are considered. The analysis revealed significant improvements in 7 participants at various extent (1-5 vertical relation increase). As seen in Figure 3, analysis of 1 participant showed a decrease in relation number and in 3 participants depth of the analysis did not show any difference between two tests. Statistical evaluation done for depth of the analysis change showed significant differences ($p< 0.05$).

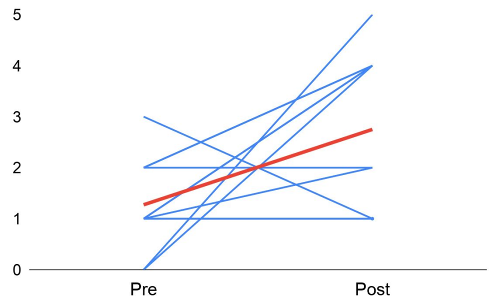


Figure 3. Depth of Analysis

The fourth criterion, the width of the analysis has also increased following ST course in 10 out of 11 participants (Figure 4). The number of increased causes ranged between 2-11. The most dramatic change was observed in student number 12; width of the analysis increased to 11 from 0. In 1 participant there was no change in this criterion. When all students are taken into consideration, the change was statistically significant ($p< 0.05$).

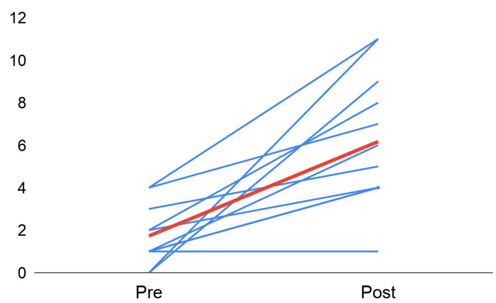


Figure 4. Width of Analysis

As the fifth criterion, the number of relations between variables in the entire analysis is examined. All but one participant showed an improvement in this context ($p < 0.05$) (Figure 5). The change in number of relations ranged between 3-19.

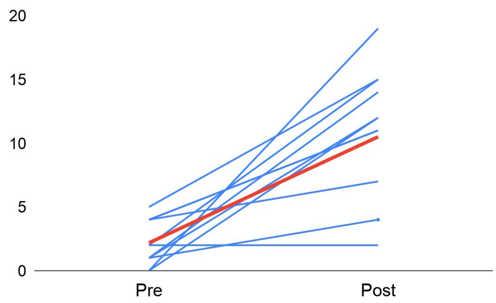


Figure 5. Number of Relations

The number of relation descriptions forming a loop pattern was investigated as the sixth criterion. In the pre-test, none of the participants depict a loop pattern in their description. However in the post-test evaluation 8 participants ended by describing at least 1 loop in their problems. Number of loops identified varied between 1-4 (Fig 6).

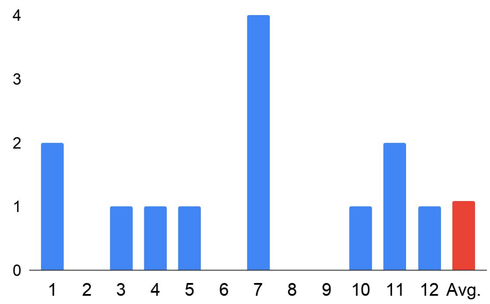


Figure 6. Number of Causal Loops (post-test)

The use of ST/SD tools that were taught during the course was also investigated in post-test evaluation. Although there was no specific instruction encouraging the use of ST/SD tools in the post-test, 9 participants preferred to use at least 1 tool in their work. The frequencies of ST tools used were as follows; stock flow diagrams (75%), causal loop diagrams (58%), ladder of inference (42%), behavior over time graph (17%) (Figure 7).

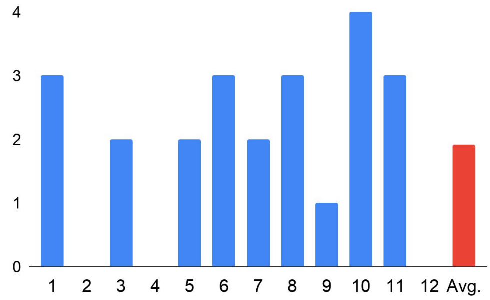


Figure 7. ST/SD Tools Used

The correlations between criteria were also investigated. Table 3 shows details of the Pearson correlation matrix for percentage, depth, width of analysis and number of relations of pre and post tests.

Table 2. Pre-test - post-test results for the assessment of effect of systems thinking course

| | Percentage of Analysis | | | Depth of Analysis | | | Width of Analysis | | | Number of Relations | | | Number of Causal Loops | | Problem Definition | | ST/SD Tools Used |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Student | Pre | Post | Diff. | Pre | Post | Diff. | Pre | Post | Diff. | Pre | Post | Diff. | Pre | Post | Pre | Post | Post |
| 1 | 30% | 77% | 155% | 1 | 2 | 100% | 2 | 8 | 300% | 2 | 15 | 650% | 0 | 2 | solution | quantifiable | 3 |
| 2 | 45% | 53% | 19% | 1 | 1 | 0% | 1 | 4 | 300% | 1 | 4 | 300% | 0 | 0 | not quantifiable | not quantifiable | 0 |
| 3 | 70% | 76% | 8% | 3 | 1 | -67% | 2 | 4 | 100% | 4 | 7 | 75% | 0 | 1 | not quantifiable | quantifiable | 2 |
| 4 | 78% | 69% | -12% | 2 | 2 | 0% | 1 | 1 | 0% | 2 | 2 | 0% | 0 | 1 | not quantifiable | not quantifiable | 0 |
| 5 | 57% | 71% | 24% | 2 | 4 | 100% | 3 | 5 | 67% | 4 | 11 | 175% | 0 | 1 | not quantifiable | quantifiable | 2 |
| 6 | 28% | 89% | 224% | 1 | 1 | 0% | 4 | 11 | 175% | 4 | 11 | 175% | 0 | 0 | not a systemic problem | quantifiable | 3 |
| 7 | 76% | 86% | 14% | 2 | 4 | 100% | 4 | 7 | 75% | 5 | 15 | 200% | 0 | 4 | not quantifiable | quantifiable | 2 |
| 8 | 0% | 78% | | 0 | 5 | | 0 | 9 | | 0 | 12 | | 0 | 0 | not a systemic problem | not quantifiable | 3 |
| 9 | | 32% | | | 1 | | | 4 | | | 4 | | | 0 | | quantifiable | 1 |
| 10 | 47% | 91% | 92% | 1 | 4 | 300% | 1 | 4 | 300% | 1 | 14 | 1300% | 0 | 1 | not quantifiable | quantifiable | 4 |
| 11 | 25% | 56% | 124% | 0 | 4 | | 0 | 11 | | 0 | 19 | | 0 | 2 | not quantifiable | quantifiable | 3 |
| 12 | 68% | 64% | -7% | 1 | 4 | 300% | 1 | 6 | 500% | 1 | 12 | 1100% | 0 | 1 | not quantifiable | not quantifiable | 0 |
| **Avg.** | **48%** | **70%** | | **1.27** | **2.75** | | **1.73** | **6.17** | | **2.18** | **10.50** | | **0.00** | **1.08** | **0.00** | **0.67** | **1.92** |
| **Effect** | | | **47%** | | | **116%** | | | **257%** | | | **381%** | | **1.08** | | **0.67** | **1.92** |
| **t-test** | | 0.0217 | | | 0.0251 | | | 0.0009 | | | 0.0003 | | | | | | |

*A paired, two-tailed t-Test is computed on student's pre and post test results*

| | |
|---|---|
| (green) | Progress |
| (blue) | No change |
| (red) | Regress |

Table 3 - Pearson correlation matrix for percentage, depth, width of analysis and number of relations of pre and post tests

| | Per. of Analysis (Pre) | Depth of Analysis (Pre) | Width of Analysis (Pre) | Num. of Relations (Pre) | Per. of Analysis (Post) | Depth of Analysis (Post) | Width of Analysis (Post) |
|---|---|---|---|---|---|---|---|
| Depth of Ana. (Pre) | 0.76 | | | | | | |
| Width of Ana. (Pre) | 0.11 | 0.53 | | | | | |
| Num. of Rela. (Pre) | 0.37 | 0.77 | 0.93 | | | | |
| Per. of Ana. (Post) | 0.06 | 0.20 | 0.55 | 0.48 | | | |
| Depth of Ana. (Post) | 0.14 | -0.42 | -0.29 | -0.33 | 0.31 | | |
| Width of Ana. (Post) | -0.72 | -0.63 | 0.11 | -0.10 | 0.24 | 0.28 | |
| Num. of Rel. (Post) | -0.48 | -0.49 | 0.03 | -0.13 | 0.43 | 0.65 | 0.74 |

## CONCLUSION

In the current study, the effect of a Systems Thinking course on the analysis skill of the MA students is investigated. The participants have learned the use of ST/SD tools including behavior over time graph, stock flow diagram, causal loop diagram, ladder of inference during the course of 42 hours. Data obtained from participants pre and post-test evaluations is analysed with an assessment tool having 7 criteria. These 7 criteria question the definition of a problem, the percentage of the analysis, the width and the depth of the analysis, number of relation, number of loops and ST/SD tools used. The assessment using 7 criteria showed that the majority of the 12 participants demonstrated statistically significant improvements in the analysis of a given problem. The participants were found to be able to transfer what they learned to the analysis of the problem they have chosen. Stock flow diagram was the most used tool in the analysis. It was followed by the causal loop diagram.

We can conclude that the use of ST/SD tools is effective in the improvement of analysis skills.

***Suggestions***

1. As a result of the research, an improvement in problem analysis skills was observed. After taking the system thinking course, it is noteworthy that there are positive changes in problem definition and analysis skills. This result should be validated using different measurement and evaluation tools.

2. The persistence of acquired skills during the course should be tested in further studies.

3. This research was focused on problem definition and analysis. Further studies may focus on assessment of proposed solutions by students generated before and after the course.

4. Correlations between criteria indicate that "Number of Relations" and "Depth/Width of Analysis" seem to be correlated in both pre and post tests. This result can be used to decrease number of criterion in assessment by omitting either of the criteria, namely; "Number of Relations" or "Depth/Width of Analysis"

## REFERENCES

Arnold, R. D., & Wade, J. P. (2015). A definition of systems thinking: A systems approach. Procedia Computer Science, 44(2015), 669-678.

Assaraf, O.B.-Z., & Orion, N. (2010). System thinking skills at the elementary school level. Journal of Research in Science Teaching, 47(5), 540–563.

Ben-Zvi Assaraf, O., & Orion, N. (2005). Development of system thinking skills in the context of Earth System education. Journal of Research in Science Teaching, 42, 518–560.

Boersma, K., Waarlo, A.J., & Klaassen, K. (2011). The feasibility of systems thinking in biology education. Journal of Biological Education, 45(4), 190–197.

Cabrera, D. A. (2006). Systems thinking (Doctoral dissertation). Retrieved from http://dspace.library.cornell.edu/bitstream/1813/2860/1/DerekCabreraDissertation.pdf

Cox, M., A. Steegen, and J. Elen. (2018). "Using Causal Diagrams to Foster Systems Thinking in Geography Education." International Journal of Designs for Learning 9: 34–48. doi:10.14434/ijdl.v9i1.22756.

Dorani, K., Mortazavi, A., Dehdarian, A., Mahmoudi, H., Khandan, M., & Mashayekhi, A. N. (2015). Developing Question Sets to Assess Systems Thinking

Skills. In Proceedings of the 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts, USA.

English, L.D. (2006). Introducing young children to complex systems through modeling. In: P. Grootenboer, R. Zevenbergen, & M. Chinnappan (Eds.), Identities, cultures, and learning spaces (pp. 195–202). Adelaide: Mathematics Education Research Group of Australasia.

Forrester, J.W. (2007). System dynamics—A personal view of the first fifty years. System Dynamics Review, 23, 345–358

Gilbert, L. A., Gross, D. S., & Kreutz, K. J. (2019). Developing undergraduate students' systems thinking skills with an InTeGrate module. Journal of Geoscience Education, 67(1), 34-49.

Hari, R., Himberg, T., Nummenmaa, L., Hamalainen, M., & Parkkonen, L. (2013). Synchrony of brains and bodies during implicit interpersonal interaction. Trends in Cognitive Sciences, 17, 105–106.doi:10.1016/j.tics.2013.01.003

Heinich, R. (1968). Application of systems thinking to instruction. Los Angeles,CA:EducationandTrainingConsultants.

Hogan, K. (2000). Exploring a process view of students' knowledge about the nature of science. Science Education, 84(1), 51–70.

Hopper, M., & Stave, K. A. (2008). Assessing the effectiveness of systems thinking interventions in the classroom. In the 26th International Conference of the System Dynamics Society.

Hrin, T. N., D. D. Milenković, M. D. Segedinac, and S. Horvat. 2017. "Systems Thinking in Chemistry Classroom: The Influence of Systemic Synthesis Questions on Its Development and Assessment." Thinking Skills and Creativity 23: 175–187. doi:10.1016/j.tsc.2017.01.003.

Hung, W. (2008). Enhancing systems‐thinking skills with modelling. British Journal of Educational Technology, 39(6), 1099-1120.

Lee, T. D., Jones, M. G., & Chesnutt, K. (2019). Teaching Systems Thinking in the Context of the Water Cycle. Research in Science Education, 49(1), 137-172.

Lehrer, R., & Schauble, L. (2005). Developing modeling and argument in elementary grades. In: T.A. Romberg, T.P. Carpenter, & F. Dremock (Eds.), Understanding mathematics and science matters (pp 29–53). Mahwah, NJ: Lawrence Erlbaum Associates.

Meadows, D. H. (2009). Thinking in systems : a primer. London ; Sterling, VA: Earthscan,

Orion, N., & Basis, T. (2008). Characterization of High School Students' System Thinking Skills in the Context of Earth Systems. Presented in the 2008 NARSTAnnual Meeting. March, 2008. Baltimore, U.S.A.

Penner, D.E. (2000). Explaining systems: Investigating middle school students' understanding of emergent phenomena. Journal of Research in Science Teaching, 37(8), 784–806.

PISA, (2019). Organisation for Economic, Co-operation and Development. PISA 2021 ICT Framework)

Plate, R., & Monroe, M. (2014). A structure for assessing systems thinking. The Creative Learning Exchange, 23(1), 1-12.

Rempfler, A., and R. Uphues. (2012). System Competence in Geography Education. Development of Competence Models, Diagnosing Pupils‘ Achievement. European Journal of Geography 3:6–22. http://www.eurogeography journal.eu/articles/EJG_Vol3_No1.pdf#page=7

Richmond, B. (1990). Systems thinking: a critical set of critical thinking skills for the 90s and beyond. System dynamics, 90, 935.

Richmond, B. (2000). The thinking in systems thinking - Honing your skills. Pegasus Communications.

Schaffernicht, M. F., & Groesser, S. N. (2016). A competence development framework for learning and teaching system dynamics. System Dynamics Review, 32(1), 52-81.

Schuler, S., D. Fanta, F. Rosenkränzer, and W. Riess. (2018). Systems Thinking within the Scope of Education for Sustainable Development (Esd). A Heuristic Competence Model as a Basis for (Science) Teacher Education. Journal of Geography in Higher Education 42: 192–204. doi:10.1080/03098265.2017.1339264.

Senge, P. (2006). The fifth discipline: The art and practice of the learning organization (2nd ed.). New York, NY: Currency, Doubleday.

Sheehy, N. P., Wylie, J. W., Mcguinness, C., & Orchard, G.(2000). How children solve environmental problems: Using computer simulations to investigate system thinking. Environmental Education Research, 6, 109–126.

Sommer, C., & Lüken, M. (2010). System competence are elementary students able to deal with a biological system? NorDiNa, 6(2), 125–143.

Stave, K., & Hopper, M. (2007). What constitutes systems thinking? A proposed taxonomy. In the 25th International Conference of the System Dynamics Society.

Sweeney, L. B., & Sterman, J. D. (2000). Bathtub dynamics: initial results of a systems thinking inventory. System Dynamics Review, 16(4), 249–286. doi:10.1002/sdr.198

Tu, C. K. (1999) The Meaning for 3-6 Grade Students Learning Systems Thinking.

Waters Center for Systems Thinking. (n.d.) Habits of a Systems Thinker. Retrieved from https://waterscenterst.org/systems-thinking-tools-and-strategies/habits-of-a-systems-thinker/