Application of a Computerized Method for Evaluating Systems-Level Thinking

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This work describes the application of a computerized tool to assess systems thinking capabilities of non-engineering students in an engineering literacy course and novice engineering students in an introductory engineering course. The program can analyze any block diagram node-and-link map of a system created by a student and then compare this to an expert-generated diagram. A similarity rating is then produced. The ability to describe a technological system in the form of a diagram is an important element of engineering literacy. Creating a diagram that shows how system inputs are transformed into outputs by a network of interconnected components is also one characteristic of systems-level thinking. In this study students are asked to extract information from multiple sources to create a systems-level block diagram that describes how a technological system works. Evaluating student-developed diagrams or concept maps is a time-consuming challenge for educators. We report results from preliminary testing of a computerized tool that compares student diagrams to an instructor-developed reference diagram. The rating of the student diagrams by the tool is in reasonable agreement with by-hand grading of the student diagrams by the instructor. Potential ways to improve the tool are discussed. This work has applications in promoting technological and engineering literacy by making it easier to evaluate engineering competencies that are different from numerical problem solving.

Significance of Systems Thinking in Engineering

Most products of engineering are technological systems. A system is a group of interconnected and interacting elements forming a complex whole serving a common purpose. Engineered products as varied as medical devices, agricultural machinery, bridges, satellites and integrated circuits can be considered as a group of interconnected elements serving a common purpose.

The ability to carry out system thinking is critical for engineering professionals. In a survey conducted by American Society for Engineering Education (ASEE) as part of the Transforming Engineering Education (TUEE) effort, representatives from industry rated systems thinking as a high priority for engineering education [1]. Even more noteworthy, this industry survey rated systems knowledge as more critical than "understanding of design." According to these industry respondents, "problems and challenges are generally system problems." Industry representatives also advocated for introducing students to systems concepts early in undergraduate engineering programs [1].

Systems thinking also provides a means to develop the technological and engineering literacy of non-engineers. In *Technically Speaking: Why all Americans need to know more about technology* [2], the NAE advocated a wider understanding of technology broadly defined as the products of all the engineering disciplines. Since systems span all engineering disciplines it offers a unique opportunity to serve as a common theme in engineering literacy courses. In addition systems thinking doesn't rely on higher level mathematics and is conceptual in nature. Mathematics perquisites are not needed and a systems view of technology is accessible to non-engineers.

Definition of Systems Thinking

Other disciplines besides engineering have an interest in systems thinking. Definitions of systems thinking can be found in fields as wide ranging as environmental science, business management and even popular culture [3-7]. Definitions of systems thinking do vary in some details across disciplines; however the essential features of systems thinking extend beyond disciplinary boundaries. A common general feature of systems thinking is adoption of a holistic, integrative, synthesis perspective.

The work reported here employs a working definition of systems thinking taken from recent definitions focused on engineering applications. A key feature in common among recent formulations of system thinking is an emphasis on identifying major system elements and identifying the relationships between those elements. Stave and Hopper created a set of systems thinking measures by interviewing systems educators [8]. While the educators interviewed expressed a range of opinions, the ability to recognize key components of a system was a consistent theme. A set of systems thinking outcomes related to ABET criteria and Bloom's taxonomy was proposed by Froyd [9]. Behl and Ferreira [10] proposed a model for systems thinking that includes the ability to comprehend a system holistically by taking into consideration all its components, subsystems, and subassemblies. Camelia and Ferris [11] proposed a definition of system thinking based on an ability to ask appropriate questions about a system. Arnold and Wade [12] developed a systems thinking approach that places particular emphasis on the ability to assess each relevant skill.

In the work reported here the definition of systems thinking proposed by Arnold and Wade [12] is used. This definition is consistent with the Camelia and Ferris [11] and the Behl and Ferreira [10] models and is focused on engineering applications. The essential features of this definition include: identification of the system boundary and identification of the objective of the system; understanding of the components of a system of interest, the processes within the system, and the inter-linking of components or processes to each other to make integrated wholes. Also included is an ability to recognize transformations of components or processes within the system of interest that may change over time. Arnold and Wade also note that systems thinking should demonstrate the ability to observe the system of interest from multiple points of view.

System Diagrams

Systems naturally lend themselves to the use of diagrams or other visual representations. In this work, the term system diagram is used describe a visual depiction of the elements of a system and their interactions. Systems are then a graph of nodes and links. In some cases the term concept map has been used to describe visual representations of systems. However, the application of concept maps is more general than node and link system diagrams. While system diagrams could be classified as a type of concept map, not all concept maps are system diagrams. To avoid confusion with the more general nature of concept maps, this work uses the term "system diagram" to refer to a visual representation of the elements and interconnections of a technological system. A system diagram is node and link diagram in which the nodes represent system component and the links describe the component interactions.

Assessment of Systems Thinking

System thinking has been challenging to assess. Unlike quantitative calculations with a single right or wrong answer, assessment of student system analysis work typically requires evaluation by a trained instructor. The process is generally time consuming. A range of approaches to the assessment of systems thinking have been introduced by educators [13-23]. These approaches can be described as integrating systems thinking with other topics such as critical thinking, sustainability, design projects, case studies and analysis problem scenarios. System thinking abilities are then inferred from changes in other learning outcomes. In some cases surveys have been developed that ask students to self-report attitudes, beliefs, and habits that are then interpreted as indicators of system thinking [24-30]. In a different approach, Hu and Shealy sought to identify evidence of system thinking by measuring brain activity using functional near-infrared spectroscopy (fNIRS) while students draw concept maps [31]. Automated computerized analysis of student verbal responses to questions were used by Kopainsky et al. to characterize system thinking [32]. Some researchers have tried to measure systems thinking directly in STEM-related applications. These studies are summarized in Table 1.

Table 1: Summary of Some Published Direct Assessments of Systems Thinking.

Study	Students	Application	Assessment Method
Sweeney & Sterman [33]	Graduate students in the MIT Sloan School of Management	Manufacturing facility process flow	Student make predicting system behavior
Assaraf & Orion [34]	Middle school biology students	Environmental water cycle	Comparison of student's to expert's diagram
Plate (2010)	Middle school biology students	Fictional marine ecosystem	Comparison of student's to expert's diagram
Brandstädter Harms, & Großschedl [36]	Middle school biology students	Blue mussel ecosystem	Comparison of student's to expert's diagram
Huang et al. [37]	Undergraduate Engineering students	Analysis of a toaster	Written description of system elements
Gilbert et al. [38]	Undergraduate geoscience students	The carbon cycle	Diagrams, simulations, written descriptions

Sweeny and Sterman found that graduate students at the MIT Sloan School did poorly on systems thinking tasks without prior system thinking instruction. The occurred despite the students' having completed advanced courses in mathematics [33]. Assaraf [34], Plate [35] and Brandstädter [36] each assessed systems thinking by comparing system diagrams created by students to diagrams created by experts. Huang et al. [37] measured systems thinking abilities by having students to prepare written descriptions of systems and then compared these to the instructor's interpretations. Gilbert et al. [38] combined diagrams and written descriptions in assessing systems thinking. These studies show that the most common mode of direct assessment is comparing student diagrams to expert diagrams. In each case evaluation was done manually.

Systems Thinking in Context of Technological and Engineering Literacy

To help incorporate systems thinking into engineering literacy courses Krupczak and collaborators have developed an approach to describing technology emphasizing systems, components, and functions [39-41]. The approach is based the characterization of technological systems as transforming materials, energy, and information as developed by Pahl [42]. Student-created diagrams engineered systems are assessed based on identification of major components, depiction of functional transformations at the component level, and recognition of appropriate component interactions. The system diagram based assessment emphasizing components and functions brings systems-level thinking to non-engineers and can also be used with first-year engineering students. A difficulty with this approach is assessment must be done manually by the instructor. Each student diagram is individually analyzed by the instructor. Specific feedback is provided by the instructor to each student.

Prior work by Shahhosseini served as a foundation for machine-based diagram evaluation [43-46]. Software was developed to compare two node-and-link diagrams and produce an overall similarity rating. The algorithm is a based on Melnik's similarity flooding algorithm [47]. The software then provides an overall similarity rating and colors the components of the student map in proportion to the level of similarity to the instructor's "expert" diagram.

Current Work-in-Progress Project

The initial preliminary study reported here has been conducted to investigate the feasibility of this software to carry out automatic assessment of student system diagrams. The study was conducted with Introduction to Engineering students at a private Midwestern college with an ABET-accredited engineering degree program. Part of the course involved the study of hybrid vehicles. Students were asked to create a diagram describing how a Chevy Volt works. For this particular assignment students were provided with a variety of source material describing the Volt. The material described the basic features of the Volt powertrain. Material was provided that was technically accurate and accessible to first year engineering students. This included sections from the detailed Volt owner's manual describing basics of operation [48]; detailed product descriptions [49]; articles from popular tech websites that described the Volt; and visual aids in the form of photographs and CAD-like renderings of the Volt [50,51]. All of these were selected by the instructor for simplicity and technical accuracy. Students were asked to create a system diagram of the Volt operating in its Extended Range Mode.

This question was asked as an examination question. Students answered individually. The students had prior practice in creating similar system diagrams for other technological systems. Other parts of the course include class activities, laboratories, and homework assignments that involve creating system diagrams. Some of the other technological systems studied include: automotive systems, home appliances, refrigeration systems, and biomedical devices. The students are familiar with this type of question and have had the opportunity to practice making system diagrams in a variety of contexts.

To provide some background on this system, the Extended Range Mode for the Chevy Volt is an interesting mode of operation. The Volt utilizes extended range mode after batteries have been depleted. In extended range mode the Volt operates as a series hybrid. The gasoline-fueled internal combustion engine turns an electric generator. The generator provides electrical energy for an electric motor that powers the driven wheels via a gearbox/transmission. A critical aspect is the internal combustion engine does not directly power the driven wheels but only supplies mechanical power input to the electric generator. Electrical energy generated that is not needed in the electric motor is directed to recharge the battery. Figure 1 is a system diagram that shows the main components of the Volt and their interaction during extended range mode.

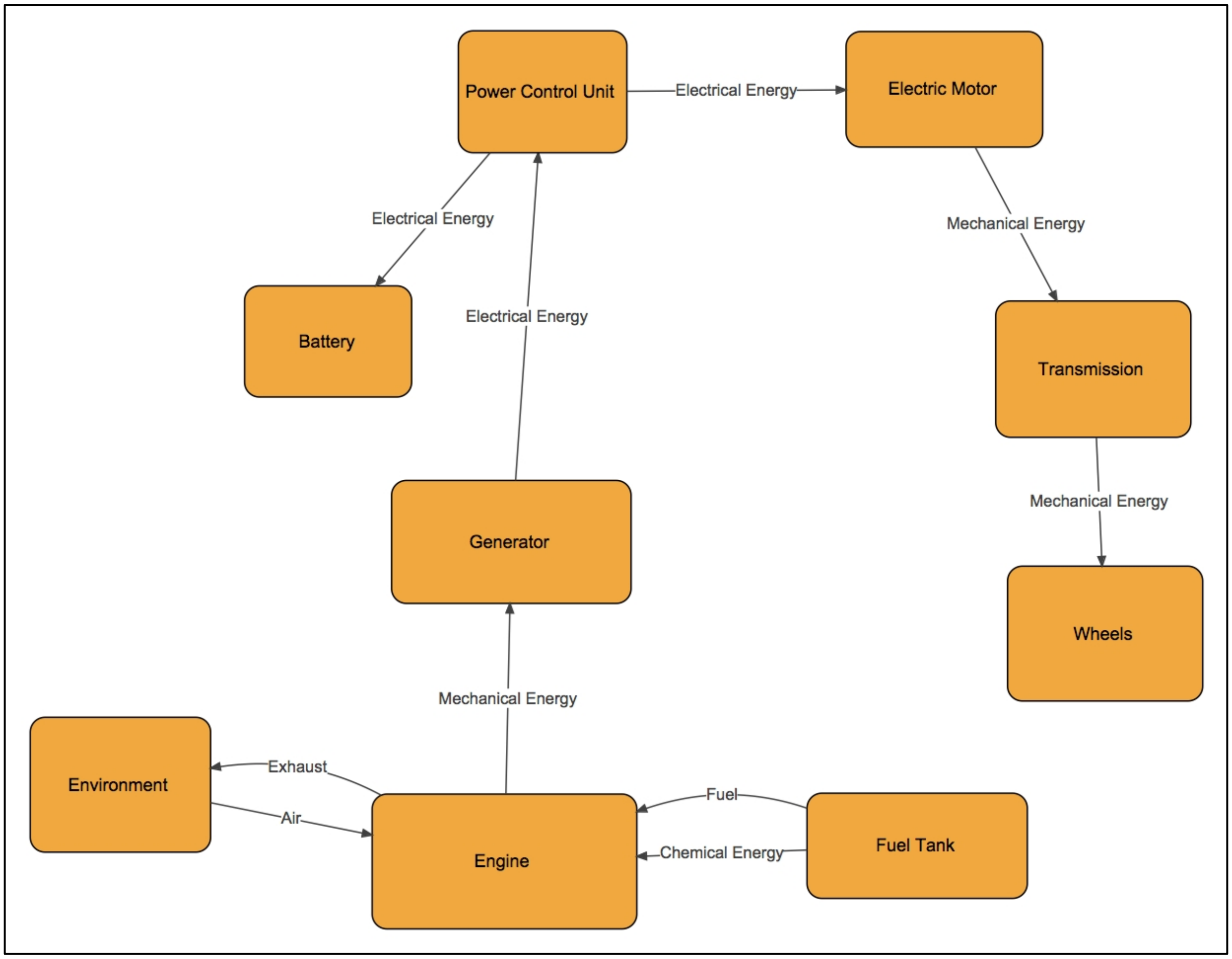

Figure 1: System Diagram of Chevy Volt Operating in Extended Range Mode.

Manual grading of student work by the instructor using a rubric took more than 5 hours to grade and provide feedback for a class of 85 students. To test the algorithmic software-based approach 22 student diagrams were selected at random. These were then evaluated by the software algorithm and then compared to the instructor's evaluation. The algorithm compared diagrams created by students to the instructor's "expert" diagram that was shown in Figure 1. Figure 2 summarizes the results. If the instructor and algorithmic ratings were all identical, all points would fall on a line with a slope of 1.0 with intercept of 0. The resulting slope of 1.05 with intercept of -8.9 shows close agreement between algorithm and instructor across the wide range of student work. On the average, the instructor rated students about 5 to 7 percent lower than the algorithm. The time required to run the software and conduct an evaluation was about one minute per diagram.

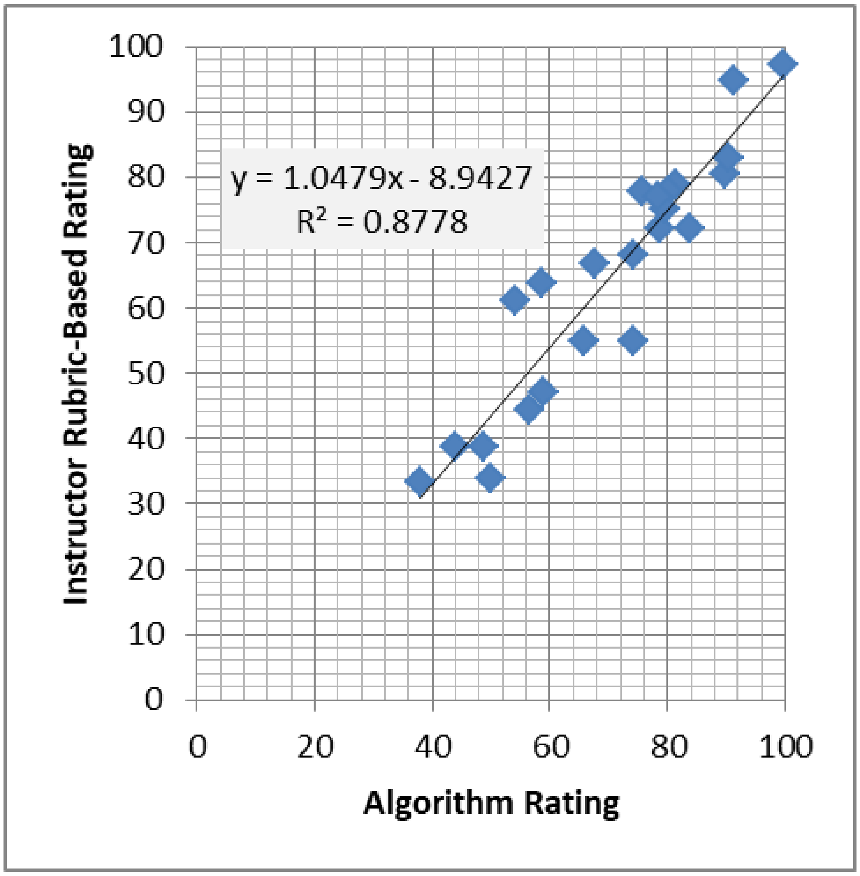

Figure 2: Preliminary Study Results of Comparison of Algorithm and Instructor Grading of Student Chevy Volt Hybrid Car System Diagram.

In the current work-in-progress study the students used pencil and paper to create the diagrams during the examination. Researchers then transcribed the pencil-and-paper diagrams into machine-readable format using the VUE map generation software [52]. In future work we hope to improve the usability of the tool so that students directly generate a machine-readable diagram themselves using a laptop or tablet computer. It is hoped to improve the degree of correspondence between instructor and algorithmic ratings. The goal is for algorithm-to-instructor inter-rater agreement to be comparable to the inter-rater agreement between two experienced instructors.

It is also hoped that the tool could be improved to the point at which students could use it for self-learning. A student could create a diagram and then obtain a comparison using the software to the instructor's expert diagram along with suggestion for possible areas to consider for improvement. The student could then iterate his or her analysis and repeat the process.

Review of Typical Student Responses

Some representative student diagrams demonstrate the types of responses from students in analyzing the Chevy Volt system. Figure 3 shows a student diagram that obtained a low degree of comparison with the expert diagram. The student diagram is showing the Chevy Volt as a type of perpetual motion machine. The internal combustion engine is omitted. The transmission turns the generator and this in turn provides power to the transaxle in a closed loop with energy also delivered to the wheels. The electric motor is also missing so there is a miss-match in energy type between the electrical energy output of the power control unit and the input of the transaxle which should be mechanical energy. This was rated 44 percent similar to expert map by the algorithm while the instructor rubric rated this a 38 percent.

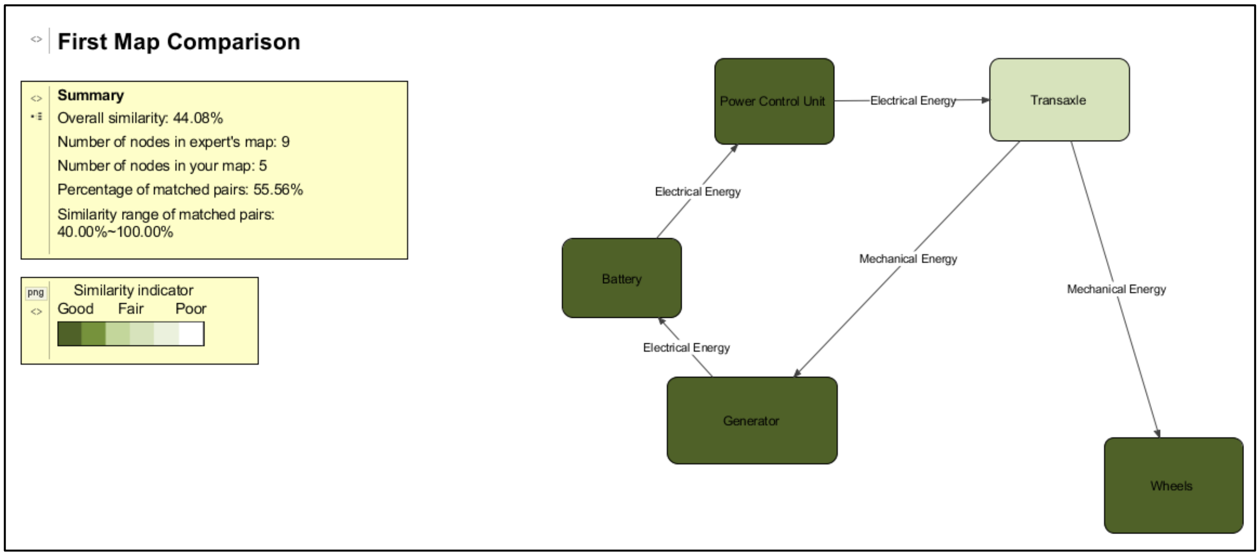

Figure 3: Example of a Student-Generated System Diagram with Low Correspondence to the Expert's Diagram.

Figure 4 shows another problematic student map. The student's description of the system has not depicted a hybrid vehicle but rather a conventional internal combustion engine power train. There is no generator or electric motor. The internal combustion engine provides power to the wheels via a transmission. Other errors include duplication of the function of the transmission, and showing a flow of electrical energy from the transmission. This should be mechanical energy. The algorithm rated this as 56 percent similar to the expert diagram, while the instructor's rubric resulted in a score of 44. The instructor is considerably lower because of the importance of the missing electric motor and generator in the student diagram. The current algorithm uses equal weightings for all components of the expert diagram. This example shows the need to accommodate some type of weighting in the algorithm process so some components can receive higher weighting than others.

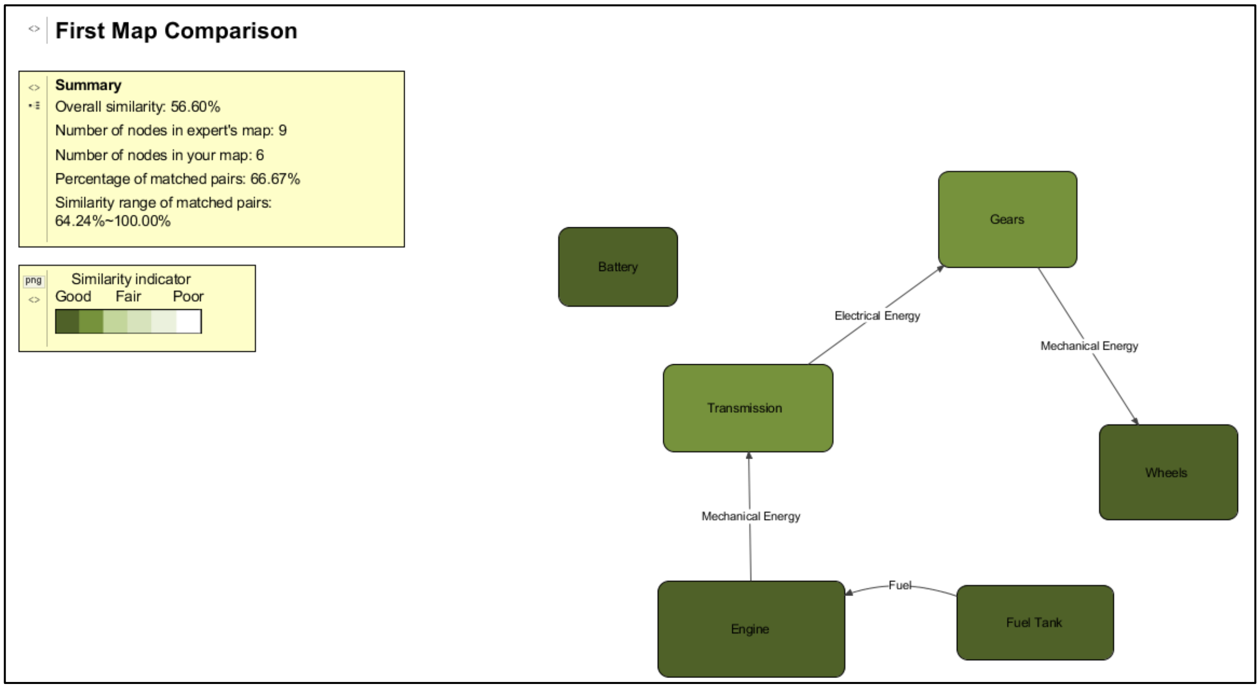

Figure 4: Example of a Student-Generated System Diagram Indicating Major Deficit in System Understanding.

Figure 5 is an example of a moderately good student diagram that received similar ratings from the instructor and the algorithm. The student omitted the power control unit and incorrectly shows the battery providing electrical energy during the extended mode operation. The algorithm rated this at 78 percent which the instructor rubric resulted in a 77 percent rating.

The last student diagram example shown in Figure 6 is representative of high-scoring student diagrams. This received a rating of 91 percent from the algorithm and 94 percent from the instructor. The diagram is substantially accurate but is not including the flow of electrical energy to recharge the battery. In addition, the student has misidentified the input of the generator as electrical energy rather than mechanical energy. The lower score from the algorithm compared to the instructor can again be attributed to the equal weighting of all links and nodes utilized by the algorithm compared to the instructor's prioritizing of some nodes and interactions.

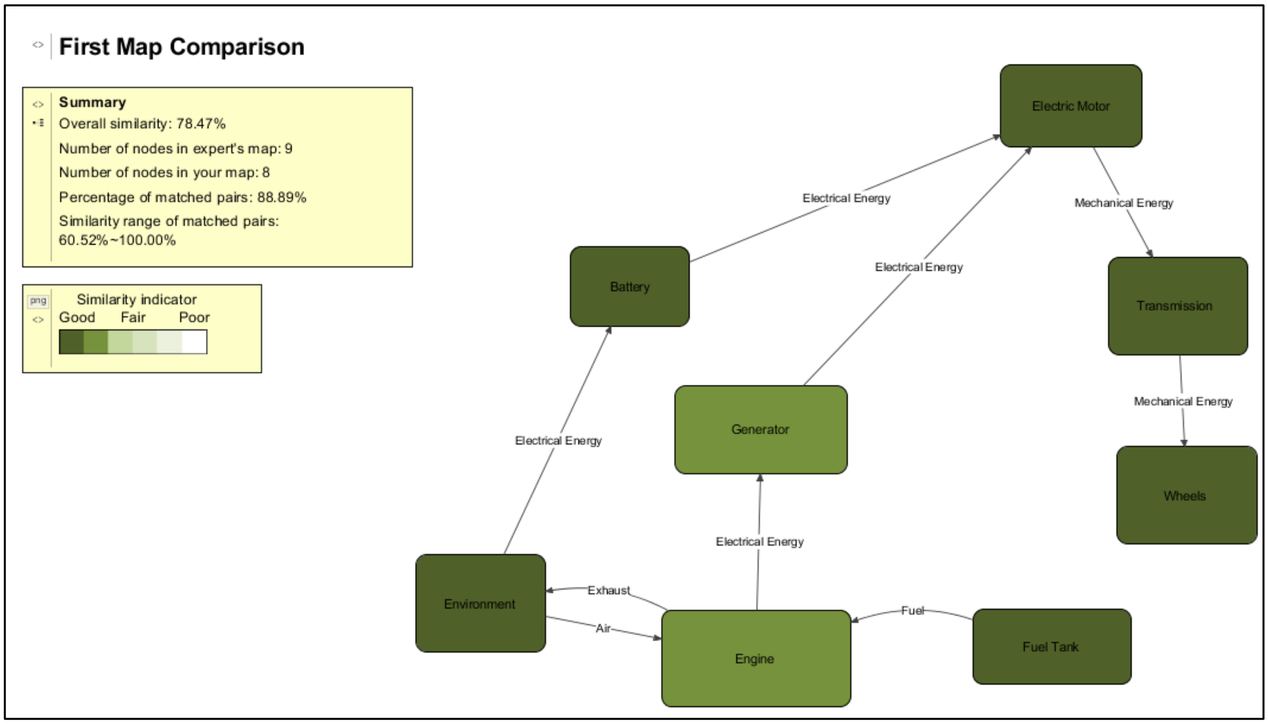

Figure 5: Example of a Moderately Good Student-Generated System Diagram and Close Agreement between Instructor and Algorithmic Assessment.

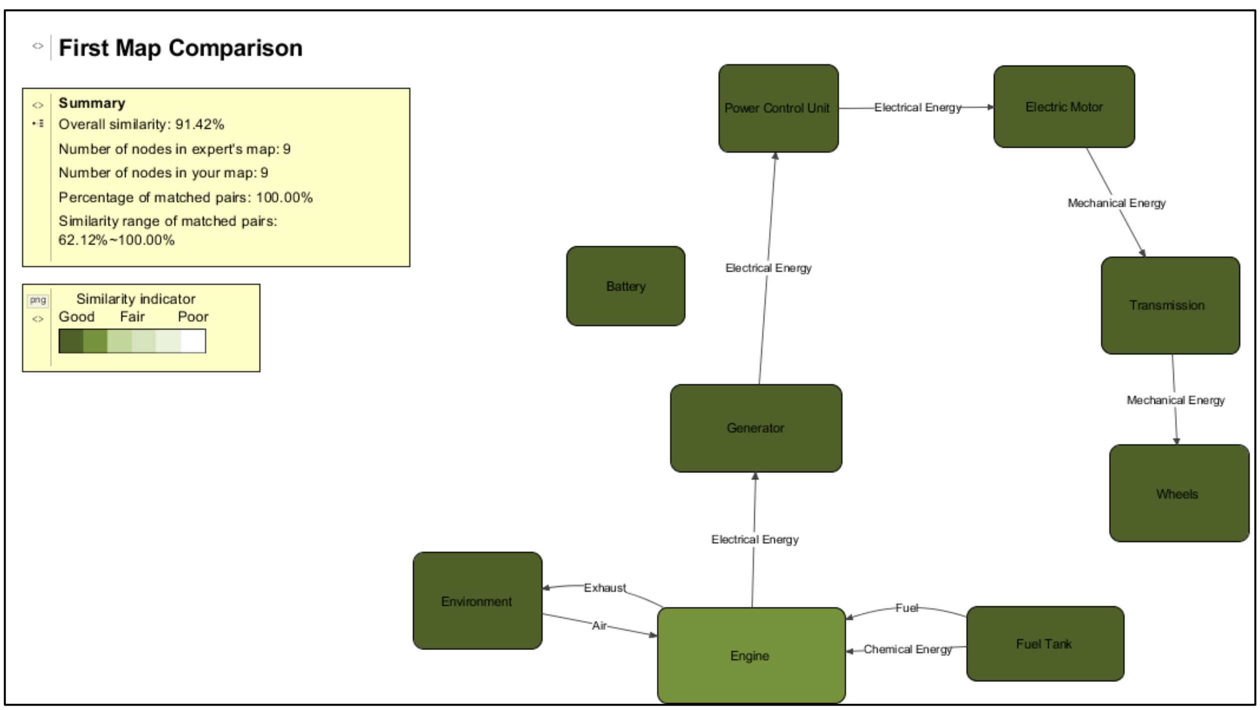

Figure 6: Example of a Student-Generated System Diagram in Close Agreement with Expert-Generated Diagram.

Conclusions and Future Work

These work-in-progress results indicate promise for the use of automated software-based assessment of systems thinking. The initial study shows that algorithmic analysis of student diagrams is comparable to by-hand assessment by an instructor. We anticipate that use of a weighting function to indicate higher priority nodes and links will improve agreement. Improvements to the software to allow students to directly generate diagrams and receive feedback are also needed to more fully realize the potential of automated assessment to improve systems thinking. Additional testing is planned with both engineering students enrolled in introduction to engineering and non-engineers in a general education engineering literacy course.

References

1. "Transforming Undergraduate Education in Engineering (TUEE) Phase I: Synthesizing and Integrating Industry Perspectives," American Society for Engineering Education, 2013. http://tuee.asee.org/phase-i/report/
2. G. Pearson and A. T. Young, Ed., *Technically Speaking: Why All Americans Need to Know More about Technology*, Washington, DC: National Academies Press, 2002. https://doi.org/10.17226/10250.
3. B. Richmond, *The 'Thinking' in Systems Thinking: Seven Essential Skills*. Waltham, MA: Pegasus Communications, 2000.
4. L. B. Sweeney and D. Meadows, *The Systems Thinking Playbook*. White River Junction, VT: Chelsea Green, 2010.
5. G.M. Weinberg, *An Introduction to General Systems Thinking*. New York: Dorset House Publishing, 2011.
6. D.P. Stroh, *Systems Thinking for Social Change: A Practical Guide to Solving Complex Problems, Avoiding Unintended Consequences, and Achieving Lasting Results*. White River Junction, VT: Chelsea Green, 2015.
7. W. Donaldson, *Simple Complexity: A Management Book for The Rest of Us: A Guide to Systems Thinking*. New York: Morgan James Publishing, 2017.
8. K. Stave and M. Hopper, "What Constitutes Systems Thinking: A Proposed Taxonomy." *25th International Conference of the System Dynamics Society*, Jul. 1, 2007. https://digitalscholarship.unlv.edu/sea_fac_articles/201.
9. J. Froyd, L. Pchenitchnaia, D. Fowler, and N. Simpson, *Systems Thinking and Integrative Learning Outcomes* paper presented at 2007 Annual Conference & Exposition, Honolulu, Hawaii.
10. D.V. Behl, and S. Ferreira, "Systems Thinking: An Analysis of Key Factors and Relationships." *Procedia Computer Science*, Complex Adaptive Systems, Philadelphia, PA Nov. 3-5, 2014, vol. 36, pp. 104–9, Jan 1, 2014. https://doi.org/10.1016/j.procs.2014.09.045.
11. F. Camelia and T. Ferris, "Systems Thinking in Systems Engineering," *INCOSE International Symposium,* vol. 26, no. 1, pp. 1657–74, Jul. 1, 2016. https://doi.org/10.1002/j.2334-5837.2016.00252.x.
12. R.D. Arnold and J.P. Wade, "A Complete Set of Systems Thinking Skills," *INCOSE International Symposium,* vol. 27, no. 1, pp. 1355–70, Jul. 2017. https://doi.org/10.1002/j.2334-5837.2017.00433.x
13. C.E. Hmelo, D.L. Holton, and J.L. Kolodner, "Designing to Learn about Complex Systems." *The Journal of the Learning Sciences,* vol. 9, no. 3, pp. 247-98, 2000.
14. R. Jain, K. Sheppard, E. McGrath, and B. Gallois, "Promoting Systems Thinking in Engineering and Pre-engineering Students" presented at 2009 Annual Conference & Exposition, Austin, TX, Jun. 2009. https://peer.asee.org/15627

15. D.M. Rizzo, "Incorporating Systems Thinking and Sustainability within Civil and Environmental Engineering Curricula at UVM" presented at 2011 ASEE Annual Conference & Exposition, Vancouver, BC. June, 2011. https://peer.asee.org/18134

16. C.R. Rehmann, D.T. Rover, M. Laingen, S.K. Mickelson, and T.J. Brumm, "Introducing Systems Thinking to the Engineer of 2020" presented at 2011 ASEE Annual Conference & Exposition, Vancouver, BC., Jun. 2011. https://peer.asee.org/18173

17. C.M. Wigal, "Identifying and Defining Relationships: Techniques for Improving Student Systemic Thinking," presented at 2011 ASEE Annual Conference and Exposition, Vancouver, BC., June 2011. https://peer.asee.org/18074

18. K.T. Aung, "Integration of System Thinking, Engineering Reasoning, and Decision-making Skills in Design of Thermal Systems Course" presented at 2012 ASEE Annual Conference & Exposition, San Antonio, TX. June, 2012. https://peer.asee.org/21579

19. X. Yuan, H. Malki, "Developing System-Thinking Oriented Learning Modules of Networked Measurement Systems for Undergraduate Engineering Curriculum" presented at 2013 ASEE Annual Conference and Exposition, Atlanta, GA, Jun, 2013. https://peer.asee.org/19420

20. R.L. Nagel, K.G. Gipson, J.H. Spindel, and E.M. Barrella, "Blending Sustainable Design, Systems Thinking, and Engineering Science Concepts in an Introductory Engineering Course" presented at 2013 ASEE Annual Conference and Exposition, Atlanta, GA. June, 2013. https://peer.asee.org/19260

21. K.H. Muci-Kuchler, M.D. Bedillion, S. Huang, C.M. Degen, and M.D. Ellingsen, W.M. Nikshi, and J. Ziadat, "Incorporating Basic Systems Thinking and Systems Engineering Concepts in a Mechanical Engineering Sophomore Design Course" presented at 2017 ASEE Annual Conference and Exposition, Columbus, OH, Jun. 2017. https://peer.asee.org/28504

22. M. Tomko, J. Nelson, R.L. Nagel, M. Bohm, and J. Linsey, "A Bridge to Systems Thinking in Engineering Design: An Examination of Students' Ability to Identify Functions at Varying Levels of Abstraction." *AI EDAM,* vol. 31, no. 4, pp. 535–49, Nov. 2017. https://doi.org/10.1017/S0890060417000439.

23. J.R. Grohs, G.R. Kirk, M.M. Soledad, and D.B. Knight, "Assessing Systems Thinking: A Tool to Measure Complex Reasoning through Ill-Structured Problems." *Thinking Skills and Creativity*, vol. 28, pp. 110-30, June 1, 2018. https://doi.org/10.1016/j.tsc.2018.03.003

24. D. Nightingale, "Enablers and Barriers to Systems Thinking Development: Results of a Qualitative and Quantitative Study," in *Proceedings CSER,* Conference on Systems Engineering Research, Mar. 23-25, 2005. Hoboken, NJ: Steven Institute of Technology. ISBN 0-615-12843-2

25. M. Frank, "Knowledge, Abilities, Cognitive Characteristics and Behavioral Competences of Engineers with High Capacity for Engineering Systems Thinking (CEST)." *Systems Engineering* vol. 9, no. 2, pp. 91-103, June 1, 2006. https://doi.org/10.1002/sys.20048.

26. S. Kordova, S. Koral, G. Ribnikov, and M. Frank, "Developing Systems Thinking among Engineers: Recent Study Findings," in *2015 Annual IEEE Systems Conference (SysCon) Proceedings*, pp. 50–53, 2015. https://doi.org/10.1109/SYSCON.2015.7116728.

27. A. Halpin and R. Kurthakoti, "Can Systemic Thinking Be Measured? Introducing the Systemic Thinking Scale (STS)." *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL Conference,* vol. 42, no. 0, 2015. https://journals.tdl.org/absel/index.php/absel/article/view/2925.

28. D. Burnell, "Systems Thinking Orientation Assessment Framework (STOAF): Towards Identifying the Key Characteristics of the Systems Thinker and Understanding Their Prevalence in the Layperson." *Systems Research and Behavioral Science*, vol. 33, no. 3, pp. 471-82, May 1, 2016. https://doi.org/10.1002/sres.2347.

29. A.C. Davis, C. Adam, and M.L. Stroink, "The Relationship between Systems Thinking and the New Ecological Paradigm." *Systems Research and Behavioral Science,* vol. 33, no. 4, pp. 575–86, 2016. https://doi.org/10.1002/sres.2371.

30. F. Robinson-Bryant, “Developing a Systems Thinking Integration Approach for Robust Learning in Undergraduate Engineering Courses” presented at 2018 ASEE Annual Conference and Exposition, Salt Lake City, UT, https://peer.asee.org/30294

31. M. Hu and T. Shealy, “Methods for Measuring Systems Thinking: Differences between Student Self-assessment, Concept Map Scores, and Cortical Activation during Tasks about Sustainability” presented at 2018 ASEE Annual Conference and Exposition, Salt Lake City, UT, June, 2018. https://peer.asee.org/30807 .

32. B. Kopainsky, P. Pirnay, Dummer, and S.M. Alessi, “Automated Assessment of Learners’ Understanding in Complex Dynamic Systems.” *System Dynamics Review,* vol. 28, no. 2, pp. 131–56, 2012. https://doi.org/10.1002/sdr.1467

33. L.B. Sweeney and J.D. Sterman, “Bathtub Dynamics: Initial Results of a Systems Thinking Inventory.” *System Dynamics Review*, vol. 16, no. 4, pp. 249–86, Dec. 1, 2000). https://doi.org/10.1002/sdr.198.

34. O. Ben-Zvi Assaraf and N. Orion, “Development of System Thinking Skills in the Context of Earth System Education.” *Journal of Research in Science Teaching*, vol. 42, no. 5, pp. 518–60, May 1, 2005. https://doi.org/10.1002/tea.20061.

35. R. Plate, “Assessing Individuals’ Understanding of Nonlinear Causal Structures in Complex Systems.” *System Dynamics Review*, vol. 26, no. 1, pp.19–33, Jan. 1, 2010. https://doi.org/10.1002/sdr.432.

36. K. Brandstädter, U. Harms, and J. Großschedl, “Assessing System Thinking Through Different Concept-Mapping Practices.” *International Journal of Science Education*, vol. 34, no. 14, pp. 2147–70, September 2012. https://doi.org/10.1080/09500693.2012.716549.

37. S. Huang, K.H. Muci-Kuchler, M.D. Bedillion, M.D. Ellingsen, and C.M. Degen, “Systems Thinking Skills of Undergraduate Engineering Students,” in *IEEE Frontiers in Education Conference (FIE),* 2015, pp. 1–5. El Paso, TX: IEEE, 2015. https://doi.org/10.1109/FIE.2015.7344341.

38. L.A. Gilbert, D.S. Gross, and K.J. Kreutz, “Developing Undergraduate Students’ Systems Thinking Skills with an InTeGrate Module.” *Journal of Geoscience Education,* pp. 1–16, Nov. 9, 2018. https://doi.org/10.1080/10899995.2018.1529469.

39. J.J. Krupczak, “Using Functional Analysis as a Framework for Understanding Technology,” in *Proceedings of the American Society for Engineering Education 2010 Annual Conference*, Jun. 20-23, 2010, Louisville, KY. https://peer.asee.org/16300

40. J. J. Krupczak, L. Aprill, and D.J. Langholz, "Development of a Simplified Method for Representing Technological Systems for Non-Engineers" presented at 2014 ASEE Annual Conference and Exposition, Indianapolis, IN, Jun. 2014. https://peer.asee.org/20309

41. J. J. Krupczak and M. Mina, "Work in Progress: An Approach to Engineering Literacy Emphasizing Components, Functions, and Systems" presented at 2015 ASEE Annual Conference and Exposition, Seattle, WA, Jun. 2015. 10.18260/p.25084 https://peer.asee.org/25084

42. G. Pahl and W. Beitz, *Engineering Design: A Systematic Approach*. London: Springer-Verlag, 1991.

43. A.M. Shahhosseini, H. Ye, G. Maughan, and T. Foster, "Implementation of Similarity Flooding Algorithm to Solve Engineeering Problems Using Diagnostic Skills Training Technique," *ASME International Mechanical Engineering Congress and Exposition*, IMECE 2014, November 14-20, 2014, Montreal, Canada. IMECE2014-39698

44. Y. Lin, A. M. Shahhosseini, M. A. Badar, T. Foster, and J. Dean, “A Concept Map-Based Cognitive Framework for Acquiring Expert Knowledge in Industrial Environment,” in *2016 IEEE Frontiers in Education Conference (FIE)*, 2016, pp.1–5. https://doi.org/10.1109/FIE.2016.7757702.

45. Y. Lin, A. Shahhosseini, M. Affan Badar, W. Foster, and J. Dean, “Using Conceptual Mapping to Help Retain Tribal Knowledge,” in *2016 ASEE Annual Conference and Exposition Proceedings*. New Orleans, LA: ASEE Conferences, 2016. https://doi.org/10.18260/p.27141.

46. L. Yuetong, A.M. Shahhosseini, and M. Affan Badar,"Assessing Conceptual Mapping Based Active Learning for Advancing Engineering Diagnostic Skills," in *American Society for Engineering Education Annual Conference*. ASEE Conferences, 2017. https://peer.asee.org/27620.

47. S. Melnik, H. Garcia-Molina, and E. Rahm, "Similarity Flooding: A Versatile Graph Matching Algorithm and Its Application to Schema Matching," Article presented at the Data Engineering Proceedings, 18th International Conference, 2002.

48. General Motors, Chevrolet Volt, Owner's Manual, Getting to Know Your 2017 Chevy Volt, https://my.chevrolet.com/content/dam/gmownercenter/gmna/dynamic/manuals/2017/Chevrolet/Volt/Get%20to%20Know%20Guide.pdf

49. General Motors, Chevrolet Volt, http://www.chevrolet.com/electric/volt-plug-in-hybrid#

50. GM's Chevy Volt Plug-in Concept: How It Works, *Popular Mechanics*, https://www.popularmechanics.com/cars/hybrid-electric/a1584/4215492/

51. How the Chevrolet Volt is a different kind of electric car, *Vox Creative*, https://www.voxcreative.com/sponsored/11265192/how-the-chevrolet-volt-is-different-from-every-other-electric-car

52. VUE, Visual Understanding Environment, Tufts University, Vue.tufts.edu/.