Member Viewpoint
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NAC Executive Insights

Systems Thinking in the Construction Industry

Key Points

- Systems thinking is a fundamentally new skill set that the construction industry requires.
- Systems thinking examines connected wholes rather than separate parts—making sense of complexity.
- The construction industry must recognize the unintended consequences of decisions being made.
- Systems thinking is a disciplined approach to examining challenges more completely before acting.
- Systems thinking is a challenge to traditional engineering practice: it reframes engineers' approaches to complex problem solving, regardless of discipline.
- Today's engineers must understand the psychological, cultural, economic, political, and environmental implications of their engineering decisions.

Introduction

The industry has identified systems thinking as a key future competency. This broadened competency is driven by the need for current and future engineers and constructors to address significantly more complex challenges. These challenges can be best characterized by:

- **Growing complexity**, with significant degrees of coupling, including often unseen constraint coupling.
- **Emergence**, both the problem set to be addressed and the available solution set.
- **Extended life cycles**, measured in generations versus years or decades.
- **The growing need for a holistic focus**, balancing environmental, social, and costs over these now extended lifetimes.
- **System of Systems** (SOS) problem sets for which no singular deterministic solution exists.

This Executive Insight focuses on defining the challenge of systems thinking, particularly as it relates to engineering education.

Role of the Construction Industry

The construction industry must recognize that systems thinking is a fundamentally new skill set that is needed—without question—in the industry's mission. The industry must foster and drive the broadened mindset that is required to protect and advance the health, safety, and welfare of the public while delivering ever more safe, resilient, and sustainable infrastructure. Utilizing this systems approach, the construction profession can better assure that industry efforts foster good environmental, social, and governance (ESG) outcomes.

The role of construction industry organizations is to:

- Raise awareness of the importance and elements of systems thinking within industry leadership.
- Define the types of changes that may be required for the industry.
- Define how the role of engineers and constructors may change and how new opportunities may be created.
- Identify potential new skill sets that engineers/constructors may require and identify gaps in existing educational programs (discussed in this Executive Insight).
- Identify required expansions in the profession's body of knowledge.
- Identify the new challenges to be met and the current gaps in focus, research, codes, and standards.

What Is Systems Thinking?

Systems thinking is a holistic approach that focuses on the way a system's constituent parts interrelate and how systems work over time and within the context of larger systems of systems. The systems thinking approach contrasts with traditional analysis, which studies systems by breaking them down (decomposing) into their separate elements. Systems thinking looks at connected wholes rather than separate parts. It seeks to make sense of complexity by looking in terms of these wholes and relationships rather than decomposed parts. It is a framework for seeing *interrelationships* rather than *things*, for seeing *patterns of change* rather than static *snapshots*.

Systems thinking seeks to expand the range of options available for solving a problem. It is about looking not only at the direct challenge, but at other factors acting on it. With systems thinking, problems are solved by investigating factors and outcomes of those factors. It is particularly useful when confronted with a "wicked problem."

> Wicked Problems — an idea or problem that cannot be fixed, a problem where there is no single solution.
>
> - The problem involves many stakeholders with different values and priorities.
> - The issue's roots are complex and tangled.
> - The problem is difficult to come to grips with and changes with every attempt to address it.
> - The challenge has no precedent.
> - There is nothing to indicate the right answer to the problem.

Comprehensive systems thinking is a holistic approach to problem solving in which connections and interactions between constituent parts and the immediate work, stakeholder needs, broader contextual aspects (e.g., social, and environmental), and potential impacts over time are identified and integrated into decision making. It must not be conflated with systems engineering.

In some sense, systems thinking is a system of thinking about systems.

Characteristics of a Systems Thinker

Systems thinkers share several important characteristics. They:

- Are curious (system thinking is a framework for curiosity).
- Have an open mind.
- Are good listeners.
- Seek out root causes.
- Seek clarity through different perspectives (cross-functional teams).
- Articulate problems in new and creative ways.
- See the big picture rather than get derailed by details.
- Recognize that the whole is greater than the sum of its parts.
- Recognize that all the pieces and processes are connected, directly or indirectly, and all affect the outcome.
- Create new, informed choices (recognize that multiple solutions may exist).
- Have the courage of their convictions.

Examples of Systems Thinking

An iceberg metaphor is often used to describe systems thinking. With an iceberg, there are two aspects: what is visible above the water, and a bigger, unseen portion below the water.

A systems thinker might approach a problem by asking:

- What could be under the water that is not seen?
- What are the conditions (client or workplace expectations, staffing issues, budget or other resource constraints, regulatory requirements or stability) that influence the problem?
- What issues, factors, people, or systems are working together to create what is seen above the water?
- What ripple effects (unintended impacts or consequences) might be created by our ideas/solutions?

A second example, relevant to engineers, relates to a piece of machinery where one gear breaks repeatably and frequently. Instead of replacing the gear over and over, a systems thinking approach might look at:

- the gear's construction and design (casting, forging, metallurgy).
- the operational conditions (weight, friction, torque, noise).
- the environmental conditions (temperature, humidity, sanitation).
- the maintenance (cleanliness, lubrication).

Various interconnected factors could be affecting the gear's performance and durability.

A third example of the importance of fully investigating and understanding the ripple effects created in complex systems (such as are found in human nature and ecosystems that are a significant domain of civil engineers) can be seen in a seventy-year-old example from Borneo. In this case, the people of Borneo were suffering from an outbreak of malaria. They appealed for a solution from the World Health Organization {WHO). A decision was then made to spray pesticide to control the malaria outbreak. This killed malaria-carrying bugs, but it also killed wasps, which controlled a worm population. Worms ate through the thatch roofs, many of which collapsed. The pesticides also were ingested by other insects, which were consumed by lizards, which were the food for Borneo’s cats. Eventually, the cats died off from pesticide poisoning, which caused the rat population to explode.

Systems thinking takes into account possible ripple effects before a decision is made. It recognizes the inherent complexity and coupling that exists in large complex systems.

A fourth example of where systems thinking is essential is in a construction project that is behind schedule. Adding another crew or working overtime for a few weeks may aid in catching up. Adding too many crews or working overtime for extended periods, however, may lower productivity as the crews interfere with each other (both directly and indirectly) and fatigue sets in.

Core Building Blocks in Systems Thinking

Throughout the engineering curriculum in higher education, students now must be challenged to adopt a more holistic, systems thinking approach. This does not mean displacing traditional design thinking. Rather, the curriculum needs expanding to include systems thinking. Some of the building blocks to be integrated into the engineering curriculum include:

- **Understanding interconnections** — This must begin with a recognition that people (human system) and systems (engineered systems and ecosystems) are interconnected and that actions in one system influence the outcomes in another system. A comprehensive understanding of these interconnections requires the student to identify them and then to look at potential second or third order interconnections, including hidden coupling through constraints. The problems considered in the curriculum must have a broadened solution set that moves the student’s thinking from simply linear solutions to circular solutions that are more holistic and life-cycle oriented.
- **Understanding the concept of emergence** — This is particularly important as it relates to large complex systems, which are the domain of the greatest engineering problems now being faced: global climate change, natural and

engineered resilience, and re-envisioned cities. Emergence shapes both the problems to be addressed and the outcome set that may result. It results from interactions of parts of a system as well as system-to-system interactions. Emergence is a force that results in new, more innovative solutions that are not possible with traditional design thinking.

- **Lateral synthesis** — This requires a more granular look at cross-domain factors and knowledge. It is characterized by combining well-established ways in a broadened domain set to achieve a new solution and gain added information for even deeper insights.
- **Importance and nature of flows** — Many of the complex systems challenges engineers/constructors face are living systems, where various flows within and into the system shape the success of short-term solutions and longer-term outcomes. Engineers must move beyond solving problems through decomposition linked by transformative flows. Instead, broader systems environments must be recognized, such as influencing flows from stakeholders and other systems as well as induced flows and attendant feedback loops that are created.
- **Coupling and causality** — Systems contain myriad couplings of several types and strengths. These couplings can contribute to perturbations and changes in system behaviors, both forward and backward. Cause and effect are no longer simply obvious but require the systems thinker to understand both direct and indirect influences.
- **Map is not the territory** — System mapping describes aspects of a system setting that appear to be important yet do not necessarily tell the full story of the system's context. Nevertheless, having a systems map is important in gaining a clearer picture of the system or challenge being addressed. The systems thinker recognizes the map is a two-dimensional simplification of a multi-dimensional challenge.

System Thinking Methodologies

The most important change required for systems thinking is a changed mindset and perspective. A range of methodologies are available that engineering students should be exposed to, remembering in all instances that it is the broader, more holistic perspective that is essential. Some methodologies to be considered include:

- Scenario analysis.
- Computer simulations and other dynamic modeling tools where both assumptions and behaviors are tested as well as testing relationships between system elements.
- Behavior-over-time graphs, which look at how variations of key assumptions or variables affect not only outputs but outcomes as well.

- Causal loop diagrams, which seek to capture relationships between system elements. These can also be applied to system of systems problems.
- Stock-and-flow diagrams.
- Systemic root-cause analysis.
- Archetypes (universal, inborn models of people, behaviors, and personalities that play a role in influencing human behavior).

Systems thinking requires sensitivity to the circular nature of the world; an awareness of the role of structure in creating the conditions faced; a recognition that powerful laws of systems operate that humans are not unaware of; and a realization that there are consequences to actions. While the tools described above are important, the broader context of systems thinking must not be lost. It is a disciplined approach to examining challenges more completely before acting on them.

Systems Thinking in Engineering

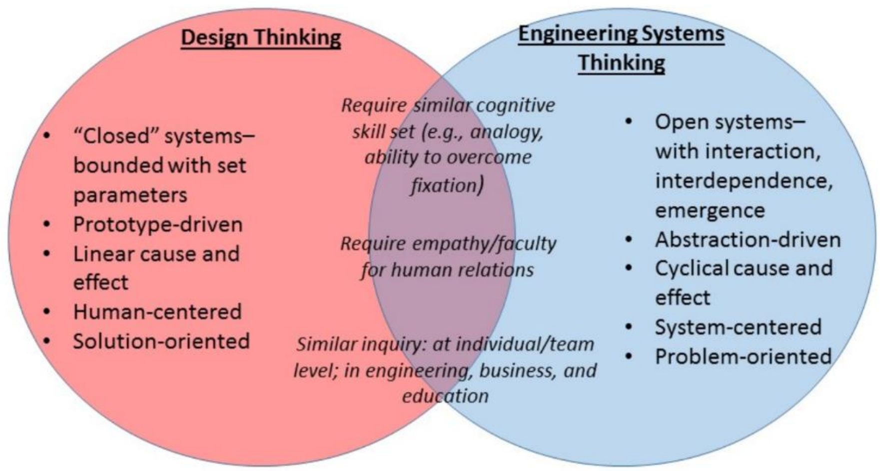
Engineering systems thinking research often emphasizes recognition of the constituent elements of an immediate problem. The research, however, frequently underplays the range of contextual factors that *interact* with the problem. Several recent studies recognize the importance of integrating context into engineering solutions but have not explicitly tied contextual competence to systems thinking.

Systems thinking is related to other competencies, abilities, and frameworks, including interdisciplinary competence, socio-technical thinking, and the holistic contextual framework for design. Interdisciplinary competence is multidimensional and includes students' ability to synthesize information within discipline, beliefs regarding the nature of engineering problems, and valuation of interdisciplinary work. Socio-technical thinking is "the ability to integrate social and technical dimensions in solving a design problem."

The holistic contextual framework aims to aid designers in understanding contextual factors when working in low-resource settings. While systems thinking often necessitates drawing on various aspects of these competencies and can benefit from existing assessments and frameworks of related competencies, systems thinking differentiates itself with its attention to and concern with complexity, particularly the interconnectedness of various aspects of a problem.

Systems thinking is a challenge to traditional engineering practice. Comprehensive systems thinking is not a methodology; it reframes engineers' approaches to complex problem solving, regardless of discipline, and provides a framework for what such problem-solving approaches should look like. It advocates a holistic rather than reductionist approach, incorporating broader contextual factors in addition to the constituent elements of an immediate problem. It also recognizes that, increasingly, the problems that engineers work on are sociotechnical problems, which integrate technology, people, and services and thus create a need to combine perspectives from engineering, management, and social sciences.

Traditional design thinking, which engineers have been and still are trained in, differs noticeably from systems thinking as shown in the following figure. Design thinking's closed-systems approach contrasts sharply with the abstraction-driven, open-systems approach inherent in systems thinking.



The Undergraduate Challenge

Systems thinking is usually not integrated into undergraduate engineering curricula; instead, it is either taught as a stand-alone independent program or is not included in the curricula. Increasingly, however, the emphasis on how to improve performance by exploiting the interconnections of infrastructure with the various interfacing technological systems, society, and the environment shifts the undergraduate engineering emphasis squarely into approaches dominated by systems thinking.

Psychology, sociology, culture, politics, and economics have been viewed as domains separate from and independent of engineering. It is now recognized that these societal elements are intimately tied to the technologies that serve them, often in complex ways. Today's engineers must be educated in understanding the psychological, cultural, economic, political, and environmental implications of their engineering decisions.

Traditional engineering education does not provide the broad systemic perspective required, nor does it facilitate holistic thinking. Nontechnical issues such as culture, politics, and psychology are not considered, yet they are intimately tied to the performance and function of engineered systems. Traditional engineering is taught from a linear perspective (problem-action-solution) and does not consider feedback, nor does it identify the user system into which engineered solutions fit. System thinking addresses these shortcomings.

Barriers to incorporating systems thinking into undergraduate engineering curricula include:

- Systems thinking benefits are not understood by administrators and instructors.
- Systems thinking methodology and tools are not well-understood by instructors.
- Systems thinking is perceived to be a substitute or replacement for (as opposed to an adjunct to) conventional, tried-and-true engineering approaches.

- Engineering curricula are full and cannot accommodate additional courses.

Engineers of today must be trained to think and problem-solve as systems thinkers. They must think holistically and adopt a broad definition of “system,” and they must understand the complex interactions (including feedback and emergence) among system components. They must recognize more than one solution usually exists to any complex problem and their engineering judgment must be tempered with an appreciation for sociological, cultural, ethical, political, and psychological factors. Addressing socio-technical challenges requires a global perspective since perceptions of engineering solutions acceptable to various cultures can differ widely.

A more integrative approach that embeds the lessons and tools of systems thinking into the context of traditional engineering courses will aid in the contextual shift that today’s engineers must make. These systems thinking tools include:

- **Conceptual modeling tools** to articulate and frame issues, elicit knowledge and beliefs, and meaningfully organize information to appreciate underlying causal structures. These include causal loop diagrams; stock-and-flow diagrams; behavior-over-time plots; and the iceberg model (discussed earlier).
- **Dynamic modeling tools** to assess the dynamics of those causal structures and to evaluate potential interventions.
- **Holistic thinking tools** to ensure that complex problems are not addressed using unidimensional solutions.

Instructors must seek opportunities to demonstrate systems thinking as an adjunct and not a replacement to traditional methods. For example:

- Whenever a differential equation is used, a system dynamics model may be used in addition.
- Whenever a solution is sought to an infrastructure or design problem, systems thinking should be applied since complex socio-economic problems cannot be solved by technology alone.

Accreditation Board of Engineering and Technology (ABET) Challenge

Behavior-based, comprehensive systems thinking assessments are an obvious need in university engineering instruction. The Accreditation Board of Engineering and Technology (ABET), a non-governmental organization that accredits post-secondary education programs in applied and natural sciences, computing, engineering, and engineering technology, continues to include student outcomes that are related to contextual competence. Although many of these assessments are relatively new and cover system element identification, connections between elements, and temporal considerations, few address the broader context or stakeholders.

Most of the assessments that push beyond a narrow technical focus are preference based, and thus do not provide an in-depth understanding of the systems thinking skills that engineering students or professionals need. This means engineering as a field will continue to devalue the importance of contextual aspects of developing systems thinking skills. This is despite ABET stating that all engineering baccalaureate graduates should possess "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."

Overcoming Resistance in Undergraduate Engineering

The following is a partial list of recommendations for academia to consider:

- Engineering instructors and administrators should educate themselves about systems thinking tools and their application. Several courses are available, as are several good books.
- College administrators should invoke the teaching of systems thinking to support ABET standards.
- Systems thinking researchers and practitioners should continue to demonstrate and publish the beneficial results accruing from the application of systems thinking to engineering problems. Initial applications can focus on incorporating conceptual modeling approaches (such as causal loop and stock and flow diagrams) into typical engineering texts that address dynamic modeling of systems.
- College administrators should require that systems thinking be taught as a part of every engineering program—not as a stand-alone course or courses, but integrated with the other engineering disciplines, just as calculus and physics are.
- Industry advisory boards to university engineering departments should stress the importance of systems thinking concepts in undergraduate engineering education.

Academic Sources of Note

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Kelley E. Dugan, PhD candidate, Department of Mechanical Engineering, College of Engineering, University of Michigan, Ann Arbor, MI.

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