Concept Mapping: Renewing Learning and Thinking
Proc. of the Eighth Int. Conference on Concept Mapping
Medellín, Colombia 2018

INTERDISCIPLINARITY OF CONCEPT MAPS

Priit Reiska, Aet Möllits
Tallinn University, Estonia
Email: priit@tlu.ee , aet.m@tlu.ee

Abstract. In modern life an increasing percentage of jobs require employees to think critically and creatively, and to be make innovative but knowledge-based decisions. This requires the ability to connect different domain areas, to understand interdisciplinary connections. One of the main difficulties in the attempt to improve interdisciplinary knowledge in schools is a lack of effective assessment and evaluation tools. How to facilitate students' demonstration of their interdisciplinary understanding by integrating multiple source of knowledge from two or more disciplines is a constant challenge for educators. The primary focus of this study is to explore the viability of assessing students' interdisciplinary understanding through the construction of concept maps. In this study we compare two methods of measuring the interdisciplinarity of concept maps. The results showed that the two methods (experts' ratings and Interdisciplinary Quality Index) correlate very highly.

Keywords: concept mapping, interdisciplinary learning, interdisciplinarity, assessment

1 Introduction

Modern jobs require employees to think critically and creatively, and to be able to make innovative decisions that often require analyzing information and data from different disciplines. Therefore, a primary focus of the 21st[st] century science classroom should be to develop students with profound knowledge understanding (You, et al., 2018; Rimini & Spiezia, 2016; Ananiadou & Claro, 2009). This can be achieved by leading students to higher order thinking skills that highlight problem solving, decision-making and question-asking capabilities (Cañas et.al, 2017, Ghani et. al, 2017). In addition to that researchers emphasize the advantages of knowledge domain, which connects different disciplines. In other words, subject content should be taught with the aim of developing student interdisciplinary knowledge (Begg & Vaughan, 2011; Barisonzi & Thorn, 2003, Mansilla & Duraising, 2007). It doesn't mean that science teachers need to be experts in all disciplines, but they have to be able to give different meanings of concepts so that students can use them together or develop new knowledge (Mansilla & Duraising, 2007). Thus, interdisciplinary education faces the needs of the modern world, where professional parameters are not defined and there is no available toolbox with ideas or methods how to solve unknown problems. Therefore, creating an interdisciplinary learning situation is one way to teach subject matter in interdisciplinary way (Klaassen, 2018).

One difficulty in pedagogical approaches to improve interdisciplinary knowledge is a lack of effective tools to assess and evaluate interdisciplinarity (Repko, 2007, Ghani et. al, 2017). It is challenging for teachers to understand how to enable students to demonstrate their interdisciplinary understanding by integrating multiple source of knowledge from two or more disciplines. The primary focus of this study is to explore different methods of assessing students' interdisciplinary understanding by constructing concept maps.

The research questions of this study are:

1. What methods are there to measure the level of interdisciplinarity of concept maps?
2. Do the different methods lead to the different results?

In this paper interdisciplinarity is viewed as a major element in concept mapping. It is a process of integrating two or more concept from different discipline by bringing a learner to create new meaning, perspective or approach, that enhance formation of interdisciplinary knowledge (Novak, 2010, Reiska et al., 2018).

2 Interdisciplinary Understanding in Teaching and Learning Science

There is no easy answer to the question "How do we learn?" and not everyone learns in the same way. Students bring different backgrounds and experiences with them to learning. The suitable and sustainable knowledge structures are the base of interdisciplinary learning (Schaal, et al., 2010). Learning occurs when there is change in learners' knowledge structures. Meaningful learning takes place when learners relate new knowledge to that what they already know" (Novak & Gowin 1984). Learning the different sciences involves understanding complex topics that require subject-integration approaches in order to reach a long-term and conceptual understanding. The conceptual knowledge involves interconnection of basic science concept from different disciplines, for example from chemistry and biology. Therefore, interdisciplinary teaching and learning in sciences may lead learners to complex thinking and crosslinking abilities (Schaal, et al., 2010).

Interdisciplinary learning usually aims to identify solutions that foster breaking down the disciplinary boundaries and integrate knowledge or skills to see larger context (Mansilla & Duraisingh, 2007). Davis (1995, p. 39) argued that interdisciplinarity requires for learners “considerably more help than they usually get” to understand and use information because “problems come in ‘layers’ that need to be separated and analyzed, but solutions usually need to be comprehensive, addressing the problem as a system, not as pieces”. He continues “in interdisciplinary courses, where the focus is on developing critical thinking skills, employing multiple perspectives, and relating information to some larger conceptual framework than the concerns of a single discipline”.

In learning natural sciences, we often face the fact that the learning goals and topics fall each in different subject fields. One important aspect in learning sciences is to help students get in-depth conceptual understanding, and it can be achieved through interdisciplinary studies (Schaal, et al., 2010, Shen, et al., 2014, You, et al., 2018). The common aspect among widely used definitions of interdisciplinarity is the concept “integration”, which means overlapping boundaries by integrating methods, knowledge, skills, theories and perspectives for creating something new (Meneken & Keestra 2016, Repko, 2012, Mansilla, 2006, Schneider, 2004, Barisonzi & Thorn, 2003, Newell, 1997). Mansilla (2006) and Repko (2012) discuss that interdisciplinarity is a mode of thinking that brings together individuals or groups to pursuit bodies of knowledge that integrate two or more disciplines with the goal to understand multi-faceted issues. Mansilla (2006) brings out three important features about interdisciplinary knowledge: (1) purposeful, that advance understanding (2) disciplined, that embody not only disciplinary finding, but also the modes of thinking of the disciplines involved and (3) integrative, that add value of intertwine disciplinary perspectives to leverage the understanding. The purpose of interdisciplinary teaching and learning is to develop students’ cognitive and intellectual abilities to think, perceive, analyze, create and solve problems (Repko & Szostak, 2016). As stated above, interdisciplinary studies engage students to solve the real-world complexities, which means that problem-based approach is often used (Meneken & Keestra, 2016). The main characteristics of interdisciplinary learning are listed by Klaassen (2018) and ASHE (2009).

Interdisciplinary learning approach may improve traditional learning skills like writing competencies, communication, scientific reasoning and computer literacy (Field, et al., 2002). However, several authors believe that interdisciplinary learning provides also enhancement of cognitive skills. (Ivanitskaya et al., 2002; Field, et al., 2002). There is no good platform or method to assess these desired or predicted outcomes of interdisciplinary learning. There are indeed evidences and best practices from the literature about positive interdisciplinary outcomes, but this is still a challenge to design empirically improved ways to evaluate such claims (You, et al., 2018). In the next paragraph we discuss the assessment challenges that are specifically related to interdisciplinary learning outcomes.

3 Assessment of Students’ Interdisciplinary Understanding in Science

As discussed above there is now single definition of interdisciplinarity, no consensus of expected learning outcomes or widespread level of integration in interdisciplinary studies (Field, et al., 2002). One of the main challenges of interdisciplinarity is how to assess learners’ ability to integrate knowledge from two or more disciplines (Reiska, et al., 2018, You, et al., 2018). For assessing interdisciplinary understanding, You et al. (2018, p. 380-381) emphasize the role of disciplinary knowledge “In mapping students’ understanding of an interdisciplinary topic, it is important to distinguish whether an inability to solve a problem is due to the lack of the disciplinary building blocks, or to the inability to apply them together to solve interdisciplinary problems.” Additionally, many researchers have asked how students will demonstrate not only a final product or solution, but also various parts of interdisciplinary knowledge (Mansilla & Duraisingh, 2007, Mueller, et al., 2014). According to the ASHE Higher Education Report (2009), there are three important components to consider in interdisciplinary assessment: (a) knowledge of key concepts from the contributing disciplines; (b) knowledge of the connections among these key concepts, or the skill of integration; (c) the ability to actively apply these concepts to an interdisciplinary problem or topic.

Field, et al. (2002) divides interdisciplinary assessment into indirect and direct methods. The indirect techniques observe the quality and quantity of learners’ study outcomes. For example, surveys, interviews, and written questionnaires are used to ask learners to reflect what they have experienced or achieved, but not directly what they have learned. Direct methods, on the other hand, assess whether or not the learners have achieved learning outcomes, for example in the form of examinations (true or false, multiple-choice standardized tests etc.). In addition demonstration by performance is also a direct, where students create their own unique response and learning is revealed through the students' performance on real tasks, e.g. projects, presentations, simulations, portfolios. However, these tasks are not exactly the assessment techniques, they are rather measurement activities. Field, et al., (2002, p. 265) added in their classification that "…we believe that effective assessment will require both indirect and direct measures of learning, with an increasing emphasis on direct techniques."

There are a number national and international assessment items designed for assessing interdisciplinary understanding. For example:

1) PISA's (The Program for International Student Assessment) aim is to assess fifteen-year-old students' knowledge in science and how they can apply this in real-life situations where the elements of knowing are interdisciplinary. According to OECD (2016)'s report, the capability in science requires learners three forms of knowledge: (1) content knowledge, (2) knowledge of methodological procedures used in science and (3) knowledge of reasons and ideas used by scientists to explain their claims. The assessed understanding was selected from the fields of physics, chemistry, biology and Earth and space in science. Nevertheless, the response types of the items were simple multiple-choice (e.g. single response from four options, an answer that is a selectable element within a graphic or text) complex multiple choice (e-g. more than one response from a list, selecting choices from a drop-down menu to fill multiple blanks "drag-and-drop" responses) and constructed response (written or drawn responses). In addition to that, most of the items focused on one or two discipline, for example "bird migration" item assessed knowledge from biology, "meteoroids and craters" needed knowledge from Earth and space and physics and "running in a hot water" knowledge from biology and procedural skills.
2) TIMSS (The Trends in International Mathematics and Science Study) science assessment has two dimensions: (1) content knowledge that is specified in the subject matter and (2) cognitive understanding that is specified to assess thinking processes. TIMSS assess at grade 4 students' knowledge in the fields of life science, physical science and Earth science and at grade 8 in the fields of biology, chemistry, physics, and Earth science. The item in TIMSS were primarily in forms of multiple-choice and constructed-response (Mullis, et al., 2013). No questions in TIMSS were found that required for students' interdisciplinary understanding (Liu, et al., 2008, You, et al., 2018).
3) NAEP (The National Assessment of Educational Progress) is the largest nationally representative assessment in the United States that is intended to measure students' ability to infer relationships using scientific knowledge, link scientific ideas with social problems and integrate these ideas to make conclusions. NAEP items require students to interpret data from tables and draw conclusion from experimental results. The outcomes of these items are measuring the recall of isolated facts and logical reasoning rather than interdisciplinary understanding (Liu, et al., 2008, You, et al., 2018).

The effective assessment methods of interdisciplinary understanding differ from a discipline-based approach. For example, Mansilla & Duraisingh (2007) argue that the interdisciplinary assessment depends on: tasks - that should invite students to built and demonstrate mastery of "whole" performances; standards and criteria - that should be shared by faculty and students and evaluation approach - that should be ongoing and should provide feedback to support learning. To conclude, when assessing the complex interdisciplinary knowledge, the close-ended methods and multiple-choice tests do not adequately measure the outcomes we expect. Even the national and international tests do not outstand their assessment approaches. Therefore, every empirical endeavor about assessing interdisciplinarity is needed.

4 Assessing Interdisciplinarity with Concept Maps

Many authors have inferred that concept mapping can facilitate higher-order thinking skills in different learning domains (Cañas et al., 2017, Ghani, et al., 2017). However, "the process of constructing a concept map is arguably more important than the final map, particularly if we are interested in learning and exercising higher-order thinking skills" (Cañas et al., 2017, p. 352).

4.1 Theory of Concept Maps

Concept mapping was developed by Joseph Novak and his research team in the 1970's (Novak & Cañas, 2006) and is based on Ausubel's (1968) meaningful learning theory. It is a visual learning tool that consists of concepts (usually surrounded by circles or boxes) and arrows that show the relationship between two concepts. Propositions in concept maps consist of two or more concepts that are connected with linking words, and are an important component of concept maps as they convey a learners' understanding of one concept (Novak & Gowin, 1984; Novak, 2010). The creation of an accurate proposition between concepts can show the higher level of understanding that can be achieved by the learner. Thus, the construction of concept maps contributes to the learning process and the students' understanding, and to how the concept is permanently placed in their minds (Novak, 1990).

Concept maps have three important characteristics (Cañas et al., 2012): 1) hierarchical structure – represents the particular domain of knowledge and usually is depicted as more general concept at the top of the map and the more specific ones at the bottom. 2) cross-links - show relations between concepts in different subdomain areas on the map. Cross-links are an important feature as they can represent a student's ability to make creative leaps from one part of the map to the other. 3) content – the concept map's content, together with its structure, should respond to a previously given focus question. Although concept maps are widely used in education to promote better understanding in teaching and learning, there is still a big problem, that students cannot receive timely feedback from teachers, which influence the students' learning achievements. (Po-Han, et al., 2012, Ingeç, 2009, BouJaoude, et al., 2003).

4.2 Concept Maps for Assessment

In using concept mapping as an assessment tool, two factors need to be considered: the type of concept mapping task and the type of concept mapping scoring method. Ruiz-Primo (2004) put forward a directness of concept mapping tasks, where directness is related to the amount of information that is provided with concept mapping task that varies from high to low. High-directed tasks provide students with concept or linking words, but do not restrict how maps may be drawn. A low-directed mapping technique gives freedom to decide which concepts and linking words can be used and how many and in which way (Ruiz-Primo, 2004).

There are several measures for analyzing concept maps. By using a quantitative assessment method, a range of characteristics can be assessed (Croasdell et al., 2003) e.g. number of concepts; number of propositions; number of cross-links, which describe the size of concept maps. The structure of the map can also be described by centrality of concepts, number of cross-links, density of concepts, inter and intra cluster proposition count and branch point count. The main problem with such quantitative assessment methods is that they might make assumptions such as that bigger maps are better. Actually, experts often produce smaller concept maps than novices do, because the focus is placed on the most important concepts, which are then connected by highly informative statements (Kinchin 2011; Cañas, Reiska & Novak, 2016). Thus, the quality of a concept map is shown by which concepts, linking word and propositions are in the map. Typical quality indicators are the number of correct propositions, average rating of propositions and relevance of concepts. Commonly, experts are used to assess the accuracy of propositions (Reiska, et al., 2008).

4.3 The Use of Concept Maps to Assess Interdisciplinarity

There are numerous studies on the successful use of concept maps as an assessment or reflection tool (Tan, et al., 2017; Popova-Gonci et al., 2012; Cañas, et al., 2012; Po Han, et al., 2012; Lopez et al., 2011; Ruiz-Primo, 2004; Stoddart, et al., 2000;). On the other hand, there is not much literature on using concept maps to evaluate learners' interdisciplinary knowledge. Borrego et al. (2009, p. 21) brings out the efficiency of concept maps by evaluating students' ability to make connections across different disciplines: "…this representational complexity makes them ideal vehicles to evaluate one of the hallmarks of successful interdisciplinary collaboration: knowledge integration". Borrego et al. (2009)'s study included pre-and post concept maps with 10 students. Different faculty members assessed the interdisciplinarity of these 20 concept maps and used a rubric that considered three map characteristics: comprehensiveness, organization and correctness, and scored maps with points 1 to 3. In the study the time-consuming manual process of assessing the maps raises questions about the efficiency of such assessment procedure.

Reiska et al. (2018) developed the Interdisciplinary Quality Index (IQI), a measure of the interdisciplinarity of a concept map, and which can be calculated by a computer and can thus be easily applied to a large number of concept maps. Concept maps with a high IQI score of tend to be characterized by a well-structured, correct subject matter and interdisciplinary propositions. In their 2018 study, the decision of whether a proposition is interdisciplinary was made by nature of the two concepts: a) if the concepts in the proposition were from the same subject matter they defined the proposition as a disciplinary proposition; b) if the concepts were from different subject matter they defined it as an interdisciplinary proposition.

5 Research Design, Methods and Data Collection

As stated earlier, the research questions of this study are:

1. What methods are there to measure the level of interdisciplinarity of concept maps?
2. Do the different methods lead to the different results?

To answer these questions, we compare different methods for assessing interdisciplinarity of concept maps based on seven sample maps. These seven sample maps were taken from a longitudinal study where high school students' interdisciplinary understanding was evaluated in biology via the question "Milk - is it always healthy? (metabolism, redox reaction, energy transformation etc.).

We chose these seven maps so that they were of different size, structure and content. The general characteristics of these seven concept maps are displayed in Table 1.

Map no.	Concept Count	Proposition Count	Avg. Propositions Per Concept
Cmap1	23	22	0,73
Cmap2	29	29	0,97
Cmap3	29	34	1,13
Cmap4	27	27	1,00
Cmap5	30	36	1,20
Cmap6	28	35	1,17
Cmap7	18	17	0,57

Table 1. Main characteristics of seven concept maps

5.1 Expert Rating

We asked 8 experts to rate from 1 to 5 the seven concept maps, answering different the following questions about the maps' interdisciplinarity:

Q1: How many concepts from different subject areas (biology, chemistry, physics, geography, everyday life) are used in this concept map?
Q2: How many connections are between concepts from different subjects?
Q3: How interdisciplinary is the concept map?
Q4: How good is the focus question answered?
Q5: How do you evaluate the concept map generally (correctness, size, structure)?

5.2 Interdisciplinary Quality Index (Reiska et al., 2018)

We calculated the value of the Interdisciplinary Quality Index (IQI) (Reiska et al., 2018) for all seven sample maps. The IQI consists of three different sub measures of quality and quantity and the maximum IQI value is 3. The sub measures are related to the number of correct interdisciplinary propositions, number of branch points and number of 2-scored propositions (high-quality and correct propositions, Table 2).

Map no.	Correct ID propositions	Branch Point Count	2-scored propositions
Cmap1	13	4	6
Cmap2	13	5	10
Cmap3	9	12	6
Cmap4	14	6	13
Cmap	18	6	16
Cmap6	18	11	13
Cmap7	9	3	3

Table 2. Values of measures for IQI calculation

6 Results and Discussion

6.1 Results of Expert Rating

Table 3 shows the average values of the experts' ratings. We also calculated averages for all questions. The experts' ratings show Cmap number 5 (see appendix) has the highest scores for every question. Four Cmaps are in average scores almost equal good: 2, 3, 4 and 6. Among these, if we look only at the interdisciplinary connections, then Cmap number 6 has higher ratings than the other three Cmaps (2, 3 and 4). Cmap number 7 has the lowest ratings.

Map no.	Q1	Q2	Q3	Q4	Q5	Avg.
Cmap1	3,3	2,8	2,8	2,5	2,4	2,7
Cmap2	3,9	3,3	3,3	3,0	3,1	3,3
Cmap3	4,0	3,1	3,5	3,1	2,9	3,3
Cmap4	4,0	3,3	3,6	2,9	2,5	3,3
Cmap5	4,5	4,1	4,1	4,5	4,1	4,3
Cmap6	3,9	3,8	3,4	2,6	2,5	3,2
Cmap7	2,1	2,3	2,5	2,1	1,8	2,2

Table 3. Average values of experts' ratings

6.2 Results of Interdisciplinary Quality Index

Table 4 shows the IQI for each of the seven concept maps.

Map No	Cmap1	Cmap2	Cmap3	Cmap4	Cmap5	Cmap6	Cmap7
IQI	1,4	1,8	1,9	2,1	2,5	2,7	0,9

Table 4. Interdisciplinary Quality Index

Cmap 6 has highest IQI. High values of IQI resulted also for Cmaps number 5 and 4. Cmap number 7 has the lowest IQI value.

6.3 Correlation between two the Methods

We calculated the correlations between the experts' ratings and the IQI. The expert ratings related to the map interdisciplinarity correlated significantly and very high with IQI. The highest correlation was between Q2 (interdisciplinary links) and IQI: 0,95. The lowest correlation was between question Q4 (focus question) and IQI:

0,59. Among the different components of IQI the branch point count correlated least with expert ratings (correlations: 0,17 – 0,52).

Cmap number 6 has the highest IQI value, while experts rated Cmap number 5 the highest. If we are look at the different components of the IQI, we can see that Cmap number 6 has many more branch points than the Cmap number 5, which leads to a higher IQI. It seems that experts didn't take the structure of the map into account as strongly as the IQI does. Still, the correlation analysis shows that IQI correlates very highly with the expert's ratings. The figure 1 shows the values of IQI and some expert ratings.

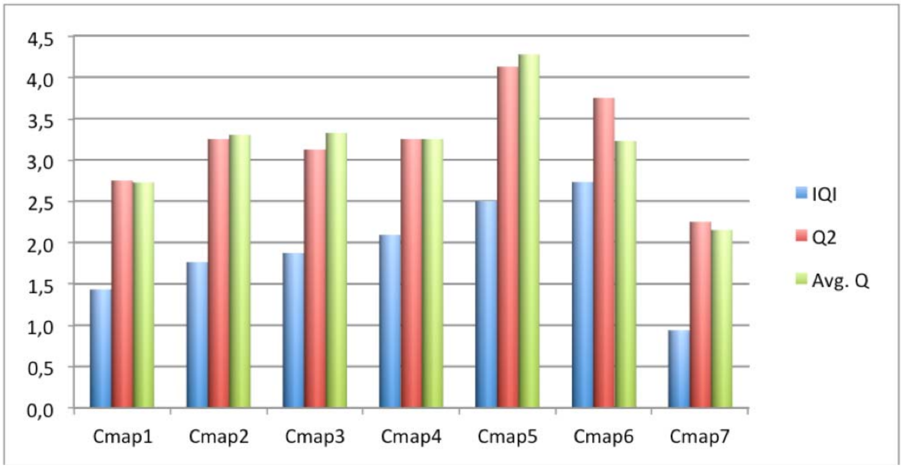

Figure 1. IQI and experts' ratings.

7 Conclusions

The study had as an aim to measure interdisciplinarity of concept maps with different methods and to compare the methods. The results showed that experts' ratings of the concept maps' interdisciplinarity correlated very highly with the Interdisciplinary Quality Index. Even if the overall correlation was very high, there are still some differences between IQI and expert ratings. It seems that the IQI takes the structure of the map (number of branch points) more into account than the experts do. The reason for that might be, that the experts were experts in subject, not in concept mapping.

The correctness of concept maps seems to have very high influence on both the experts' ratings and IQI (see table 2 and table 3, Q2). This is also understandable, because it is impossible to have high quality and interdisciplinary map without having high number of correct propositions.

This study used only seven maps and 8 experts to rate the maps. Still, the results are promising, and suggest we should carry out the similar study with more maps and more experts to verify the results.

References

Ananiadou, K., & Claro, M. (2009). *21st Century Skills and Competences for New Millennium Learners in OECD Countrie*s (OECD Education Working Papers, No. 41). OECD Publishing.

ASHE Higher Education Report. (2009). *Defining Interdisciplinarity*. 35(2), 11-30.

Ausubel, D. P. (1968). *Educational Psychology*: A Cognitive View. Holt, Rinehart and Winston, Inc., New York. pp. 45-46; 107-110; 509-514.

Barisonzi, J., & Thorn, M. (2003). Teaching Revolution: Issues in Interdisciplinary Education. *College Teaching*, 51(1), 5-8.

Begg, M. D., & Vaughan, R. D. (2011). Are Biostatistics Students Prepared to Succeed in the Era of Interdisciplinary Science? (And How Will We Know?). *The American Statistician*, 65(2), 71-79.

Borrego, M., Newswander, C. B., McNair, L. D., McGinnis, S., & Paretti, M. C. (2009). Using Concept Maps to Assess Interdisciplinary Integration of Green Engineering Knowledge. *Advances In Engineering Education*, 1(3), 1-26.

BouJaoude, S., & Attieh, M. (2003). The Effect of Using Concept Maps as Study Tools on Achievement in Chemistry. *Eurasia Journal of Mathematics, Science & Technology Education*, *4*(3).

Cañas A. J., Novak J. D. & Reiska P., (2012), Freedom vs. Restriction of Content and Structure during Concept Mapping – Possibilities and Limitations for Construction and Assessment, In A. J. Cañas, J. D Novak, J. Vanhear (Eds). *Concept Maps: Theory, Methodology, Technology. Proc. of the Fifth Int. Conference on Concept Mapping*, 2(1), 247–257. Valetta: University of Malta.

Cañas, A. J., Reiska, P., & Novak, J. D. (2016). Is My Concept Map Large Enough? In A. J. Cañas, P. Reiska, & J. D. Novak (Eds.), *Innovating with Concept Mapping. Proceedings of the Seventh International Conference on Concept Mapping* (Vol. 1). Berlin: Springer.

Cañas, A. J., Reiska, P., & Möllits, A. (2017). Developing Higher-Order Thinking Skills with Concept Mapping: A Case of Pedagogic Frailty. *Knowledge Management & E-Learning*, 9(3), 348–365.

Croasdell, D.T., Freeman L.A., Urbaczewski A. (2003). Concept Maps for Teaching and Assessment. *Communications of the Association for Information Systems*. 12, 396-405.

Davis, J. R. (1995). *Interdisciplinary Courses and Team Teaching: New Arrangements for Learning*. Phoenix, AZ: American Council on Education, Oryx Press.

Dewey, J. (1933). *How We Think: A Restatement of the Relation of Reflective Thinking to the Educative Process*. Boston: D.C. Heath and Company.

Field, M., and Stowe, D. (2002). Transforming Interdisciplinary Learning through Assessment. In C. Haynes (Ed.), *Innovations in Interdisciplinary Teaching* (pp. 256–274). Westport, CT: American Council on Education Oryx Press.

Ghani I.B.A, Ibrahim N. H, Yahaya S.A, Surif J (2017) Enhancing Sudents' HOTS in Laboratory Educational Activity by Using Concept Maps as an Alternative Assessment Tool. *Chem Educ Res Pract* 18:849–874

Haynes, C. (2002) 'Laying a Foundation for Interdisciplinary Teaching' In Haynes, C. (Ed) *Innovations in Interdisciplinary Teaching American Council on Education*, Oryx Press: West port. xi – xxii.

Ingec, S. K. (2009). Analysing Concept Maps as an Assessment Tool in Teaching Physics and Comparison with the Achievement Tests. *International Journal of Science Education*, 31(14), 1897-1915.

Ivanitskaya, L., Clark, D., Montgomery, G., and Primeau, R. (2002). Interdisciplinary Learning: Process and Outcomes, *Innovative Higher Education*, V. 27, No. 2, pp 95-111.

Kinchin, I.M. 2011. Visualising Knowledge Structures in Biology: Discipline, Curriculum and Student Understanding. *Journal of Biological Education*, 45-4, 183-189.

Klaassen, R. G. (2018). Interdisciplinary Education: ACase Study. *European Journal of Engineering Education*.

Lattuca, L., Voigt, L., & Fath, K. (2004). Does Interdisciplinarity Promote Learning? Theoretical Support and Researchable questions. *Review of Higher Education*, 28(1), 23–48.

Liu, O. L., Lee, H. S., Hofstetter, C., & Linn, M. C. (2008). Assessing Knowledge Integration in Science: Construct, Measures, and Evidence. *Educational Assessment*, 13(1), 33–55.

Lopez E., Kim J., Nandagopal K., Cardin N., Shavelson R. J. and Penn J. H., (2011), Validating the Use of Concept-Mapping as a Diagnostic Assessment Tool in Organic Chemistry: Implications for Teaching, *Chem. Educ. Res. Pract.*, 12(2), 133–141.

Mansilla, V. B., & Duraisingh, E.D. (2007). Targeted Assessment of Students' Interdisciplinary Work: An Empirically Grounded Framework Proposed. *The Journal of Higher Education*, 7 (2), 215-237.

Mansilla, V. B. (2006). Interdisciplinary Work at the Frontier: An Empirical Examination of Expert Interdisciplinary Epistemologies. *Issues in Integrative Studies* 24: 1–31.

Mueller, A., Juris, S. J., Willermet, C., Drake, E., Upadhaya, S., & Chhetri, P. (2014). Assessing Interdisciplinary Learning and Student Activism in a Water Issues Course. *Journal of The Scholarship Of Teaching And Learning*, 14(2), 111-132.

Mullis, I.V.S. & Martin, M.O. (Eds.) (2013). TIMSS 2015 Assessment Frameworks. Retrieved from Boston College, TIMSS & PIRLS International Study Center website: http://timssandpirls.bc.edu/timss2015/frameworks.html

Newell W.H. 2001. A Theory of Interdisciplinary Studies. *Issues in Integrative Studies* 19: 1–25.

Newmann, F. M. (1988). Higher Order Thinking in the High School Curriculum. *NASSP Bulletin*, 72(508), 58–64.

Novak J. D., (2010), Learning, Creating, and Using Knowledge: Concept Maps as Facilitative Tools in Schools and Corporations, *J. E-Learn. Knowl. Soc*., 6, 21–30.

Novak, J. D., & Cañas, A. J. (2006). The Origins of the Concept Mapping Tool and the Continuing Evolution of the Tool. *Information Visualization*, 5(3), 175-184.

Novak, J. D., & Gowin, D. B. (1984). *Learning How to Learn*. New York, NY: Cambridge University Press.

OECD. (2016). PISA 2015 results (Volume I): Excellence and Equity in Education. OECD Publishing, Paris. doi: http://dx.doi.org/10.1787/9789264266490-en

Po-Han, W., Gwo-Jen, H., Milrad, M., Hui-Ru, K., & Yueh-Min, H. (2012). An Innovative Concept Map Approach for Improving Students' Learning Performance with an Instant Feedback Mechanism. *British Journal of Educational Technology*, 43(2), 217-232.

Popova-Gonci, V., & Lamb, M. C. (2012). Assessment of Integrated Learning: Suggested Application of Concept Mapping to Prior Learning Assessment Practices. *Journal of Continuing Higher Education*, 60(3), 186-191.

Reiska, P., Cañas, A. J., Novak, J. D., Miller, N. L. 2008. Concept Mapping as a Tool for Meaningful Learning and Assessment. In: *The Need for a Paradigm Shift in Science Education for Post-Soviet Societies* (Holbrook, J., Rannikmäe, M., Reiska, P., Ilsley P., Lang, P. eds) Germany.

Reiska, P., Soika, K., & Cañas, A. J. (2018). Using Concept Mapping to Measure Changes in Interdisciplinary Learning during High School. *Knowledge Management & E-Learning*, 10(1), 1–24.

Repko, A. (2007). Integrating Interdisciplinarity: How the Theories of Common Ground and Cognitive Interdisciplinarity Are Informing the Debate on Interdisciplinary Integration. *Issues in Integrative Studies* 3 (25): 1–31.

Rimini, M., & Spiezia, V. (2016). Skills for a Digital World: Background Report, 2016 Ministerial Meeting on the Digital Economy. Paris: OECD.

Ruiz-Primo, M. A. (2004). Examining Concept Maps as an Assessment Tool. In *Concept Maps: Theory, Methodology, Technology, Proceedings of the 1st International Conference on Concept Mapping*, Vol. 1, Cañas, A. J, Novak, J. D., González, F. M., (Eds). Universidad Pública de Navarra, Spain, 555-563.

Schaal, S., Bogner, F. X., & Girwidz, R. (2010). Concept Mapping Assessment of Media Assisted Learning in Interdisciplinary Science Education. *Research in Science Education*, 40(3), 339–352.

Shen, J., Liu, O. L., & Sung, S. (2014). Designing Interdisciplinary Assessments in Sciences for College Students: An Example on Osmosis. *International Journal of Science Education*, 36(11), 1773–1793.

Stoddart, T., Abrams, R., Gasper, E., & Canaday, D. (2000). Concept Maps as Assessment in Science Inquiry Learning - a Report of Methodology. *International Journal of Science Education*, 22(12), 1221-1246.

Tan, S., Erdimez, O., & Zimmerman, R. (2017). Concept Mapping as a Tool to Develop and Measure Students' Understanding in Science. *Acta Didactica Napocensia*, 10(2), 109-122.

You H. S, Marshall J. A, Delgado C. (2018). Assessing Students’ Disciplinary and Interdisciplinary Understanding of Global Carbon Cycling. *Journal of Research in Science Teaching*, 55, 377–398.

Appendix. Sample concept map number 5.