

AC 2007-270: SYSTEMS THINKING AND INTEGRATIVE LEARNING OUTCOMES

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Systems Thinking and Integrative Learning Outcomes

Abstract

Although the eleven program educational outcomes in the ABET Engineering Criteria require considerable breadth and depth in the capabilities of engineering graduates, additional outcomes have been offered to encompass the modes of thinking required for engineering graduates. One of these additional outcomes is systems thinking. Many different subjects have at one time or another been included under the umbrella of systems thinking, but more specific statements of learning outcomes are required. The paper proposes a preliminary set of learning outcomes, based on framework which combines an established taxonomy of learning outcomes, the revised Bloom's taxonomy, with a set of expectations for engineering graduates that has been supported by employers and at least twenty-two institutions.

Introduction

Modern universities are facing numerous social and organizational challenges. Today, institutions have to deal with significant reductions in financial resources, increases in costs, demands for accountability for student learning outcomes, globalization, advancements in information technologies, and intense competition among numerous providers of education¹⁻³. Universities are asked to produce graduates who are skilled in higher-order cognition, such as critical thinking and complex problem solving; behave in a principled ethical fashion; can accept and work harmoniously and productively with people unlike themselves; have the ability to adapt to diverse and changing situations; and take responsibility for their work^{4,5}.

Modern educational organizations are no longer viewed as formal, rational and hierarchically closed systems with hierarchical control patterns. A way to address old organizational structures is to build learning organizations. For Senge a learning organization is "an organization that is continually expanding its capacity to create its future. . .it is not enough merely to survive (survival learning or adaptive learning) . . .adaptive learning must be joined by generative learning, learning that enhances our capacity to create"^{6, p.14}. The primary purpose of higher education in this new paradigm will be producing learning, not providing instruction. The focus on campus is shifting from faculty teaching to student learning^{7,8}, with emphasis on active learning and assessment of learning outcomes. The modern academic workplace is characterized by the increasing demands from stakeholders (e.g. accrediting bodies and employers) for documenting and improving student learning outcomes. Levine states that "with the individualization of education, growing diversity of students and the multiplication of providers, the emphasis will shift from standardizing process to measuring outcomes. . .the emphasis will change from how students are taught to determining how much students have learned"^{8, p. 265}.

In engineering, one external impetus for change comes from ABET, which establishes criteria for accrediting engineering, technology, and computer science programs. In its Engineering Criteria, ABET established a set of student outcomes in Criterion 3. Institutions seeking accreditation may create their own sets of student outcomes that are supersets of the ABET student outcomes. For the set of student outcomes, each program must have processes that demonstrate that (1) program performance with respect to its outcomes is being assessed, (2) results of program evaluation are being used to develop and improve the program, and (3) results and processes are being documented. As a result, engineering faculty members must develop methodologies for assessing performance with respect to outcomes in competency in addition to developing new curriculum⁹. Need for these methodologies has created increased interest in developing and identifying relevant assessment instruments¹⁰. However, only a handful of tools and methodologies are publicly available^{11,12}. Meeting ABET Engineering Criteria created significant challenges for almost every engineering program.

For each student outcome, engineering programs must address the following questions:

- What observable student performances would demonstrate competence in this particular area, i.e., what must students be able to do in order to satisfy the outcome?
- How might evidence of student performance with respect to the outcome, while the student is still on campus¹³, be acquired and analyzed in order to evaluate a program?
- How might student performance with respect to the outcome be improved? That is, what types of instruction are likely to result in improved student performance and what meaningful learning experience can contribute to the development of these outcomes in undergraduate students¹³?

Some engineering education researchers have suggested that the eleven program outcomes specified in the ABET Engineering Criteria do not encompass some modes of thinking that should be expected for future engineering graduates¹⁴. One mode of thinking not mentioned in the program outcomes is systems thinking, even though several researchers have made the case for the importance of adding systems thinking to the set of capabilities expected for future engineers. If systems thinking were added as a program outcome, one of the challenges facing engineering educators would be articulating expectations for learning associated with systems thinking. In other words, what would be a set of learning outcomes from which a particular undergraduate program could select to express its expectations for learning associated with systems thinking?

Systems Thinking

One of the challenges associated with communicating learning expectations associated with systems thinking is the breadth of subjects that have been placed under the umbrella of systems thinking. These subjects include system dynamics¹⁵⁻¹⁸, which includes in its toolkit ideas such as feedback, time delay, difference equations, and differential equations. Another frequently included subject is complexity theory, which variously includes self-organizing systems, highly organized tolerance¹⁹, chaos, and complex adaptive systems²⁰. A third subject is project management²¹, which includes capabilities for planning, scheduling, monitoring, and constructively intervening across a set of

numerous interacting activities to realize a stated goal at a predetermined time. A fourth subject is less well defined than the previous three, yet it is probably the most frequently mentioned. The fourth subject stresses the value of perceiving a system as a set of interconnected components whose pattern of interconnections may reveal important characteristics to people who must make decisions about interventions intended to improve the performance of the system. Several decades ago, the subject was optimistically, and perhaps arrogantly, labeled general systems theory^{22,23}. The name has dropped from favor, but the essence of the subject is cited by many who call for systems thinkers. Senge⁶ provides important insight into how educators can achieve meaningful change and transform schools into learning organizations that renew themselves. Senge⁶ proposed that organizations must develop five capacities, called disciplines: systems thinking, personal mastery, mental models, shared vision, and team learning. By systems thinking, Senge is referring to a “body of knowledge and tools” that helps us see underlying patterns and how they can be changed. Systems thinking allows individuals to see processes over time and to break away from the assumptions that have prevented lasting results. The array of different subjects makes development of a set of learning outcomes challenging.

Another challenge with defining systems thinking is its connection with interdisciplinary thinking. Many proponents of systems thinking contend that systems thinkers must be able to integrate ideas, concepts, knowledge, and evidence across disciplinary boundaries. Schools need to focus on thinking skills and learning skills because those are what prepare students for a world of increasing interdependency and increasing change²⁴. While the value of interdisciplinary thinking now may be unchallenged, recognizing learners who have achieved some level of competence with respect to interdisciplinary thinking is often unaddressed. In this respect, recent work by Boix-Marsilla²⁵ on assessment of interdisciplinary work by students may offer some elements of a useful framework for systems thinking.

With at least two of the challenges elucidated, the paper will draw upon a breadth of existing research to offer a proposed set of learning outcomes with which the level of competence of a learner might be more clearly discerned. The proposed methodology is a thorough review of the literature to ascertain what learning outcomes have been clearly articulated. Second, the literature review will attempt to determine expectations for learning that have been articulated, but not codified as learning outcomes. From these lists, a set of learning outcomes will be offered. It is not expected that the set of learning outcomes will be definitive, but it might stimulate additional productive and thoughtful dialogue regarding an important attribute of future engineers.

Systems Thinking and Learning Outcomes

Many authors have stressed the importance of systems thinking. For example, Dym et al, in their work on engineering design, have identified four areas of systems thinking that are relevant for thinking about designing systems:

- Thinking about system dynamics,
- Reasoning about uncertainty,

- Making estimates, and
- Conducting experiments²⁶.

Gharajedaghi, in considering systems thinking from a business architecture perspective, has espoused five systems thinking principles:

- Openness,
- Purposefulness,
- Multidimensionality,
- Emergent property, and
- Counterintuitiveness²⁷.

Another set of expectations for systems thinking has been generated by the CDIO Initiative, which is “an innovative educational framework for producing the next generation of engineers set in the context of Conceiving – Designing – Implementing – Operating real-world systems and products”²⁸. CDIO was derived from these four words: Conceiving – Designing – Implementing – Operating, which attempted to capture the comprehensive practice of engineering. The CDIO Initiative started with five institutions and now involves twenty-two institutions.²⁸ Initial work of the CDIO Initiative concentrated on a study, involving both faculty members and employers, to clearly articulate a detailed set of expectations for engineering graduates. The desired set of capabilities for engineering graduates was called the CDIO Syllabus²⁹, which intended “to create a rational, complete, universal, and generalizable set of goals for undergraduate engineering education”³⁰. The CDIO Syllabus organizes system thinking into four areas:

- Thinking holistically,
- Emergence and interactions in systems,
- Prioritization and focus, and
- Trade-offs, judgment and balance in resolution²⁹

However, none of the resources that were found as a part of this study articulated learning outcomes for systems thinking, where learning outcomes have the characteristics described in the literature on assessment³¹.

Since resources on systems thinking that have been found by the authors do not set forth learning outcomes, recognizing the degree to which a learner possesses the knowledge and capabilities required for systems thinking becomes problematic. A two-dimensional matrix is a useful strategy for developing a framework to address this situation. The CDIO Syllabus²⁹ provides one dimension of the matrix. For the second dimension, the authors considered several possibilities. Several models of intellectual development: Perry’s Model of Intellectual Development³², the model of women’s ways of knowing by Belenky et al.³³, the Baxter-Magolda Model of Epistemological Development^{34,35}, and the Reflective Judgment Model by King and Kitchener³⁶ were considered. However, the authors were not looking for complex development models, but instead were seeking a framework to organize many different learning outcomes for systems thinking. Another alternative was Stephen Toulmin’s argumentation model³⁷, but the authors were looking for a model that had wider recognition among the engineering education community. Bigg’s Structure of Observed Learning Outcome (SOLO)^{38,39} could have been selected, but the authors selected the revised Bloom’s taxonomy of educational objectives⁴⁰. They had more experience with the latter taxonomy and the upper levels of Bloom’s taxonomy were a better fit for describing desired learning outcomes for systems thinking.

The revised Bloom's taxonomy of educational objectives is a framework for classifying statements of what we expect or intend students to learn as a result of instruction⁴¹. The original taxonomy was developed by Benjamin S. Bloom⁴² in the early 50s and it has since been translated into 22 languages and is one of the most widely applied and most often cited references in education⁴³. The original taxonomy represented a multi-tiered model of classifying thinking according to six cognitive levels of complexity: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. The taxonomy was later revised by Lorin W. Anderson and David R. Krathwohl⁴⁰ and the six levels of learning in the revised Bloom's taxonomy (together with representative verbs used to write learning outcomes at each level of learning) are:

- **Remember** (recognize, recall...)
- **Understand** (interpret, exemplify, classify, summarize, infer, compare, explain...)
- **Apply** (execute, implement...)
- **Analyze** (deconstruct, organize, break into parts...)
- **Evaluate** (check, critique...)
- **Create** (generate, plan, produce...)⁴⁰

Combining the four areas identified in the CDIO Syllabus²⁹ with Bloom's revised taxonomy⁴⁰ generates a framework that can be represented in tabular form (see Table 1). The following four sections will look at the areas of systems thinking from the CDIO Syllabus²⁹ and offer learning outcomes at each of the six levels of learning in the revised Bloom's taxonomy⁴⁰. The approach resembles the method used by researchers who constructed learning outcomes for the eleven ABET Educational Program Outcomes in the Engineering Criteria using the original Bloom's taxonomy⁴⁴.

Thinking Holistically

Section 2.3.1, Thinking Holistically, of the CDIO Syllabus Report describes the ideas associated with student learning in this area of systems thinking:

- "A system, its behavior, and its elements
- Trans-disciplinary approaches that ensure the system is understood from all relevant perspectives
- The societal, enterprise and technical context of the system
- The interactions external to the system, and the behavioral impact of the system"³⁰

These ideas are related to two of the systems thinking principles which Gharajedaghi identified: openness and multidimensionality²⁷. The areas are related to openness in that both emphasize the need to (a) define a system, which Gharajedaghi associates with controllable variables, and (b) consider interactions of a system with its environment, which Gharajedaghi associates with uncontrollable variables, Thinking holistically in the CDIO Syllabus is related to Gharajedaghi's multidimensional principle because both emphasize the wide range of disciplinary perspectives that should be considered when studying the interactions of a system with its environment. These interactions include physical exchanges (mass, energy, charge, momentum, angular momentum), economic exchanges, social interactions, and interactions explored from perspectives associated with the humanities.

Table 1. Framework for Systems Thinking Learning Outcomes

		Levels of Learning: Revised Bloom's Taxonomy					
		Remember	Understand	Apply	Analyze	Evaluate	Create
CDIO Syllabus: Systems Thinking Areas	Thinking Holistically						
	Emergence and Interactions in Systems						
	Prioritization and Focus						
	Trade-offs, Judgment and Balance in Resolution						

Although the CDIO Syllabus provides more detailed ideas associated with thinking holistically, the authors of the report did not frame their expectations in terms of observable student performance. As a result, additional work is needed to clarify how students would be expected to demonstrate acquired competence related to thinking holistically. The key ideas of thinking holistically appear to be system, its environment, and the diverse perspectives required to thoroughly understand the interaction of the system with its environment. Using these key ideas, the follow learning outcomes are offered for thinking holistically.

Bloom's Level: Remember (recognize, recall...)

- Define the terms: system, boundary, environment, system component
- Define the terms: variables that are controllable, variables that can be influenced, variables that are uncontrollable, and variables that can be predicted

Bloom's Level: Understand (interpret, exemplify, classify, summarize, infer, compare, explain...)

- Explain how a system, its boundary, and its environment are related to the terms: controllable variables, uncontrollable variables, variables that can be influenced and variables that can be predicted
- Give an example of a system, describe its boundary, its environment, and the associated controllable and uncontrollable variables
- Explain why the ideas of system, boundary, and environment are important in the practice of engineering design
- Explain the roles of natural science, social science, and the humanities in the practice of engineering. Billington has long stated that engineering is not applied science, but rests on three pillars of natural sciences, social sciences, and the humanities^{45,46}.

- Interpret the concepts of system and environment from the perspectives of engineering and business
- Explain interactions between a system and its environment
- Give an example illustrating how different system components might interact
- Explain how focusing on “managing environments/systems” rather than “managing individuals/functions/tasks” might lead to higher quality

Bloom’s Level: Apply (execute, implement...)

- Given the context of a design challenge, identify a system, boundary, and environment relevant to the design challenge that is posed. Describe how interactions between the system and its environment might influence decisions made in the process of addressing the design challenge. Describe how the system, boundary, environment, and their interactions change if the decision maker shifts focus among natural science, social science, humanities or combinations of the three.
- Given the context of a design challenge and an identified system, identify various system components and describe interactions among the system components

Bloom’s Level: Analyze (deconstruct, organize, break into parts...)

- Given the context of a design challenge, create a concept map that depicts the system parts, its boundary, its environment, and the relationships among them.
- Create a chart that illustrates the effect of at least two decisions on the parts of the system and the interactions among the parts.
- Describe how interactions between the system and its environment might influence decisions made in the process of addressing the design challenge.
- Create a chart that shows how the system, boundary, environment, and their interactions change if the decision maker shifts focus among natural science, social science, humanities or combinations of the three.

Bloom’s Level: Evaluate (check, critique...)

- Given the context of a design challenge and a proposal in which the system and its environment have been identified and interactions relevant to the design challenge have been described, construct a set of criteria against which the proposal can be evaluated, evaluate the proposal, and justify the conclusions that have been reached
- Given the context of a design challenge and several alternative proposals in which systems and their environments have been identified and interactions have been described, select one project and justify the selection.

Bloom’s Level: Create (generating, planning, producing...)

- Construct processes with which decisions about identification of a system and its environment can be made. Apply these processes to develop examples of the identification of a system and its environment. Analyze interactions between the system and its environment and demonstrate the relevance of these interactions to design decisions that might be made in the context of the example.
- Given a design challenge, create a solution, describe the probable effect of solution on the system parts and their relationships; discuss the assumptions made in the generation of the solution.

Emergence and Interactions in Systems

Section 2.3.2, Emergence and Interactions in Systems, in the CDIO Syllabus Report describes the ideas associated with student learning in this area of systems thinking:

- “The abstractions necessary to define and model system
- The behavioral and functional properties (intended and unintended) which emerge from the system
- The important interfaces among elements
- Evolutionary adaptation over time”³⁰

Emergence and interactions in systems is the area in which system dynamics and its various tools: system archetypes⁶, difference equations, differential equations, system stability analysis, etc plays a prominent role. The key ideas in this area include: (a) breaking a system into components, (b) studying interactions among components, (c) predict the evolution of the system over time, and (d) illustrating effects the complexity of possible behaviors when the number of components and interactions become large, e.g., emergent behavior, on potential design decisions. The conceptual and mathematical models that can be constructed and analyzed for various systems range from simple to extremely complex. From a business context, Senge has highlighted the role that time delay in interaction among system components may place in giving rise to unforeseen behavior¹⁶. Analyzing stability and behavior of mathematical models that include delay can be extremely challenging. Dym et al²⁶ cite research⁴⁷ on difficulties that management and engineering students have with learning to understand and apply models and results from system dynamics. Using the key ideas of system components, interaction, and system dynamics, the following learning outcomes are offered.

Bloom’s Level: Remember (recognize, recall...)

- Define the terms: system component, interaction, interrelatedness
- Define complexity, chaos, self-organizing systems

Bloom’s Level: Understand (interpret, exemplify, classify, summarize, infer, compare, explain...)

- Explain how different system components might interact
- Explain a causal loop model^{6,26} of a system
- Explain how Senge’s archetypes of system dynamics operate
- Given a description of the behavior of a system, decide whether the system is stable or unstable and explain.
- Explain how a stocks and flow model⁴⁸ of a system might be developed
- Explain some of the best known strategies used to implement systems thinking including systems modeling, simulations, and scenario planning⁴⁹

Bloom’s Level: Apply (execute, implement...)

- Given a design challenge and an identified system, identify various system components and describe interactions among the system components
- Generate new examples of applications of Senge’s archetypes of system dynamics

- Solve a set of difference equations and describe the evolution of the solution over time
- Solve a set of differential equations and describe the evolution of the solution over time
- Apply stability analysis tools (root locus, Nyquist Criterion, etc) to determine the stability of a system

Bloom's Level: Analyze (deconstruct, organize, break into parts...)

- Given a design challenge to provide context and an identified system, construct a model that organizes system components and their interactions
- Given a system, system components, and interactions, construct a set of difference or differential equations for the system

Bloom's Level: Evaluate (check, critique...)

- Given a design challenge to provide context and an identified system, use results from analysis of system stability and behavior to select one or more choices from a set of design options

Bloom's Level: Create (generate, plan, produce...)

- Create new approaches to modeling systems and estimating the evolution of their behavior over time

Prioritization and Focus

Section 2.3.3 Prioritization and Focus, of the CDIO Syllabus Report describes the ideas associated with student learning in this area of systems thinking:

- “All factors relevant to the system in the whole
- The driving factors from among the whole
- Energy and resource allocations to resolve the driving issues”³⁰

Emphasis for this area of systems thinking shifts from the detailed complexity of system dynamics, with its conceptual and mathematical tools to determine the evolution of the behavior of a system, back to holistic decisions involving the entire system. Estimation and reasoning about uncertainty, which were identified by Dym et al.¹⁹, are relevant to this area. Estimation is valuable in at least three different fields. First, students should be able to construct estimates for the performance of potential designs or estimates for the impacts of alternative decisions being considered. Second, students should be able to construct estimates for the costs of various approaches to project implementation. Third, students should be able to construct estimates for timelines for project implementation. Since these are estimates, there will be uncertainty in each estimate and students should be able to estimate risks associated with the uncertainties in the estimates and incorporate the risks in the decision-making process. Using the key ideas of uncertainty and estimation in decision-making and project management, the following learning outcomes are constructed.

Bloom's Level: Remember (recognize, recall...)

- Define uncertainty in the context of engineering design and decision-making situations
- List several approaches that can be used in estimation
- Define risk
- List several approaches to risk management

Bloom's Level: Understand (interpret, exemplify, classify, summarize, infer, compare, explain...)

- Explain how uncertainty affects engineering design and decision making
- Explain why estimates are necessary in engineering design and decision making contexts
- Give an example of a situation in which a decision might be made to ignore particular variables; explain why this decision might be made.
- Given a design challenge to provide context, identify sources of uncertainty, examples where estimates will be required, and sources of risk
- Explain how scenario analysis might be used as one approach to risk management
- Explain how experiments can be used to reduce uncertainty in estimates and lower risk to successful completion of the project
- Describe how to determine the resources that are available for a project

Bloom's Level: Apply (execute, implement...)

- Given a context, provide an estimate for a specified quantity; state assumptions made in arriving at the estimate
- Given a context, apply several different approaches to risk management to construct strategies for project implementation
- Given a context and a list of factors, quantify the uncertainty due to each of the factors

Bloom's Level: Analyze (deconstruct, organize, break into parts...)

- Prepare a flow chart to illustrate steps in an estimation process
- Prepare a flow chart to illustrate steps in an approach to risk management
- Prepare a flow chart to illustrate steps to constructing a timeline for project implementation
- Compare and contrast risks associated with at least two different approaches to a project

Bloom's Level: Evaluate (check, critique...)

- Develop criteria for choosing among several estimates for a specified quantity
- Develop criteria for choosing among several approaches to risk management
- Given several different approaches that have been developed for project implementation, including timelines and cost estimates, select one approach and justify your selection
- Critique the use of probability theory as a general approach for addressing uncertainty

Bloom's Level: Create (generate, plan, produce...)

- Develop a new approach to constructing estimates
- Develop a new approach for risk management

Tradeoffs, Judgment and Balance in Resolution

Section 2.3.4, Trade-offs, Judgment and Balance in Resolution, of the CDIO Syllabus Report describes the ideas associated with student learning in this area of systems thinking:

- “Tensions and factors to resolve through trade-offs
- Solutions that balance various factors, resolve tensions and optimize the system as a whole
- Flexible vs. optimal solutions over the system lifetime
- Possible improvements in the systems thinking used”³⁰

The key idea in this area is system optimization, which can range from generic exhortations to consider the performance and costs of the whole when making decisions to formulating utility functions and finding optimal solutions using complex mathematical algorithms. Working from this admittedly vague background, the following learning outcomes are offered for the area of tradeoffs, judgment and balance in resolution.

Bloom’s Level: Remember (recognize, recall...)

- Define short-term and long-term outcomes
- List factors that should be considered in estimating life cycle costs
- Given a context, list factors that should be considered in system optimization
- Given a context, list environmental factors that should be considered in system optimization
- List different approaches to addressing tradeoffs in system optimization
- Given the context of a design challenge, identify stakeholders who will be interested in the outcome of the design process

Bloom’s Level: Understand (interpret, exemplify, classify, summarize, infer, compare, explain...)

- Explain differences between short-term and long-term outcomes and why both sets of outcomes should be considered when optimizing a system
- Explain why tradeoffs among desirable outcomes occur very frequently when trying to optimize a system and how these create tensions that must be resolved
- Give one or more examples of why interests of different stakeholders in a decision-making situation may create tension

Bloom’s Level: Apply (execute, implement...)

- Given the context of a design challenge, develop a set of tradeoffs that might be addressed in the process of developing a design. Illustrate how different stakeholders might address the tradeoffs differently

Bloom's Level: Analyze (deconstruct, organize, break into parts...)

- Break down the driving factors within a given design system and illustrate how they influence desired outcomes
- Compare the design with respect to two different desired outcomes (e.g., flexibility vs. short-term performance)
- Investigate the impact of one improvement in the system on each of the system outcomes

Bloom's Level: Evaluate (check, critique...)

- Given justifications for specific design decisions made in the context of a design challenge, critique the justifications

Bloom's Level: Create (generate, plan, produce...)

- Generate a new system based on suggested improvements to system parts considering trade-offs of factors and tensions posed. Desired outcome defined in advance as flexible or optimal for long-term.

Discussion

Given the importance attached in the literature to systems thinking for future engineering graduates, the authors expected that more research could be found in which expectations for learning with respect to systems thinking were articulated. However, the authors did not find resources in which researchers, who advocated for systems thinking as an attribute for engineering graduates, set out their expectations for how to recognize graduates who had the desired capability. Given this surprising result from their literature search, the authors proposed individual learning outcomes. However, the authors thought that they could create a more comprehensive set of learning outcomes if they first established a framework within which individual learning outcomes would appear.

For one component of the framework, the authors chose the CDIO Syllabus²⁹. The CDIO Syllabus is not a syllabus in the traditional sense; it is the best supported, most comprehensive, and thoroughly detailed set of expectations for engineering graduates that the authors found in the literature. The CDIO Project now includes engineering departments from at least twenty-two institutions and has surveyed numerous industrial representatives to develop the CDIO Syllabus. However, the CDIO Syllabus does not articulate its expectations in the form of learning outcomes, which would clarify expectations and provide expectations for engineering graduates in a format that would simplify the challenge of developing assessment methodologies to support the expectations. Assessment is recognized by educators as the ongoing process of establishing clear, identifiable expected outcomes of student learning^{50,51}.

To help develop learning outcomes, the author needed an additional dimension for their framework and they chose the six levels of learning in the Revised Bloom's Taxonomy. The revised taxonomy includes both the kind of knowledge to be learned (knowledge dimension) and the process used to learn (cognitive process), allowing an instructional designer to efficiently align objectives to assessment techniques⁵². Because of its six

levels of thinking, Bloom's revised taxonomy can provide a framework for planning the instruction process that incorporates low to high-level thinking activities.

Within the framework they created, the authors have offered a set of learning outcomes with which engineering graduates who are systems thinkers might be recognized. At least two directions for future research may be proposed. First, input from stakeholders interested in systems thinking for engineering graduates could be solicited to refine the learning outcomes that have been developed. One way to accomplish this research would be via surveys that ask respondents to rate the importance of learning outcomes developed to date and provide additional learning outcomes that articulate expectations that are not offered by the current set. Second, researchers could develop assessment methodologies for the learning outcomes to enable data to be collected on the performance of current engineering graduates with respect to systems thinking. Both research directions would likely promote more constructive and informed conversations about how systems thinking might be assessed and developed.

Conclusions

If systems thinking is added to the list of desired outcomes for engineering graduates, then assessment of systems thinking and instructional design for systems thinking will be aided by construction of learning outcomes that portray expectations for learning in terms of what students will be expected to do and how they will be expected to think. Searching through the literature revealed numerous and varying conceptions of what constituted systems thinking. However, very few instances were found in which authors depicted expectations in terms that conformed to requirements for learning outcomes. Constructing a preliminary set of learning outcomes might advance conversations about expanding the role of systems thinking in undergraduate engineering education. A framework for learning outcomes was developed by combining the CDIO Syllabus²⁹ with the six levels of learning in the revised Bloom's taxonomy⁴⁰. Using this framework, the authors developed a preliminary set of learning outcomes. It is the intent of the authors, that the set of learning outcomes will stimulate additional reflection and conversation about how students might demonstrate learning with respect to systems thinking and how learning might be improved.

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