Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
ASEE
Paper ID #47638

# Integrating Complexity Leadership in Thermal Fluids Capstone Design

**Dr. Fiona C. Zoutendyk, Worcester Polytechnic Institute**

Dr. Fiona Zoutendyk is an Associate Professor of Teaching in the Department of Mechanical and Materials Engineering at Worcester Polytechnic Institute. She holds a PhD in Metallurgical Engineering and Materials Science. She draws from her cross-functional team experience in applied research and development prior to moving into academia.

**Dr. Kimberly LeChasseur, Worcester Polytechnic Institute**

Dr. Kimberly LeChasseur is a researcher and evaluator with the Worcester Polytechnic Institute. She holds a dual appointment with the Center for Project-Based Learning and the Morgan Teaching and Learning Center. Her PhD is in Educational Leadership

# Integrating Complexity Leadership in Thermal Fluids Capstone Design

## 1. Introduction

Students in undergraduate engineering programs often face a series of courses that reward them for procedural knowledge that is presented, memorized, and performed. When first encountering design courses, students are challenged to engage in learning that may be organized in fundamentally different ways. This can be liberating for those who prefer to approach new concepts holistically and have learned to hold both the individual parts and their relationships to the whole system in mind simultaneously. However, it can be frustrating for those who struggle with the complexity and ambiguity of systems thinking.

In preparing the engineers of the future, we are also preparing future leaders. Doing so demands that we consider which skills and mindsets these future leaders will need; it also requires that we assess whether the methods we are using to prepare them reflect the ways they will be expected to enact leadership roles. In other words, how might faculty model the leadership students will be asked to enact in their careers? Faculty have a unique opportunity to demonstrate to future leaders how they might operate within the complex, multisystem world they inherit (see Standard 7 of the CDIO Standards 3.0, in [1]).

This paper explores how faculty might teach students how to embody complexity leadership within a capstone course that includes systems thinking as a learning outcome for students. Many capstone courses, design courses, and similar existing engineering courses address systems without explicitly teaching systems thinking skills and habits. An engineering capstone design experience provides an opportunity for students to apply knowledge and skills from their major to complex engineering problems and engineering design. During this process, students consider trade-offs and multiple parts or perspectives. Many of the designs tackled in these courses are at the system level, whereas others focus on a component or a process. Students may not inherently understand how to tackle a complex problem at the system level. While others have focused on defining systems thinking, its utility in the curriculum, and appropriate assessment practices, there has been less attention paid to how pedagogies can be used to reinforce systems thinking among students. This study uses a phenomenological design to describe a pedagogical approach to design courses that scaffolds students' development of systems thinking skills and mindsets within the context of capstones on thermal fluids in mechanical engineering.

## 2. Literature and Theoretical Frameworks

### 2.1 Systems Thinking

Engineering relies on an ability to consider systems as a whole and how its parts relate to each other in the initial design, in evaluating what is and is not working, and in improving a solution to a given problem. Systems thinking can be considered as a way of thinking which involves “a system of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects” (p.675 of [2]). The mindset of systems thinking involves considering the systems involved in each engineering design problem, which Plate and Monroe [3] call systems literacy. Students may begin their engineering studies with some intuition about systems, but need to be taught how to think about systems in explicit terms.

This study adopts Arnold and Wade’s [4] framework for understanding “systems thinking maturity” (p. 9) as a way of organizing the knowledge, skills, and attitudes we hope to instill in students. The first of the four domains in this framework is systems mindsets, which includes exploring multiple perspectives, considering the whole and the parts together, responding effectively to uncertainty and ambiguity, and being able to identify your own and others’ errors, considering issues appropriately, and making appropriate assumptions. Systems mindsets prompt students to approach engineering design from the perspective that all engineering involves systems and that design efforts must respond to the systems involved to be successful. The skills in this domain allow students to understand how to approach systemic problems. Arnold and Wade [4] describe this first domain as being the most “meta” in that developing a systems mindset informs and develops the skills involved in the remaining three domains.

The second domain is systems content, which involves the ability to recognize systems, maintain boundaries, and differentiate and quantify the elements of a system. Systems content skills allow students to analyze systems, specifically to understand what is in the system. The third domain is systems structures, including skills for identifying and characterizing relationships and for identifying and characterizing feedback loops within systems. These skills emphasize understanding how a system is organized. The final domain is systems behavior, which includes being able to describe past system behavior, predict future system behavior, respond to changes over time, and use leverage points to produce effects. This domain entails mastery over what happens when content and structure interact in a system.

Together, these domains describe the knowledge, skills, and mindsets that students must have to be able to engage in Arnold and Wade’s [2] four principles of systems thinking: identifying systems, understanding systems, predicting systems behavior, and devising modifications to systems to produce desired effects. A major reason we adopted this framework is that it is organized to make assessment pragmatic, yet holistic. However, we contend that this framework (and other existing models synthesized in its development) focus exclusively on the learning of systems thinking and fall short of describing the teaching of systems thinking.

### 2.2 Complexity Leadership

We extend the systems thinking framework used in this study to describe the teaching of systems thinking by describing it as a form of complexity leadership. Both represent applications of complexity science, which offers an alternative way of thinking than classical, reductionist engineering paradigms [5]. Complexity perspectives recognize that the challenges facing engineers – the convergence of large-scale, interdependent threats from climate change, global conflict, rapid technological transformation, among other threats – occurs through interdependent, cascading relationships [6]. This complexity renders reductionist paradigms, such as those that solely simplify problems into separate parts that can be resolved in sequence, insufficient.

Leadership practice that reflects the complexity of the world embraced in complexity science perspectives has been described by several researchers in slightly different terms in recent decades [7]. We apply Uhl-Bien and Marion's [8] Complexity Leadership Theory to our analysis of teaching. According to their approach, complexity leadership "focuses on enabling the adaptive, creative, and learning capabilities within complex adaptive systems within an organization" (p. 5). Their view is that complex adaptive systems cannot be adequately led using hierarchical organization of roles and power, as it is often organized in organizations with more simplistic goals, contexts, and mechanisms. When we apply such thinking to how an undergraduate engineering capstone course might be best facilitated, we find that a similar focus on interaction, relationships, and an emergent, adaptable approach also describe the venture of teaching as leadership.

Complexity Leadership Theory has been examined as a means of motivating transformation in engineering education at the department level [9], institutional level [10], and across the field of engineering education [5]. Little has been explored in applying it to classroom teaching practices, however. As Rosenhead and colleagues [7] asked, "What can we learn collectively from complexity theory that can inform leadership research and practice?", we ask how it can inform teaching research and practice.

### 2.3 Systems Thinking in Undergraduate Engineering Education

The need for systems thinking in undergraduate engineering education is recognized, and yet its implementation remains elusive [11] - [16]. Of note is the significant overlap between systems thinking and design thinking skills [17]. Engineering courses that ask students to engage in design activities, such as many capstone courses, involve systems thinking as they require students to consider how a system will act within their design. Part of good design in engineering is understanding and taking into account the consequences of design decisions on other parts of the engineering system under development. However, if this aspect of design work is not made explicit, students who are new to design challenges may not realize they are engaging in systems work. A case has been made for integrating systems thinking into the fabric of the curriculum, with concrete examples provided for incorporating systems thinking into discrete problems covering an array of topics in a variety of mainstream engineering disciplines using a system dynamics approach [12].

The inclusion of systems thinking in undergraduate education has primarily been in the context of systems engineering programs [12], [17] - [21]. Systems Engineering is transdisciplinary, at the intersection of science, technology and management, with systems thinking at its core [22], and is mostly offered at the graduate level [16], [23], [24].

Due to the usefulness of systems thinking skills in the profession, some mainstream undergraduate engineering programs have explicitly incorporated them into the curriculum; however, pedagogical approaches have been limited and varied [12] - [14]. In Bristol, UK, all fourth-year engineering students were taught how to develop a system architecture for an engineering problem during a one semester master's level Systems Engineering e-course. The content was structured for individual student learning and assessed using closed-form and open-response questions [13].

Another approach was to use a broader, more implicit teaching and learning model. Australian second- and fourth-year students in chemical and civil engineering classes were surveyed for their perceived usefulness of systems thinking skills and the degree to which they had learned and been assessed on these skills. The skill set consisted of fourteen accreditation requirements that mapped directly to systems thinking. The students considered skills learned from multiple sources, including team-based projects, when completing their surveys. Although students reported systems thinking skills as useful for their careers, they felt that they had not learned them sufficiently, nor had they received sufficient assessment of the skills. Open-ended problems with ambiguity (second-year) and practical group project work on real-world scenarios (fourth-year) were cited as highly relevant to developing systems thinking skills [14].

A 2015 study compared the systems thinking skills of second-year engineering students enrolled in mechanical design courses by comparing their systems thinking skills assessed by means of a survey with observed systems thinking skills demonstrated by identifying sub-systems in a disassembled toaster. The study showed that students' perceptions of their systems thinking skills were similar to their assessed skills [15].

Mechanical engineering education embodies the design of both mechanical systems and thermal systems [25]. Thermal systems design is often undertaken as a capstone in the senior year and cannot be done without relying on systems thinking – students must be able to analyze and integrate individual components and processes, as well as previously siloed subjects, to be able to understand the systems they are designing. For example, in order to optimize a system incorporating thermal energy storage to reduce household heating and cooling loads, students need to combine their knowledge of thermodynamics, fluid mechanics and heat transfer and combine this with broader engineering considerations as they design, analyze and integrate subcomponents such as heat exchangers, pumps and pipes.

Yet studies and examples of teaching systems thinking in thermal fluid systems design courses are sparse. One example [26] details how students were taught the framework for systems thinking within the context of thermal systems. During the second lecture of a 30-lecture semester-long course, systems thinking was introduced with a YouTube video, then thermal systems were defined and discussed. The interaction between components and subsystems was explored during an in-class activity and included the consideration of design variables and methods for modeling the system. These concepts were reinforced with assigned homework to compare two thermal systems, as well as a reading assignment on the design of a third thermal system. Systems thinking skills were assessed by three qualitative problems in a quiz. An end of semester student survey indicated that students found "system thinking, engineering reasoning and decision making skills [useful].” A practitioner toolkit [27] for capstone course (re)design outlines pedagogy where systems thinking is integral, albeit implicit, for both instructor and students.

## 3. Methods

This study uses a phenomenological design to describe a pedagogical approach to design courses that scaffolds students’ development of systems thinking skills and mindsets within the context of mechanical engineering. Using mixed methods with interpretative phenomenological analysis, the findings present an approach that scaffolds systems thinking in design through a series of pedagogical choices.

### 3.1 Sample

Data for this study were collected from one course section of Thermal Fluids Capstone Design taught by a faculty member in the Mechanical and Materials Engineering Department at Worcester Polytechnic Institute (WPI). The faculty member has taught this course 7 times since joining the university in 2011. Her expertise in teaching has been recognized by being awarded a tenure track line with a teaching mission (rather than a more traditional dual mission role).

Of the 20 students in the course, 18 enrolled in the study. Of the participating students, 88% self-identified as men, 12% as women, and none as gender fluid, non-binary, or other genders. The majority of students were white (82%), another 12% self-reported being Asian or Asian American and 6% self-reported being Black or African American. There was a fairly even distribution in participating students' academic histories in high school: 24% reported that it was very easy for them to get the grade they wanted in all of their classes; 35% reported that it was easy to do so with a few exceptions; 18% indicated they had to work some, but not all that hard to get the grade they wanted in their classes; and 24% indicated they had to work hard to get the grade they wanted. On the whole, students acknowledged the more rigorous demands of college-level academics: 71% reported they have to work harder than they did in high school to get the grades they want and another 24% indicated they have to work the same amount. Only 6% - a single student - reported that they have to work less than they did in high school to get the grades they want.

### 3.2 Data Collection

The study draws on several data sources:

**Faculty interviews** were conducted by Author B with Author A about teaching a thermal fluids design-based capstone course. Data were recorded through notes taken during and after the interviews.

**Observations of class sessions** were conducted by Author B over three course sessions. In the first two, she took notes on student questions, student-faculty interactions, and the pedagogical practices organizing the course session. In the third session, Author B used a rubric collated from the first three domains of Arnold and Wade's [4] systems thinking measures to annotate observations of student presentations on their final capstone designs.

**Student reflections** were assigned after each of the four major course assignments and were used to collect student perspectives on four primary prompts: 1) What learning risks, if any, did you take? 2) What parts of the assignment did you do individually, in your sub-team, and together as a whole team? 3) What feedback did you give your team members? and 4) What skills did you learn or start to develop (technical and non-technical)? A total of 55 pages of student reflections were used as data in this study.

**Student surveys** were collected at the end of the course using the Student Assessment of their Learning Gains – a validated, reliable post-only survey [28] that elicits student perceptions of their own growth in knowledge and skills and the extent to which they attribute that growth to various learning activities and aspects of the course. Items ask students the extent to which they made gains in specific aspects of their learning (eg, "identifying what type of problem you are asked to solve," "developing a logical argument to defend a proposed solution") using a five-point scale from "no gains" to "great gains." The survey also asks students how much specific aspects of the class helped their learning (eg, attending lecture), allowing us to isolate student experiences of the new tool in user testing.

The SALG has been used by more than 22,000 instructors to assess nearly half a million students and has been validated as a measure of active learning, content mastery, and self-efficacy in the context of undergraduate mechanical engineering courses [29]. For this application to systems thinking, which we believe is novel, we customized questions using the student learning objectives for the course, as is customary, in addition to using several standard items (see Appendix A for the survey).

### 3.3 Analysis Procedures

The analyses triangulate faculty teaching intentions and student experiences while differentiating impact by student learning preferences and expectations. Faculty teaching intentions, as displayed in classroom observations, written in course materials, and discussed in interviews, were coded to derive themes aligned with Arnold and Wade's domains. Within each of these areas of teaching systems thinking, two rounds of coding were conducted by Author B to establish and validate themes.

Student experiences were assessed via student reflections data, which were coded to align with the domains of systems thinking. Similar to faculty teaching intentions, data were then coded twice within each domain to establish and validate themes related to student experiences of faculty teaching intentions. The resulting data for each theme was then assessed against faculty teaching intentions to determine whether students indicated experiencing what was intended consistently, inconsistently, or rarely.

Learning outcomes were assessed for each domain using items from the SALG survey. Due to the pilot study including a small sample size and the phenomenological research design, we calculated frequencies of responses by level of learning gains reported.

## 4. Findings

As a phenomenological study, our findings are organized to describe what it means to teach systems thinking as a form of complexity leadership. We do so from multiple perspectives, which are presented here in terms of faculty intentions (e.g., course design, teaching practices), student experiences, and outcomes.

### 4.1 Teaching Systems Mindset

#### 4.1.1 Faculty Teaching Intentions for Systems Mindset

This project-based course was structured with interwoven scaffolded layers of increasing complexity that develop systems thinking skills within the context of a theoretical thermal system design challenge. The general design challenge was outlined at the start of the course, together with how the course structure mapped to intended learning outcomes, including technical and professional skills. The term “systems thinking” was not used with students; rather, the instructor spoke about learning professional-level skills for examining and designing technical systems in teams.

Exploring multiple perspectives was taught through teamwork with assigned, rather than self-selected, team members. Students were required to work with people they did not know prior to the start of the course, and this inherently provided a diverse set of approaches during the design process. Teams were created after the first week of class once the course enrollment had settled and students had submitted one assignment individually. All remaining assignments and the final project were undertaken as a team. The second half of the course consisted exclusively of team-based project work, with instructor feedback every day during class.

Initial assignments in the first half of the course considered sub-systems related to the foundational courses of Thermodynamics, Fluid Mechanics and Heat Transfer. Students were explicitly shown how to consider the wholes and the parts in four 50-minute review sessions each week, plus one 50-minute open office hour held during a regularly scheduled class period. Each assignment was graded with detailed formative feedback that students were able to incorporate into their design process for the final project. The project contained a new sub-system that was related to previous assignments but needed to be designed and integrated into the full system along with the other sub-systems.

Uncertainty and ambiguity were introduced gradually, starting with minimal missing information in the first assignment that required an assumption, design choice or information gathering. Successive assignments contained increasing levels of ambiguity related to the sub-system, and the final project was open-ended, affording teams latitude in design choices of sub-systems and the system as a whole.

Students were expected to consider broader implications of their project, including socio-economic, ethical, geographic and environmental issues. All teams needed to include a section on the broader context of their work as part of their final project report.

Using valid assumptions and determining if the scale and scope of the proposed solution was reasonable was also an ongoing topic of discussion amongst teams and during open office hours. Students were able to compare their design solutions with commercially available products and ask the instructor to check if they were within the generally accepted ballpark. This skill was honed with practice throughout the course.

#### 4.1.2 Student Experiences of Systems Mindsets Learning Activities

One skill that many students described practicing in this course was communicating, specifically with the goal of being better at addressing how to combine individual efforts into designing the whole of the system. When asked what feedback he gave his team members during Assignment 3, for example, a student described asking a teammate "to update me as she went on because sometimes she would go too far on a topic and we would not know what she was working on, therefore not helping her." Another student wrote about the assets he had learned to bring to his team, saying that "Explaining what we were doing to each other I felt helped keep everyone focused and feel included in the process so we could all work more effectively."

#### 4.1.3 Evidence of Developing Systems Mindsets

The vast majority of students reported strong gains in developing a systems mindset over the course of this capstone class on the SALG survey. Between half and two thirds of students indicated great gains in their skills working through open-ended real world problems; breaking a design problem down into manageable tasks; working with others to combine individual efforts towards fulfilling a larger goal or task; and collaborating with team members who are different from themself (see Table 1). A full 82% of students reported great gains in understanding the expectations for industry careers (e.g., teamwork, working open-ended projects, persisting through ambiguity); the remaining 18% reported good gains. This suggests relatively widespread development of students' systems mindsets.

Table 1. Gains in Systems Mindsets among Students in a Thermal Fluids Capstone Course

| Aspect of Systems Mindsets | No Gain | A Little Gain | Moderate Gain | Good Gain | Great Gain |
|---|---|---|---|---|---|
| Working through open-ended real world problems | 0% | 0% | 6% | 35% | 59% |
| Breaking a design problem down into manageable tasks | 0% | 0% | 6% | 35% | 59% |
| Working with others to combine individual efforts towards a larger goal | 0% | 0% | 0% | 35% | 65% |
| Collaborating with team members who are different | 0% | 6% | 18% | 24% | 53% |
| Understanding expectations for industry careers | 0% | 0% | 0% | 18% | 82% |

*Note.* Item asked, "As a result of your work in this capstone course, what gains did you make in your understanding of each of the following?" or "...in the following skills?"

### 4.2 Teaching Systems Content

#### 4.2.1 Faculty Teaching Intentions for Systems Content

Thermal fluid systems fall under the broad umbrella of energy systems. These systems can be abstract, and recognizing these systems, determining and working within system boundaries, and differentiating between and quantifying elements within these systems can be challenging. The fundamental principles embodied in these systems, thermodynamics, fluid mechanics and heat transfer, are typically taught in the mechanical engineering curriculum as separate courses from a systems perspective, rather than a statistical perspective. Many energy systems simultaneously incorporate principles from thermodynamics, fluid mechanics and heat transfer.

The design project for this course intentionally embodied all three fundamental content areas, so the first part of the course was devoted to a high-level review of each individual course with an associated project-focused assignment. This review was intended to do a number of things: a) refresh memories, especially for students who had taken a course during their first- or second-year; b) fill in knowledge gaps for students who had not grasped content for a number of possible reasons, including learning disruptions; c) increase student confidence about applying theoretical principles to real world problems; d) provide a common vocabulary, since there a variety of accepted terms and conventions within the field; and e) highlight differences, point out similarities and dispel common confusions about the three separate branches of study, their distinction from each other, and their overlap.

The instructor extended content review to cover applications related to foundational content such as heat exchanger design, losses during system operation, for example stray heat losses, and pressure drops due to friction in fluid flow. She also included contextual engineering considerations, such as cost implications, economic optimization and environmental consideration of system component selection.

Class time was also used to work through examples, demonstrating how to determine what comprised a system. The definition of a system is not static but rather is defined according to what is being analyzed. For example, determining the power required to cool an entire house requires the analysis of a larger system than determining the power consumption of a single fan. How to bound these systems is a necessary skill needed, as is the ability to determine which components are within the system, and how they differ. An example is that sunlight can provide either electricity or heat, depending on the system element under consideration. The instructor demonstrated how to draw diagrams of system elements and determine what comprised the system and where the boundary was.  Some students intuitively drew systems diagrams as a sense-making tool, but many needed direct coaching to help develop this skill.

For the assignments and project, students were expected to use appropriate units and conversion factors. Problem statements were given with units typically given in engineering handbooks and specifications. Students needed to learn how to convert between different systems of units, check their work and find errors for themselves and their team members. This is a critical skill for practicing engineers, and a challenging skill to learn for many students. Explicit strategies were provided as needed, such as including a unit along with every number in an equation and ensuring unit consistency along with the numerical calculation. Another helpful strategy was for students to label their entries in their code or spreadsheet in terms of equations, units and orders of magnitude used.

Teams also needed to determine when certain assumptions were valid, and which equations and variables to use for modeling their sub-systems. Students were supported in this endeavor through review, early in the course, of relevant topics from foundational courses, along with guided enquiry during open office hours. During the first part of the course, multiple additional office hours were offered each week to work with individuals and teams as they grappled with applying theory to practice. For topics that were an extension of foundational material, such as heat exchanger design, the instructor provided detailed notes with equations and guidelines for how to determine valid ranges and choose variables and equations appropriately.

### 4.2.2 Student Experiences of Systems Content

On the whole, students entered the course without confidence that they had the full foundational content knowledge required to work with thermal fluids systems. In the first reflection, many students described gaps in their knowledge of heat transfer, thermodynamics, and fluid dynamics.

Other students entered the course with some content knowledge from prior classes, but without the ability to fully recognize new systems. As one student shared in their first reflection, “I would say I feel pretty confident with the bones of the problems from what I have done in previous classes, but I do not feel confident when they are changed to involve more real world scenarios.” This often led to students finding it challenging to analyze systems. As another student described, “One of the things I struggled with the most [in the first assignment] was knowing which equations to use where and setting up the mass balance and energy balance equations for specific situations. After finding the right equations I can apply the right values and calculate, but I sometimes get lost when trying to consider all parts of the problem.” This student provides an example where the instinct of considering the parts and the whole together has been instilled, but the knowledge on which doing so relies is still weak.

Critical to this course is the ability to consider the units used in quantifying parts of the system and understanding how to convert them within equations and when combining parts into the whole system being designed. This was an issue that many students worked through across the course of the term. For example, one student noted in their reflection for Assignment 3 that “I am learning (slowly) to use units in every equation I write. I have had issues with this in the past, but I believe that I am improving.” If there were only a single open-ended assignment in which students were challenged to set their own equations and convert units, there would not have been sufficient practice for students to develop this habit regarding their knowledge of identifying systems.

### 4.2.3 Evidence of Developing Systems Content Knowledge

Students indicated strong learning of systems content knowledge in the course. All students reported good (41%) to great (59%) gains in analyzing thermofluid systems (see Table 2). The majority of students (71%) reported great gains in integrating fluid mechanics, thermodynamics, and heat transfer; another 24% indicated great gains and 6% indicated moderate gains. The development of skills for formulating problem statements was still broadly positive, though slightly less strong: 35% of students indicated great gains and 53% reported good gains, with the remaining 12% indicating moderate gains. Overall, this pattern suggests widespread systems content knowledge was supported by the course's learning activities.

Table 2. Gains in Systems Content among Students in a Thermal Fluids Capstone Course

| **Aspect of Systems Mindsets** | **No Gain** | **A Little Gain** | **Moderate Gain** | **Good Gain** | **Great Gain** |
|---|---|---|---|---|---|
| Analyzing thermofluid systems | 0% | 0% | 0% | 41% | 59% |
| Integrating fluid mechanics, thermodynamics & heat transfer | 0% | 0% | 6% | 24% | 70% |
| Formulating problem statements | 0% | 0% | 12% | 53% | 35% |

*Note.* Item asked, "As a result of your work in this capstone course, what gains did you make in your understanding of each of the following?" or "...in the following skills?"

## 4.3 Teaching Systems Structure

### 4.3.1 Faculty Teaching Intentions for Systems Structure Skills

Apart from helping students figure out what comprised the system, boundary and elements, their system diagrams were useful for understanding the structure of the system. Having a picture of the physical components and how these connected to each other and the surroundings helped students visualize the organization of components, sub-systems and the overall system. Having a diagram with clearly marked relationships also enabled students to see how the output from a certain component or sub-system became the input for another, and thereby helped students identify feedback loops.

Relationships were characterized with variables and equations, and students also determined if each relationship strongly influenced overall system performance. Since students undertook their projects with the backdrop of considering the broader context of decisions, they also evaluated relationships between their physical system and economic, environmental and societal implications. Some relationships dominated the overall system or sub-system performance or other considerations, and some feedback loops occurred in sub-systems that were connected to all or most other systems. Once students were equipped with this insight, they made initial estimates for a few key parameters and iterated the dominating relationships and feedback loops within sub-systems. They then moved on to incorporating more tangential relationships and sub-systems into their design and system optimization. Careful selection of initial performance parameters minimized the number of design iterations needed.

### 4.3.2 Student Experiences of Systems Structure Skills

There was a common experience among a subset of students who used the complexity of the systems they were asked to design to improve their ability to identify and leverage feedback loops. The primary way that students described this was having experiences in which their results clearly did not make sense, prompting them to go back through their assumptions and calculations to determine which led to the results being off. “As a group we learned to problem solve pretty well, as there were some parts of our spreadsheet that had a wrong formula, leading to wacky results. Together we worked through the equations and found the errors.” This student went on to describe how identifying these relationships up front has become part of their regular process. “We further worked through our set up skills, making sure we were all on the same page in terms of starting the project and being organized.” Although the student does not describe this in terms of feedback loops, that is essentially what they are describing.

### 4.3.3 Evidence of Developing Systems Structure Skills

Overall, systems structure skills had the greatest range of development among students. Two thirds of students (65%) reported great gains in modeling open-ended problems and the remaining third (35%) reported good gains (see Table 3). However, the other two skills in this area exhibited a broader range of learning. In specifying design requirements and constraints, 35% of students reported great gains, 41% reported good gains, and 24% reported moderate gains. In identifying my own and others’ mistakes – a process that requires a sufficient understanding of how to make sense of feedback loops within the system – 41% of students reported great gains, 35% reported good gains, and 24% reported moderate gains.

Table 3. Gains in Systems Structure Skills among Students in a Thermal Fluids Capstone Course

| Aspect of Systems Mindsets | No Gain | A Little Gain | Moderate Gain | Good Gain | Great Gain |
|---|---|---|---|---|---|
| Modeling open-ended problems | 0% | 0% | 0% | 35% | 65% |
| Specifying design requirements and constraints | 0% | 0% | 24% | 41% | 35% |
| Identifying my own and others’ mistakes | 0% | 0% | 24% | 35% | 41% |

*Note.* Item asked, "As a result of your work in this capstone course, what gains did you make in your understanding of each of the following?" or "...in the following skills?"

## 5. Teaching Systems Thinking as Complexity Leadership

Complexity Leadership Theory recasts leaders as enablers who create the conditions for successfully navigating unknown futures – which also describes what instructors do in undergraduate STEM education. This offers a stark contrast to earlier, top-down approaches in which leaders are charged with controlling strategic action more directly [30]; the same could be said of teaching in a student-centered course that emphasizes systems thinking mindsets and skills [31].

### 5.1 Implications for Teaching Systems Thinking Skills in Capstones

Several aspects of this new approach to leadership map onto the teaching strategies enacted by Author A in this study, with its emphasis on fostering an adaptive space, preparing the system for emergent realities and emphasizing the importance of social capital over individuals' knowledge and skills in isolation [8]. One of the ways that Author A prepared students to approach their design work as a complex system, rather than a simple problem set, was to set up much of the class time to mirror a consulting firm. Over the term, the course decreased lecture-based time and increased the need for students to adapt together in teams to design challenges. By having students work on teams during class time and making herself available to provide feedback, advice, or suggest fresh ways of thinking about a particular issue, Author A empowered students as systems designers. As a sign that the system was effectively structured to provide an adaptive space, students knew how to get themselves out of being stuck, as every team regularly called on the instructor to pose design problems they faced and receive feedback, and there was sufficient trust built over time for students to demonstrate this lack of perfect knowledge and skill.

Part of preparing the class system for educational realities to be emergent was allowing students substantial choice over their designs, which is a common element of project-based learning and related student-centered pedagogies [32]. Complexity leadership during instruction extended this course design by giving students increasingly complex design challenges over the term and decreasing the time allocated to reviewing relevant material from prior coursework. By assigning students reflection questions to ask themselves and to be aware of while working on these increasingly complex design challenges, the conditions for transferring what is learned to navigating future issues was indirectly addressed.

### 5.2 Future Research

Future phases of this study will continue to explore the parallels between complexity leadership and teaching systems thinking; future research beyond this study might continue to examine how these parallels can best be supported within a broad array of undergraduate teaching contexts. As the literature on systems thinking demonstrates, there is an interest across multiple fields in bringing systems thinking to the foreground in undergraduate STEM education.

**References**

[1] J. Malmqvist et al., “Towards CDIO standards 3.0,” in *Proceedings of the 15th International CDIO Conference*, *2019*, pp. 512-529.

[2] R.D. Arnold and J.P. Wade, “A definition of Systems Thinking: A Systems Approach,” in *Procedia Computer Science 44, 2015,* pp 669-678.

[3] T. Plate and M. Monroe, “A structure for assessing systems thinking” *The Creative Learning Exchange*, vol. *23 no.* 1, pp.1-3, 2014.

[4] R.D. Arnold and J.P. Wade, “A Complete Set of Systems Thinking Skills,” in *27th Annual INCOSE International Symposium (IS 2017), Adelaide, Australia, July 15-20, 2017,* in INSIGHT, vol. 20, issue 3, pp. 9-17, Sep. 2017.

[5] T.F.A C. Sigahi and L.I. Sznelwar, “Exploring applications of complexity theory in engineering education research: A systematic literature review,” *Journal of Engineering Education,* vol. 111, no. 1, pp. 232-260, 2022.

[6] A. Kwamie, S. Causevic, G. Thomson, A. Sie, R. Sauerborn, K. Rasanathan, and O.P. Ottersen, “Prepared for the polycrisis? The need for complexity science and systems thinking to address global and national evidence gaps,” *BMJ Global Health,* vol. 9, no. 9, 2024.

[7] J. Rosenhead, L.A. Franco, K. Grint, and B. Friedland, “Complexity theory and leadership practice: A review, a critique, and some recommendations,” *The Leadership Quarterly,* vol. 30, no. 5, Article 101304, 2019.

[8] M. Uhl-Bien and R. Marion, “Complexity leadership theory,” in *The SAGE handbook of leadership,* 2011, pp. 468-482.

[9] J. H. Ogle and R. Marion, “Board 116: Assessing Complexity Leadership Theory (CLT) as a Change Model for Inculcating a Shared Vision and Fostering Transformation in an Engineering Department,” in *2019 ASEE Annual Conference & Exposition,* June 2019.

[10] P. V. Gantasala, “Complexity leadership and knowledge management in higher education,” *International Journal of Educational and Pedagogical Sciences,* vol. 9, no. 2, pp. 707-714, 2015.

[11] J. Froyd, L. Pchenitchnaia, D. Fowler, and N. Simpson, “Systems Thinking And Integrative Learning Outcomes,” in *2007 ASEE Annual Conference & Exposition,* Honolulu, Hawaii, June 2007.

[12] J. Monat, T. Gannon and M. Amissah, “The case for systems thinking in undergraduate engineering education,” *International Journal of Engineering Pedagogy (iJEP),* vol. 12, no. 3, pp. 50-88, 2022.

[13] P. Godfrey, R.D. Crick and S. Huang, "Systems thinking, systems design and learning power in engineering education," *International Journal of Engineering Education*, vol. 30, no. 1, pp. 112–127, 2014.

[14] R.G. Hadgraft, A.L. Carew, S.A. Therese and D.L. Blundell, "Teaching and assessing systems thinking in engineering," in *Research in Engineering Education Symposium 2008*, pp. 230-235, January 2008.

[15] S. Huang, K. H. Muci-Kuchler, M. D. Bedillion, M. D. Ellingsen and C. M. Degen, "Systems thinking skills of undergraduate engineering students," in *2015 IEEE Frontiers in Education Conference (FIE), El Paso, TX, USA*, pp. 1-5, 2015.

[16] R. Jain, K. Sheppard, E. McGrath and B. Gallois, "Promoting Systems Thinking in Engineering and Pre-Engineering Students," in *2008 Spring ASEE Middle Atlantic Section Conference, Washington, D.C.*, April 2008, https://peer.asee.org/50375.

[17] S. Gianelloni and M.H. Goldstein, "Modelling the Design Systems Thinking Paradigm," in *2020 ASEE Virtual Annual Conference Content Access*, Virtual Online, June 2020.

[18] R. Peretz, M. Tal, E. Akiri, D. Dori and Y.J. Dori, "Fostering engineering and science students' and teachers' systems thinking and conceptual modeling skills," *Instructional Science*, vol. 51, pp. 509–543, 2023.

[19] S.C. Liu, "Examining undergraduate students' systems thinking competency through a problem scenario in the context of climate change education," *Environmental Education Research*, vol. 29, no. 12, pp. 1780–1795, 2022.

[20] F. Camelia, T.L.J. Ferris, "Undergraduate students' engagement with systems thinking: results of a survey study," *IEEE Transactions on Systems Man and Cybernetics: Systems*, vol. 47, issue 12, pp. 3165-3176, December 2017.

[21] F. Camelia, T. L. J. Ferris and M. B. Behrend, "The Effectiveness of a Systems Engineering Course in Developing Systems Thinking," *IEEE Transactions on Education*, vol. 63, no. 1, pp. 10-16, Feb. 2020.

[22] Accessed 5 Jan. 2025. Available: incose.org/about-systems-engineering/what-is-systems-engineering

[23] Accessed 5 Jan. 2025. Available: incose.org/about-systems-engineering/se-education

[24] Accessed 5 Jan. 2025. "Best Systems Engineering Degree Colleges in the U.S. | 2025." Available: universities.com/programs/systems-engineering-degrees

[25] Accessed 5 Jan. 2025. Available: abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2025-2026/

[26] K.T. Aung, “Integration of System Thinking, Engineering Reasoning, and Decision-making Skills in Design of Thermal Systems Course,” in *2012 ASEE Annual Conference & Exposition, San Antonio, Texas,* June 2012.

[27] F. Levey, Instructor Toolkit for Engineering Capstone Design, Worcester Polytechnic Institute, 2023.

[28] R. Mathieu, S. Carroll, T. Weston, E. Seymour, S. Lottridge, and C. Dolan, “Student assessment of their learning gains (SALG),” retrieved from www.salgsite.org June 25, 2022, 2012.

[29] LeChasseur, K., Wodin-Schwartz, S. J., Sloboda, A., & Powell, A. (2024). Validity of a self-report measure of student learning in active learning statics courses. *International Journal of Mechanical Engineering Education*, 03064190241253509.

[30] D. Plowman, L.T. Baker, T. Beck, M. Kulkarni, S. Solansky, and D. Travis, “The role of leadership in emergent, self-organization,” *The Leadership Quarterly,* vol. 18, pp. 341-356, 2007.

[31] E.B. Dano, “Introducing Systems Thinking Techniques into an Undergraduate Engineering Education, in *INCOSE International Symposium,* vol. 32, no. 1, pp. 199-209, July 2022.

[32] C. Hanewicz, A. Platt and A. Arendt, “Creating a learner-centered teaching environment using student choice in assignments,” *Distance Education*, vol. 38, no. 3, pp. 273-287, 2017.

**Appendix A**
SALG Survey Items

Q1 As a result of your work in this Capstone class, what GAINS DID YOU MAKE in your UNDERSTANDING of each of the following? (Response options: 1-No Gains, 2-A Little Gain, 3-Moderate Gain, 4-Good Gain, 5-Great Gain)

| |
|---|
| The main concepts explored in this class |
| The relationships between the main concepts |
| How ideas from this class relate to ideas you encounter in other classes |
| How studying this subject area helps people address real world issues |
| Expectations for industry careers (e.g., teamwork, working open-ended projects, persisting through ambiguity) |

Q2 As a result of your work in this Capstone class, what GAINS DID YOU MAKE in the following SKILLS? (Response options: 1-No Gains, 2-A Little Gain, 3-Moderate Gain, 4-Good Gain, 5-Great Gain)

| |
|---|
| Analyzing thermofluid systems |
| Modeling open-ended problems |
| Integrating fluid mechanics, thermodynamics, & heat transfer |
| Formulating problem statements |
| Specifying design requirements & constraints |
| Collaborating with team members who are different than yourself |
| Working through open-ended real world problems |
| Identifying my own and others' mistakes |
| Breaking a design problem down into manageable tasks |
| Working with others to combine individual efforts towards fulfilling a larger goal or task |

Q3 As a result of your work in this Capstone class, what GAINS DID YOU MAKE in the following? (Response options: 1-No Gains, 2-A Little Gain, 3-Moderate Gain, 4-Good Gain, 5-Great Gain)

| |
|---|
| Enthusiasm for engineering |
| Confidence that you understand the material |
| Confidence that you can design thermofluid systems |

Willingness to seek help from others (professor, classmates, friends) when working on academic problems

Connections to other WPI students

My sense that I am a valuable contributor in teamwork

Q4 HOW MUCH did each of the following aspects of this Capstone class HELP YOUR LEARNING? (Response options: 1-No Help, 2-A Little Help, 3-Moderate Help, 4-Good Help, 5-Great Help)

Attending class

Attending Open Office Hours/Group Work

The First (solo) Thermo Assignment

Assignments 2, 3, & 4

Participating in team work

Asset mapping in a team

Having a team charter

Written reflections

Being encouraged to take learning risks

Having time in class to work in teams

Q5 Please comment on how asset mapping and creating a team charter influenced your experience of teamwork in this Capstone class.

Q6 This course required project assignments with increasing assumptions over the term. How did you handle this, both yourself and with your group? What was hard and what about the course supported your success with this?

Q7 To what extent did the course require you to use new engineering concepts, information, methods, etc. that you had not learned in prior courses?

Not at all or very little
Somewhat, but I was able to catch up quickly
Somewhat, and it was hard to catch up
A lot, but I was able to catch up quickly
A lot, and it was hard to catch up

Q8 To what extent did the course require you to learn in new ways (e.g., group projects, design)?

Not at all or very little - I had all of these in other classes
There were a few new ways of working, but it was easy to learn

There were a few new ways of working, and it was difficult to learn
A lot of how we worked was new to me, but it was easy to learn
A lot of how we worked was new, and it was difficult to learn

Q9 My experience of the work required in high school classes was:
It was very easy for me to get the grade I wanted in all my classes
With a few exceptions, it was easy for me to get the grade I wanted in my classes
I had to work some, but not all that hard to get the grade I wanted in my classes
I had to work hard to get the grade I wanted in my classes

Q10 In college:
I have to work less than I did in high school to get the grades I want
I have to work the same amount as I did in high school to get the grades I want
I have to work harder than I did in high school to get the grades I want

Q11 How do you self-identify in terms of gender? (please select all that apply)
A woman
A man
Non-binary or gender fluid
Transgender
Other

Q12 If you self-identify as a gender not listed, please add to my knowledge and tell me how you self-identify:

Q13 How do you self-identify in terms of race/ethnicity? (please select all that apply)
American Indian or Alaska Native
Asian or Asian American
Black or African American
Native Hawaiian or other Pacific Islander
White
Hispanic or Latinx
Other

Q14 If you self-identify as a race/ethnicity not listed, please add to my knowledge and tell me how you self-identify: